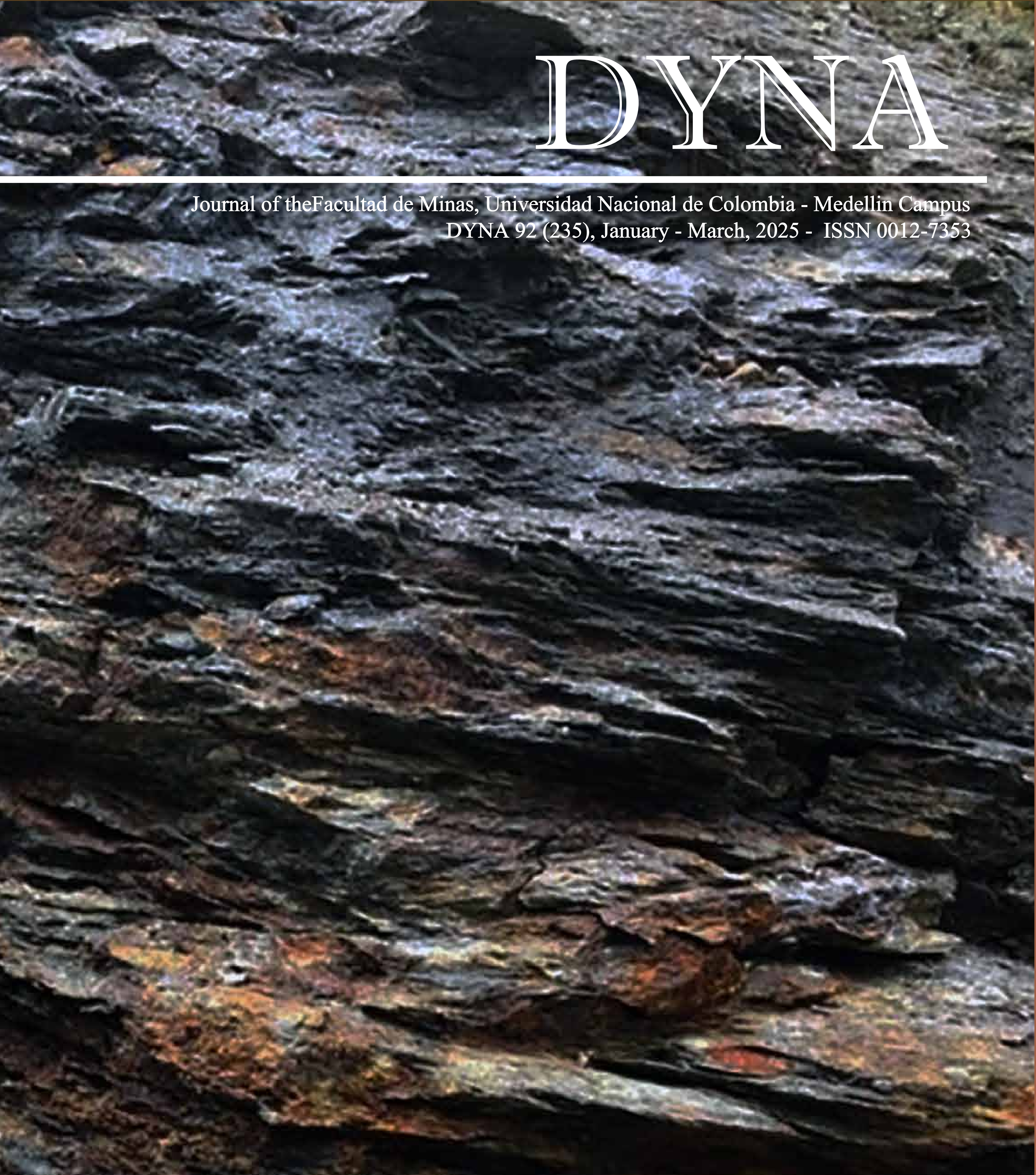

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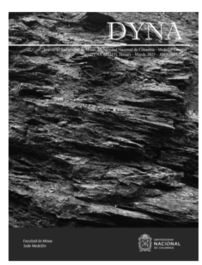

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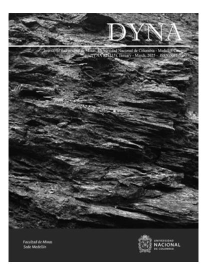

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Editorial

La revista DYNA se ha consolidado como un referente en la publicación de investigación científica de alta calidad en el ámbito de la ingeniería, con una periodicidad de cuatro ediciones al año. En cada una de nuestras ediciones, hemos tenido el honor de contar con alrededor de 20 artículos provenientes de diversos campos del conocimiento, lo que nos ha permitido mantener un alto estándar de visibilidad y credibilidad en los principales índices académicos, como Publindex, Scopus, Redalyc y otras bases de datos internacionales.

En un esfuerzo por continuar ofreciendo contenido de calidad y en cumplimiento con las políticas de indexación que rigen nuestra revista, deseamos informar a nuestros lectores y autores sobre un ajuste en nuestra política editorial. En 2025 DYNA ha tomado la decisión de paulatinamente reducir el número de artículos publicados; así, en las cuatro ediciones ordinarias del año se publicarán 20, 18, 14 y 12 artículos respectivamente. Esta modificación responde a la necesidad de mantener una selección más rigurosa y enfocada, alineada con las demandas de calidad y la sostenibilidad de nuestro proceso editorial.

Además, como parte de las políticas de indexación vigentes en Publindex – Minciencias y otros índices internacionales, solo se permite que un 20% de los artículos publicados en cada edición sean de autores internos, es decir, de la Universidad Nacional de Colombia. Por tanto, de los 12 artículos que conformarán las ediciones de DYNA, solo se publicará un artículo que provenga de autores de nuestra institución. Esta medida tiene como objetivo garantizar la visibilidad y la proyección internacional de la revista, manteniendo un equilibrio entre la representación interna y la inclusión de contribuciones externas de alta calidad.

Agradecemos a nuestros autores, lectores y colaboradores por su comprensión y apoyo en este proceso, que busca fortalecer la misión de DYNA de seguir siendo una publicación de referencia para la comunidad académica y científica, tanto a nivel nacional como internacional.

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Multi-temporal analysis of land cover changes due to hurricanes Iota and Eta on the islands of San Andres, Providencia and Santa Catalina

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Abstract
This study analyzes the how the land cover on the islands of San Andres, Providencia and Santa Catalina, Colombia, was impacted by hurricanes Iota and Eta in 2020. A multitemporal analysis using Sentinel-2 satellite images of the years 2020 and 2021 was conducted to identify changes in land cover and the spectral responses of the NDVI, NDWI, BSI and NBR indices. The results indicate that on Providencia and Santa Catalina the most affected types of land cover were forests, mangroves, secondary vegetation and beaches, particularly in the north and northeast of Providencia and throughout the entire area of Santa Catalina. On San Andres, mangrove forests and grasslands on the eastern and southern coastal edge of the island were the most affected types of cover. This kind of analysis is important to decision makers in coastal land planning because it represents the behavior of land cover in coastal areas in response to disturbances induced by hurricanes, and thus helps us to understand how such extreme natural phenomena influence islands.

Keywords: multi-temporal analysis; hurricane; remote sensing; spectral indices; land cover.

Análisis multitemporal de los cambios en la cobertura terrestre por los huracanes Iota y Eta en las islas de San Andrés, Providencia y Santa Catalina

Resumen
Este estudio analiza el impacto generado en las coberturas terrestres de las islas de San Andrés, Providencia y Santa Catalina, Colombia debido a la influencia de los huracanes Iota y Eta del año 2020. Se emplea un análisis multitemporal a partir de imágenes satelitales Sentinel-2 de los años 2020 y 2021 para identificar cambios en las coberturas terrestres y en las respuestas espectrales de los índices NDVI, NDWI, BSI y NBR. Los resultados indican que en Providencia y Santa Catalina las coberturas más afectadas fueron los bosques, manglares, vegetación secundaria y playas, especialmente en el norte y noreste de Providencia, así como en toda el área de Santa Catalina. En la isla de San Andrés se afectaron principalmente los bosques de manglar y pastos sobre el borde costero del este y sur de la isla. Este tipo de análisis son de gran importancia para los responsables de la planificación territorial costera, ya que permite representar el comportamiento de las coberturas en zonas costeras ante perturbaciones causadas por huracanes, de esta manera, facilita la comprensión del impacto que estos fenómenos naturales extremos tienen en las islas.

Palabras clave: análisis multitemporal; huracanes; sensores remotos; índices espectrales; coberturas terrestres.

1 Introduction

Hurricanes are extreme and dangerous meteorological phenomena that primarily occur in the Caribbean Sea (Fig. 1) between June and November, causing severe damage to both humans and the environment. Hurricanes typically have a significant impact on the distribution and structure of trees [1], altering biodiversity and vegetation in places where

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natural events occur [1]. Between the years 1900 and 2010, 60 hurricanes have been recorded in the Colombian Caribbean, 17 of which impacted the island of San Andres. The most severe hurricanes that caused the greatest damage include Hattie (1961), Alma (1970), Irene (1971), Joan (1988), Katrina (1999) and Beta (2005) [2,3]. Extreme events are more intense and frequent as a result of climate change, as category IV and V hurricanes have doubled since the 60's at distances less than 600 km from the island of San Andres. [4].

Hurricanes Iota and Eta struck Colombia's Caribbean Island territories between November 2 and November 17, 2020, wreaking devastation on the islands of San Andres, Providencia, and Santa Catalina with their strong rainfall, thunderstorms, and mudflows [5]. According to NOAA [6], Hurricane Eta began on October 31, 2020, and dissipated on November 13, reaching category 4 between November 2 and 3 around Puerto Cabezas, Nicaragua, approximately 200 km from Providencia and Santa Catalina and at a distance of 210 km from San Andres. Meanwhile, Hurricane Iota developed on November 13, 2020 and dissipated on November 18, becoming a category 5 hurricane on November 16 about 10 km north of Providencia and Santa Catalina. In Providencia and Santa Catalina, 98% of the infrastructure was destroyed.as a result of the hurricane's torrential rainfall, winds of up to 250 km/h, and flooding [7].

The archipelago suffered severe environmental consequences as a result of hurricanes Iota and Eta. These include a lack of clean drinking water, unhygienic conditions, and a marked decline in both terrestrial and marine ecosystems. 90% of the tropical dry forest was severely damaged, leading to the degradation of the islands' ecological structures. Moreover, there was significant damage to 70% of the mangroves on the islands' northeastern and northern borders [5].

In Colombia, several multi-temporal analyses have been carried out to identify changes in land cover generated by restoration plans and programs [8, 9], mining projects [10-12], and anthropogenic interventions in the Colombian Caribbean [13-18].

In [8], Landsat satellite images from 2003 and 2016 were used in a supervised classification procedure to quantify changes in forested areas after a reforestation program. In the municipality of Madrid, Cundinamarca, an analysis was conducted to identify changes in land cover and use in the "Casablanca" protective forest reserve area [9].

Likewise, multi-temporal analyses have been carried out in areas affected by mining projects to evaluate the impact of mining on vegetation, as demonstrated by [10] in their study of gold mines in the municipality of Manizales. [11] detected changes in the land cover of the Cerromatoso mine between 2011 and 2015. In [12], the extent to which the Ituango hydroelectric project affected vegetation cover and the Cauca River channel between 2009 and 2019 was examined using Sentinel-2 images

Studies have been conducted in the Colombian Caribbean to better understand how land cover has changed and to assess the impacts of various disturbances and improvement initiatives. For instance, in the department of Sucre, human activity has been found to lead to an increase in savannah cover [13]. In the municipality of Manaure, Guajira, land cover analysis was used to identify the expansion of desert areas and the relationship between desert expansion and population growth. [14]. Furthermore, in Uraba Antioquia, the change in land cover caused by flooding and coastal erosion was evaluated using satellite images from 1998 and 2017 [15].

In general, research in the Colombian Caribbean has been conducted to identify changes in mangroves caused by agricultural and animal operations, particularly the shrimp business [16]. Likewise, changes in land cover and soil distribution in areas of high ecological value have been investigated [17]. Finally, in Providencia, a study was conducted to assess deforestation on the island from 2005 to 2009 [18].

It is important to emphasize that while research has examined changes in coverage in the Caribbean region of Colombia, there are few multi-temporal analyses available that help us comprehend how hurricanes and tropical storms affect the islands and territory in this region.

In countries and territories located in the Caribbean Sea, such as the islands of the Dominican Republic and Puerto Rico, multi-temporal analyses have been carried out to identify the impact and assess damage from Hurricane Maria in 2017. These analyses used Landsat-8 and Sentinel-2 satellite images corresponding to the years 2015, 2016 and 2017 [19]. Additionally, [20] examined the connection between the impact of Hurricane Stan in 2005 and the land usage of coffee farms in Chiapas, Mexico by examining Spot images taken 2, 14, and 40 months after the hurricane as well as eight months prior to it.

The islands of San Andres, Providencia, and Santa Catalina suffered detrimental environmental and social repercussions as a result of hurricanes Iota and Eta. There is therefore a need to identify and analyze the changes and possible consequences that these natural phenomena have had on the islands' land cover. New strategies need to be presented to decision makers in order to prevent and mitigate for the environmental impacts caused by hurricanes. Therefore, a multi-temporal analysis was carried out using Sentinel-2 multispectral images to identify the effects that hurricanes have on land cover and determine changes in their spectral responses. The present study aims to: (1) examine the impact of hurricanes Iota and Eta on the land coverage of the islands of Santa Catalina, Providencia, and San Andres; (2) identify the regions most impacted by changes in coverage between 2020 and 2021; and (3) interpret and evaluate the variations in NDVI, NDWI, BSI and NBR spectral indices in the pre- and post-hurricane scenarios.

2 Methodology

2.1 Study area

The Islands of San Andres (SAI), Providencia and Santa Catalina (PSC) are located in the Caribbean Sea and are part of the Colombian insular territory. San Andres has an area of 26.76 km^2, Providencia covers 20.64 km^2, while Santa Catalina, which is next to Providencia, has an area of 1.17 km^2. San Andres is located 637 km northwest of mainland

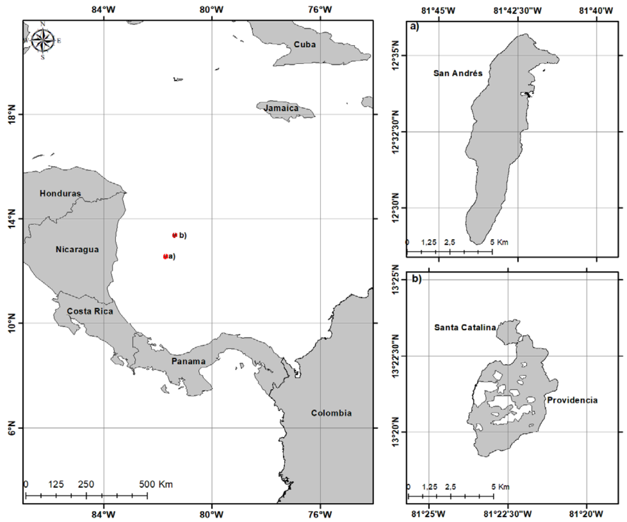

Figure 1. Study area. a) San Andres and b) Providencia and Santa Catalina islands
Source: Authors.

Colombia and 200 km away from Nicaragua, while Providencia and Santa Catalina are located 80 km northwest of San Andrés (see Fig. 1). According to data from the population census of Colombia, in the year 2018 the island of San Andres had a population of 48,299 inhabitants, while Providencia and Santa Catalina had 4,545 inhabitants [21].

2.2 Selection and processing of satellite images

The Sentinel-2 satellite mission belongs to the ESA (European Space Agency) and is well-regarded due to its varied applications, high spatial, temporal, spectral, radiometric resolution, and its easy accessibility. Sentinel-2 satellite images have a spatial resolution between 10 and 20 m, which is considered ideal for the classification of land coverage [22].

The data sets used in this study consist of satellite images obtained and processed on the Google Earth Engine platform. A filter was applied to select image sets with a percentage of clouds less than 10% in order to acquire the lowest possible proportion of cloudiness. A filter by date was also applied to obtain a set of images taken between April and May 2020 and April and May 2021, and thus represent scenarios before and after the hurricanes. These dates were selected based on the availability of images with little cloud cover and were taken at the same times of the year to minimize climate variability.

The high percentage of clouds in the satellite images of Providencia makes it difficult to classify coverage and calculate spectral indices. Therefore, a clipping mask was assigned to remove areas with high cloud cover, which includes a 50-meter buffer around the islands' coastline and the cloud extraction area. A buffer of 50 m above the coastline was applied for the San Andres study area.

2.3 Calculation of spectral indices

The normalized vegetation index (NDVI) was used to determine the amount of surface vegetation and to evaluate the health status of the plants [19], while the Normalized Difference Water Index (NDWI) was used to highlight bodies of water by measuring moisture content. The Bare Soil Index (BSI) was used to determine areas with little vegetation cover or without any vegetation cover, which helped identify degraded areas, beaches and bare soil. The Normalized Burn Ratio (NBR) was used to determine and rule out areas with high degradation or vegetation affected by forest fires [23].

The percentage difference between the values obtained in 2020 and 2021 was calculated (see eq. 1) to determine the locations that exhibited the greatest differences in spectral indices (NDVI, NDWI, BSI and NBR).

$$\left[\frac{Value\ 2021\ -\ Value\ 2020}{Value\ 2020}\right] * 100 \qquad (1)$$

2.4 Classification and comparison of land cover

Land cover was classified and compared by analyzing satellite images from the same area taken at different times [17]. Hence, a multi-temporal analysis was carried out based on supervised classifications and photointerpretation of Sentinel-2 images in settings before and after the passage of hurricanes Iota and Eta. This type of study identifies, analyzes and compares land cover changes induced by anthropogenic and natural events [24].

The Google Earth Engine platform, which geospatially analyzes satellite images stored in the cloud without the need to download them, was utilized to classify land cover. This leveraged the computing power of Google, procedural agility and the variety of analyses [25].

The supervised classification of coverage was carried out using the Support Vector Machine (SVM) classification method, which is a Machine-Learning algorithm that has performed well in different training areas. This allows training areas and classes with similar spectral characteristics to be developed [24]. Analysis is done based on coverage classes, which takes into account the shape, texture, color and roughness of the pixels of the satellite images. The types of coverage used are identified in Table 1.

Table 1.
Types of coverage

Land cover	Description
Forests	Areas with high density of trees and little anthropogenic intervention
Mangrove forests	Mangrove forest area bordering the sea
Secondary vegetation	Areas with high and medium density of vegetation with a succession process
Pastures	Land with grass, weeds and low density of trees with high anthropic intervention
Bare ground	Land surface devoid of vegetation
Urban areas	Continuous and discontinuous urban areas with the presence of homes, buildings, roads, docks
Water bodies	The sea, rivers, dams and other bodies of waters
Beaches	Areas of beaches on coastlines
Degraded areas	Areas with tree vegetation affected and burned by hurricanes and anthropogenic interventions

Source: Authors.

The areas that presented cloudiness were not considered in the classification and were excluded from the analysis and comparison areas. Finally, to reduce error and guarantee greater similarity to what is displayed in the satellite images, manual adjustments to the coverage were made in areas with less coherence.

The accuracy of the coverage results was evaluated using a confusion matrix and the Kappa index to determine agreement and correctness of the coverage validation points [22]. 20 random samples per type of coverage were considered for validation. These points were obtained from the collection of Sentinel-2 satellite images in the same temporalities evaluated.

Changes in land cover were quantified in the pre- and post-hurricane scenarios. The areas corresponding to each type of cover were calculated and changes, whether loss or gain, were analyzed. This comparison of coverage made it possible to identify the areas that experienced significant change and those that remained stable, as well as determine the positive and negative changes in coverage.

3 Results

3.1 Normalized Difference Index (NDVI)

The NDVI for the scenarios between April and May in 2020 and April and May 2021 show the presence of healthy and dense vegetation when the values are close to 1, while areas with less vegetation present lighter tones and lower values. In contrast, the absence of vegetation, indicating a predominance of soils, beaches and grasses, corresponds to values close to 0. Bodies of water, due to their level of absorbance and reflectance, exhibit values lower than 0 and have light gray tones.

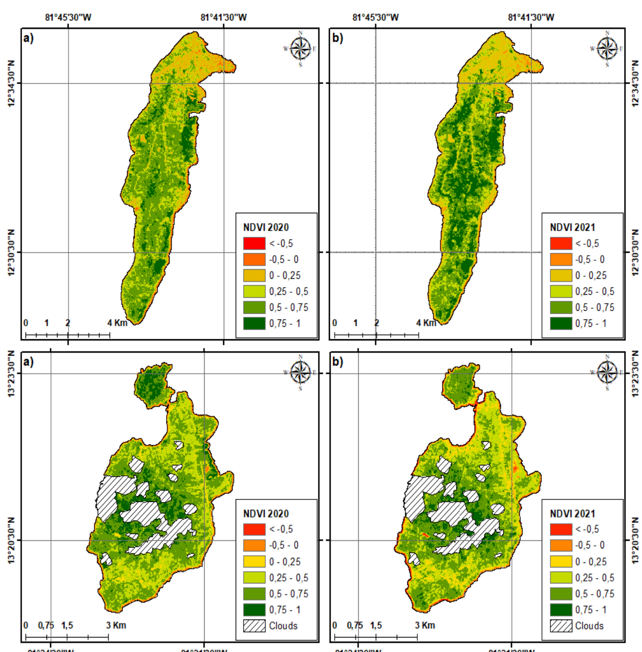

Figure 2. NDVI for the islands of San Andres (lower panel) and Providencia and Santa Catalina (upper panel) for the year a) 2020 and b) 2021.
Source: Authors.

Fig. 2 and Table 2 illustrate the 2020 and 2021 NDVI results in SAI and PSC. For 2020 (Fig. 2a), there are high NDVI values in Santa Catalina and in the northeast, central and southern areas of Providencia. For 2021 (Fig. 2b), the values decrease, especially in strips close to the coastline, and in the northeast of Providencia and Santa Catalina. On the island of San Andres, the NDVI index does not show major variations. Slight decreases are observed in some sectors adjacent to the coastline, particularly in the southwest and northeast of the island.

Fig. 3 presents the NDVI percentage difference (Diff (%)) between the years 2020 and 2021. In the northeast and on the coastal edge of Providencia, negative differences greater than 50% are observed along the coastline and on the border with Santa Catalina. There are negative differences greater than 100% in some strips in the north, northeast and east of Providencia as well as in the entire south of Santa Catalina. In the mangrove forests and the bordering areas between the two islands the index values decrease by up to 100%. The central region of SAI (Fig. 3b) shows a minor increase in the NDVI index (less than 50%), while there is a decrease in the northeast, north, and western coastal edge.

3.2 Normalized Difference Water Index (NDWI)

Fig. 4 and Table 3 show the NDWI values on SAI and PSC for 2020 and 2021. The NDWI index presents values close to 1 for bodies of water and areas with humidity

Table 2.
Results of the NDVI index for San Andres (SAI), Providencia and Santa Catalina (PSC) considering average, standard deviation (STD), minimum (Min) and maximum (Max) values and the mean of the difference (Mean diff).

NDVI	Mean	STD	Min	Max	Mean diff (%)
PSC2020	0.510	0.233	-0.525	0.868	0.000
PSC2021	0.445	0.306	-0.997	0.900	-14.79
SAI 2020	0.471	0.243	-0.268	0.921	0.000
SAI 2021	0.489	0.273	-0.431	0.928	-0.315

Source: Authors.

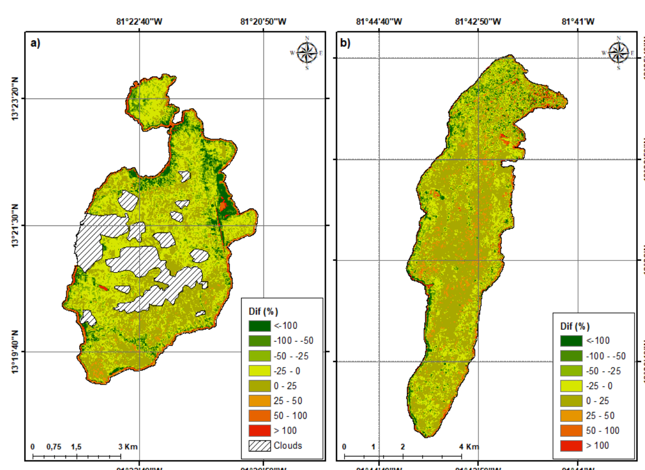

Figure 3. NDVI percentage differences for a) Providencia and Santa Catalina and b) San Andres between the years 2020 and 2021.
Source: Authors.

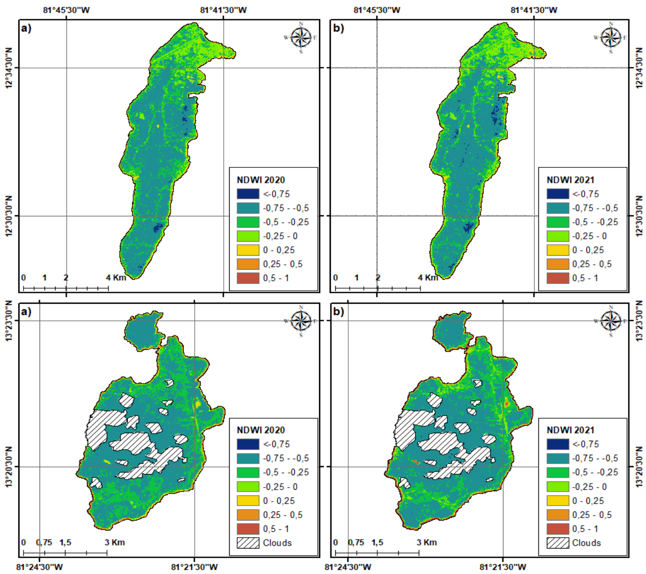

Figure 4. NDWI for the island of San Andres (lower panel) and Providencia and Santa Catalina (upper panel) for the year a) 2020 and b) 2021.
Source: Authors.

Table 3.
Results of the NDWI index for San Andrés (SAI), Providencia and Santa Catalina (PSC) considering average, standard deviation (STD), minimum (Min) and maximum (Max) values and the mean of the difference (Mean diff).

NDWI	Mean	STD	Min	Max	Mean diff (%)
PSC 2020	-0.475	0.240	-0.762	0.729	0.000
PSC 2021	-0.453	0.318	-0.787	0.999	0.695
SAI 2020	-0.445	0.225	-0.821	0.622	0.000
SAI 2021	-0.452	0.254	-0.838	0.604	-8.733

Source: Authors.

saturation, and negative values for dry or waterless areas. The 2020 scenario on PSC (Fig. 4a, upper panel) clearly identifies sea along the entire edge of the islands, as well as in the northeast of Providencia where there is a predominance of mangrove areas. For 2021 (Fig. 4b, upper panel), the index values increase mainly in the northeast and in some strips along the coast of Providencia, but on average there are higher index values in 2020 (see Table 3).

On San Andres, the NDWI does not indicate significant variations in the water masses. There is a slight increase in the index in the northeast and southwest of the island, as these are mangrove areas and have more humid surfaces, as well as in sectors bordering the edge of the island, mainly on the southwestern side. However, on average the index decreased in 2021 (see Table 3).

Fig. 5 shows the NDWI percentage difference between the 2020 and 2021 scenarios. On the island of Providencia, there are negative differences that range between 50% and 100% along the coastal edge and in the northeastern sector, as well as in the southern area and on the coastal edge of Santa Catalina. On the other hand, on San Andres the most significant negative differences are located on the eastern and southern coastal edges and generally in the north of the island, where anthropogenic influence can be seen.

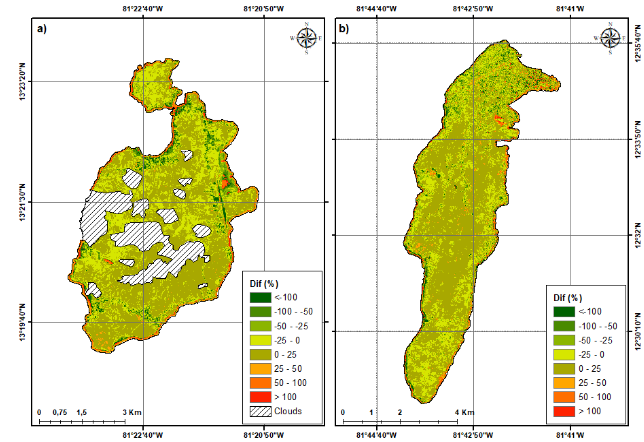

Figure 5. NDWI percentage difference for a) Providencia and Santa Catalina and b) San Andres between the years 2020 and 2021.
Source: Authors.

3.3 *Bare Soil Index (BSI)*

The results of the BSI index are shown in Fig. 6 and Table 4, where values near to 1 represent areas with bare soil or little vegetation. On the island of Providencia, in 2020 the maximum values (Fig. 6a, upper panel) are distributed in urban areas where there has been anthropic intervention. In 2021, (Fig. 6b, upper panel), the BSI increased, especially on Santa Catalina, in the northeast of Providencia and in the strip that connects the two islands.

The BSI values in 2020 on the island of San Andres are higher around the eastern side and lower around the center and southwestern side of the island. On average (see Table 4), the BSI index decreased slightly in 2021, which indicates a decrease in the presence of bare soil or areas of little vegetation.

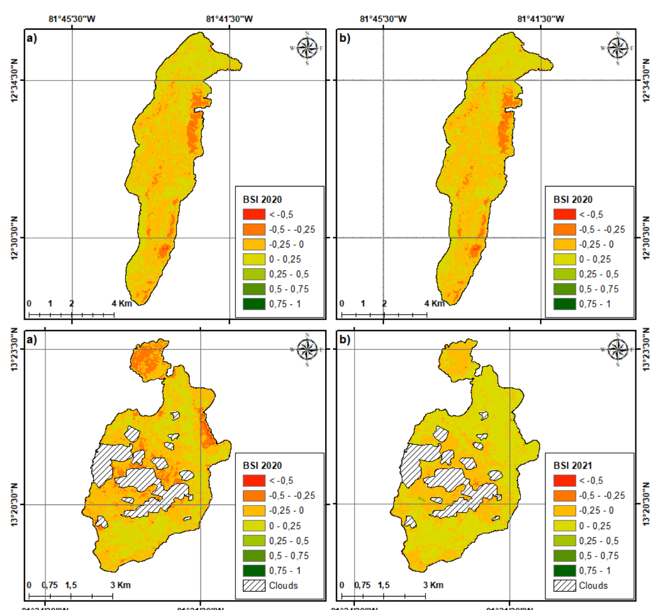

Figure 6. BSI for the islands of San Andres (lower panel) and Providencia and Santa Catalina (upper panel) for the year a) 2020 and b) 2021.
Source: Authors.

Table 4.
Results of the BSI index for San Andres (SAI), Providencia and Santa Catalina (PSC) considering average, standard deviation (STD), minimum (Min) and maximum (Max) values and the mean of the difference (Mean diff).

BSI	Mean	STD	Min	Max	Mean diff (%)
PSC 2020	-0.070	0.135	-0.540	0.219	0.000
PSC 2021	0.014	0.112	-0.825	0.569	42.62
SAI 2020	-0.040	0.126	-0.549	0.301	0.000
SAI 2021	-0.069	0.139	-0.516	0.270	22.79

Source: Authors.

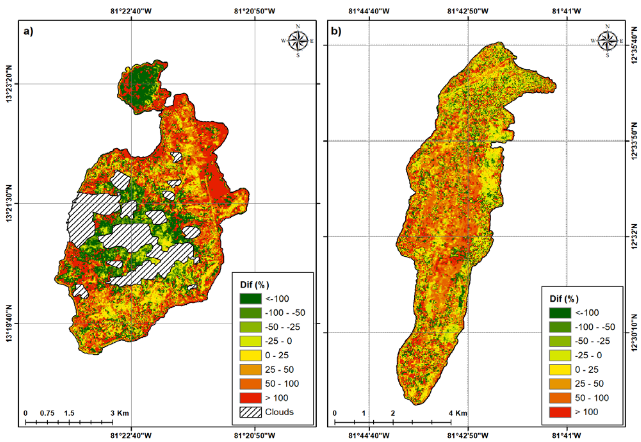

Figure 7. BSI percentage difference for a) Providencia and Santa Catalina and b) San Andres between the years 2020 and 2021.
Source: Authors.

Fig. 7 presents the BSI percentage difference between 2020 and 2021. On Providencia, the greatest variations occur along the coastal edge and in the northeast of the island. On Santa Catalina there are negative variations > 50% over almost the entire area. On San Andres, the greatest negative variations occur on the western edge and center of the island, and to a lesser extent on the eastern side.

3.4 Normalized Burn Ratio (NBR)

The results of the NBR index are shown in Fig. 8 and Table 5, where negative values represent areas degraded by fires and positive values represent healthy vegetation. On the island of Providencia, in 2020 the negative values (Fig. 8a, upper panel) are distributed in some small areas on the island. In 2021, (Fig. 8b, upper panel), the NBR decreased, on average over the entire island but maintaining positive values.

The NBR values in 2020 on the island of San Andres are negative especially in urban areas and some small areas of vegetation. On average (see Table 5), the BSI index decreased slightly in 2021 but maintaining mostly positive values. Fig. 9 presents the NBR percentage difference between 2020 and 2021. On Providencia and Santa Catalina, the greatest variations occur along the coastal edge and in the northeast, north and southwest of the island. On San Andres, the greatest variations occur along the coastal edge. On none of the islands there are representative areas that indicate influence by forest fires.

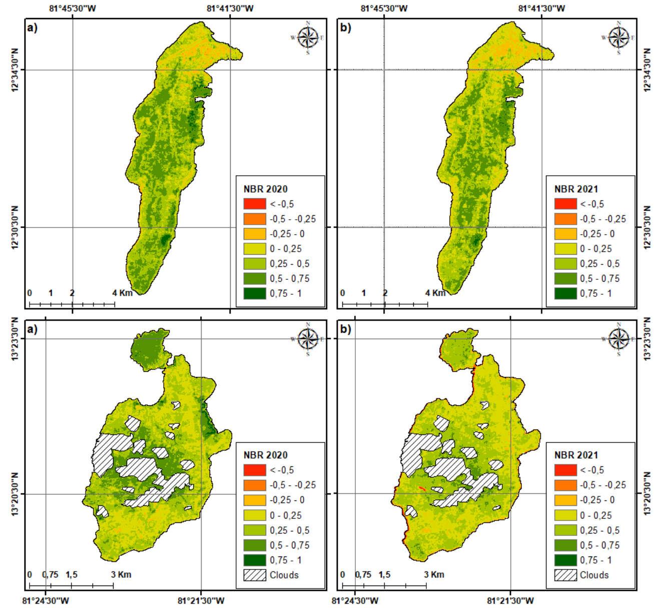

Figure 8. NBR for the islands of San Andres (lower panel) and Providencia and Santa Catalina (upper panel) for the year a) 2020 and b) 2021.
Source: Authors.

Table 5.
Results of the NBR index for San Andres (SAI), Providencia and Santa Catalina (PSC) considering average, standard deviation (STD), minimum (Min) and maximum (Max) values and the mean of the difference (Mean diff).

NBR	Mean	STD	Min	Max	Mean diff (%)
PSC 2020	0.337	0.180	-0.259	0.830	0.000
PSC 2021	0.240	0.211	-0.991	0.763	-33.018
SAI 2020	0.370	0.212	-0.482	0.823	0.000
SAI 2021	0.321	0.214	-0.347	0.805	-18.787

Source: Authors.

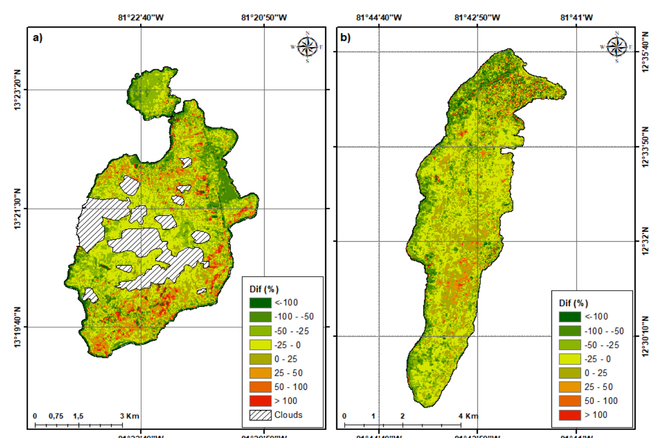

Figure 9. NBR percentage difference for a) Providencia and Santa Catalina and b) San Andres between the years 2020 and 2021. Source: Authors.

3.5 Coverage classification

Fig. 10 illustrates the coverage classification for Providencia and Santa Catalina for the 2020 scenario (Fig. 10a). It can be observed that on Santa Catalina there is a

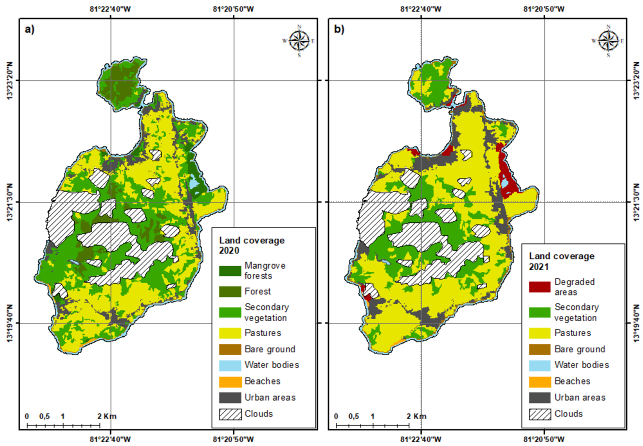

Figure 10. Land coverage classification of Providencia and Santa Catalina for a) before the hurricanes (year 2020) and b) after the hurricanes (year 2021).
Source: Authors.

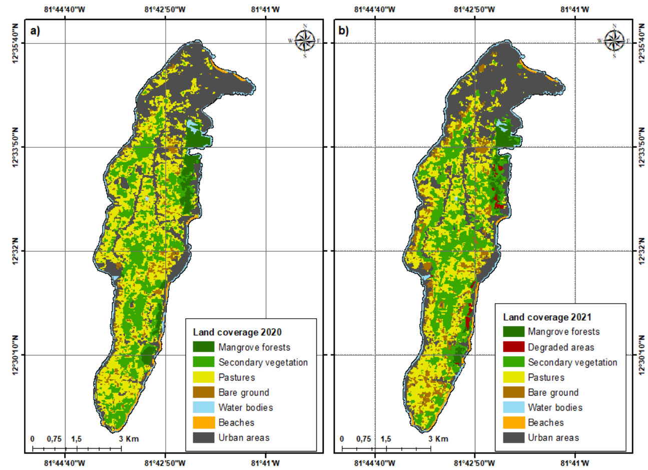

Figure 11. Land coverage on San Andres a) before the hurricanes (year 2020) and b) after the hurricanes (year 2021).
Source: Authors.

greater proportion of forests and pastures. On Providencia, there are mangrove forests in the northeast of the island and along the coastline. There are also patches of forests in the central area of both islands. Pastures and secondary vegetation are also present throughout the islands, mainly close to urban areas. There are small patches of bare soil along the littoral edge of the islands. In the southern of Providencia, pastures are more representative.

In 2021 (Fig. 10b), there is a decrease in forest coverage on the island of Santa Catalina. On Providencia, pastures and urban areas increase while mangrove forests and secondary vegetation decrease. In the southern part of Providencia, beach coverage decreases. Urban areas are seen to increase throughout the island. New coverage is mainly associated with mangrove forests that have been degraded by hurricanes.

Table 6 presents a map of land coverage and changes in coverage from 2020 to 2021. It can be observed that in 2021 the forests and mangroves from 2020 are no longer there. Moreover, secondary vegetation decreased by 31.22%, bodies of water by 8.03% and beaches by 9.65%. In contrast, pastures, bare land and urban areas increased by 41.10%, 24.22% and 36.48%, respectively. In 2021, the degraded areas had an estimated area of 56.82 ha.

Table 6.
Area according to type of coverage for Providencia and Santa Catalina (PSC) for 2020 and 2021.

Coverage	PSC 2020 (ha)	PSC 2021 (ha)	Difference (%)
Forest	144.15	0.00	-100.00
Mangrove forests	46.59	0.00	-100.00
Secondary vegetation	671.96	462.19	-31.22
Pastures	694.17	979.47	41.10
Bare ground	34.19	42.48	24.22
Urban areas	166.91	227.79	36.48
Water bodies	130.17	119.72	-8.03
Beaches	3.31	2.99	-9.65
Degraded areas	0.00	56.82	100.00
Total	1891.46	1891.46	0.00

Source: Authors.

Fig 11. classifies the coverage on the island of San Andres. In the 2020 image (Fig. 11a), mangrove forests predominate in the eastern fringe and along some coastal edges of the island. Urban areas are concentrated mainly in the north and along the main road and coastal border. Secondary vegetation, grasses and bare soils are distributed throughout the center, while the beaches are distributed along the coastal edge. Also, water bodies can be observed in the northeastern area in the mangroves and at a small point in the middle of the island called "Big Pond".

Fig. 11b classifies the land coverage in 2021, where a significant decrease in mangrove forest can be observed throughout the entire island. Secondary vegetation and bare land visibly increase on the island, while there are small variations in pastures, urban areas, water bodies and beaches. Likewise, new coverage associated with areas degraded by the passage of hurricane Eta and Iota can be identified.

Land coverage areas and changes in 2020 and 2021 are presented in Table 7. There is a significant increase in bare land of about 48.1%, followed by secondary vegetation (8.75%), beaches (8.35%), and water bodies (7.37%). On the other hand, mangrove forests decrease by 56.68% and pastures decrease by 19.81%. The degraded areas cover an area of 21.27 ha.

Table 7.
Area by type of coverage on San Andres for 2020 and 2021.

Coverage	SAI 2020 (ha)	SAI 2021 (ha)	Difference (%)
Mangrove forests	140.33	89.57	-56.68
Secondary vegetation	634.23	695.02	8.75
Pastures	944.41	788.25	-19.81
Bare ground	119.29	229.99	48.13
Urban fabric	862.26	862.59	0.04
Water bodies	155.65	168.04	7.37
Beaches	15.76	17.19	8.35
Degraded areas	0.00	21.27	100.00
Total	2871.93	2871.93	0.00

Source: Authors.

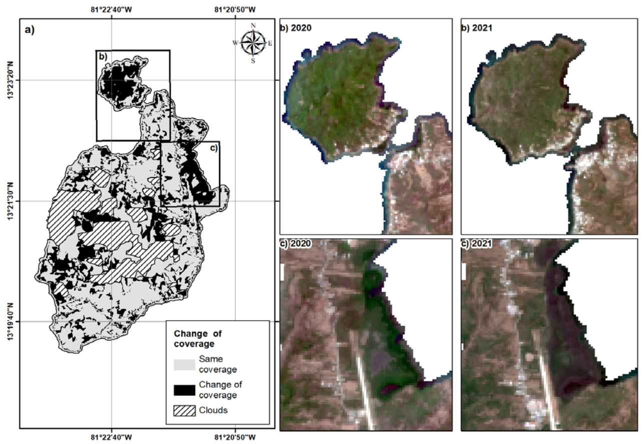

Figure 12. a) Coverage changes between 2020 and 2021 in Providencia and Santa Catalina and b) Santa Catalina and north of Providencia c) airport and mangrove areas.
Source: Authors.

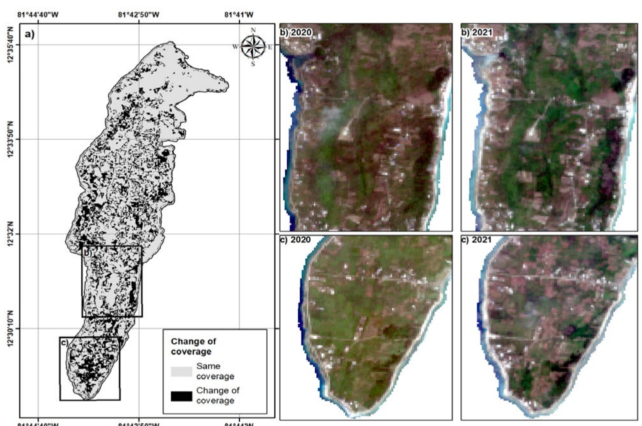

Figure 13. Coverage changes between 2020 and 2021 a) on San Andres as a whole, b) in the south of San Andres, and c) in the zone of The Cove in San Andres.
Source: Authors.

3.6 Change in coverage

On Providencia and Santa Catalina there was a significant change in land cover between 2020 and 2021 (see Fig. 12). The areas of Providencia that saw the biggest changes were in the island's northeast, mangrove region, and east. Changes can be seen throughout the entire island of Santa Catalina. Fig. 12 shows Sentinel-2 satellite images from 2020 and 2021 for a better illustration of the results.

Fig. 13 shows the coverage changes on San Andres between 2020 and 2021. The most significant changes occur along the coast, particularly in the south, southeast, and southwest of the island.

3.7 *Accuracy of coverage classification*

In order to evaluate the accuracy of the coverage classification, a confusion matrix was generated to calculate the Kappa index (K). Coverages with K values > 0.8 are considered to have a high level of success, while K values between 0.8 and 0.4 are at an intermediate level and K values < 0.4 correspond to a low level of success [20, 26]. The coverage of San Andres shows higher K values than Providencia and Santa Catalina. For San Andres, the Kappa indices in 2020 and 2021 were 0.89 and 0.93 respectively, while for Providencia and Santa Catalina they were 0.84 and 0.93 respectively.

4 Discussion

Spectral indices based on the analysis of multispectral satellite images play a fundamental role in the evaluation and monitoring of vegetation, since they allow the vigor of vegetation to be quantified and changes in the study area to be estimated [27]. Since each index has a different spectral response, the NDVI, NDWI, BSI and NBR indices were used to identify the state and type of land cover before and after the passing of hurricanes Iota and Eta. The NDVI helps identify the state and biomass of the vegetation, the NDWI illustrates water bodies and areas with high water saturation, especially in forests near the sea, the BSI shows areas with bare soil or low vegetation density, and the NBR is used to identify and rule out areas influences by forest fires.

The similar behavior in the spectral responses of the three indices showed that the northeast of San Andres and the island's western shoreline experienced the most significant changes. In Providencia, significant changes are observed in the east, near the airport and in the mangrove forests, as well as along the coastal edge. In Santa Catalina, most changes were observed along the coastline and in the western strip of the island. The variations shown by the indices occurred mainly in areas characteristic of mangrove forests and in areas with greater susceptibility to flooding by hurricanes, as reported by [28, 29]. Likewise, the increase in salinity in forested areas and estuarine wetlands may mean they are more sensitive to disturbances caused by hurricanes [30].

Spectral responses for Providencia and Santa Catalina presented more significant changes and variations than San Andres. This was expected and is strongly linked to the proximity that these islands had to the passage of Hurricane Iota. On the island of Puerto Rico, an inverse correlation was found between the distance to the track of Hurricane Maria and the negative variations of the NDVI [19]. This means that the smaller the distance between the island and the passage of the hurricane, the greater the impact on the land coverage.

The NDVI for Providencia decreased by more than 50% around the mangrove forests and on the coastal edge. On Santa Catalina, the NDVI differences occurred on the coastline and in the west of the island. The greatest decreases on San Andres occurred along the western coastline and in strips of mangrove areas located in the northeast of the island. Similarly, other studies have reported a decrease in NDVI for mangrove forests and wetlands after the passage of hurricanes [19, 20]. In Alabama, after Hurricane Katrina (2005), there was a NDVI decrease of about 50% between May and September 2005 [30]. A factor that can cause low NDVI index values in post-hurricane settings is the presence of large amounts of marine litter. Deposits of wreckage from homes and dead vegetation from defoliation and uprooting.

generate a large accumulation of debris and waste, as occurred in Providencia and Santa Catalina [31].

The NBR index helps identify vegetation affected by forest fires after hurricanes [23]. However, the index values after Eta and Iota do not indicate areas affected by forest fires on the islands. instead, the significant decreases in index values are more closely related to the loss of plant heald.

The areas of natural coverage on the islands of Providencia and Santa Catalina decreased more than on San Andres due to the passage of hurricanes Eta and Iota. Most changes involve a transition from forested areas with a high vegetation density to pastures, bare soil and degraded areas. Similar changes (reduction of individual trees, stems, area and basal height) occurred in Providencia after the passage of hurricane Beta in 2005 [32] as well as in the Dominican Republic and Puerto Rico after the passage of Hurricane Maria [19].

It is crucial to emphasize that despite its spectral properties, crop cover can be mistaken for secondary vegetation and woods. Due to crop exposure and potential changes in cover, these agricultural areas are also extremely vulnerable [20].

On San Andres, there was less variation in the coverage of water bodies, secondary vegetation, beaches and urban areas from 2020 to 2021. Likewise, water bodies and urban areas did not present notable changes on Providencia and Santa Catalina either. However, beaches were more significantly affected on Providencia, especially one located in the south (Manzanillo beach), losing 9.65% of its area between 2020 and 2021. Similarly, some beaches on Providencia were also eroded and decreased in area with the passage of Hurricane Beta in 2005 [33].

In some small areas of the islands of San Andres and Providencia, darker tones were presented close to urban areas. This mainly indicates an increase in density of grasses, bare soil and secondary vegetation, or a greater density of vegetation and individual trees. Such changes may be due to anthropic agricultural activities which have been developed on the islands in a traditional way to counteract economic difficulties caused by hurricanes and as a management alternative to mitigate the effects of climate change [34].

Accurately classifying cover is a significant challenge as the type of cover and the spectral differences present in satellite images may be confused, especially when considering meteorological conditions such as the presence of clouds. Furthermore, the use of satellite images with a spatial resolution of 20 meters can generate errors when training the algorithm to generate the correct classification of coverage. For these reasons, it is crucial to evaluate the quality of the output and its agreement with reality using methods that measure accuracy, such as the confusion matrix and the Kappa index.

5 Conclusions

In this work, a methodology of multitemporal analysis of land cover and spectral indices was developed. The natural covers in Providencia y Santa Catalina were significantly affected by hurricanes Iota and Eta, compared to San Andres between April and May of 2020 and 2021.

For future studies, we recommend exploring the evolution of the vegetation covers affected on the islands after the hurricanes, and using of multitemporal analyzes at different spectral and temporal scales.

Finally, it is worth emphasizing that this form of geospatial analysis is critical. Based on the findings of these studies and the identification of hurricane-prone areas, decision makers can focus their territorial planning efforts in ways that most effectively reduce the impact of such hazards,

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Estimation of emerald mineralization probability using machine learning algorithms

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Abstract
This research proposes a machine learning (ML) model that estimates the probability of emerald mineralization in rocks of the Western Emerald Belt (CEOC). Element concentrations, lithologies and coordinates were used as input variables and productivity as the target variable (176 samples). The variables were transformed to be integrated into the model. (1) Variable selection was performed using the Boruta method and backward elimination. (2) A logistic regression, a neural network, and a support vector machine were trained. (3) Calibration was achieved with the Platt method. (4) Calibration assessment was conducted by using the Brier score and calibration curves. The model selected was a calibrated support vector machine ($C = 0.19$ and $\lambda = 0.1$) that included 17 geochemical variables and the coordinates. The results were presented in a 3D plot. Assigning a probability value to each sample allows the mining targets to be ranked.

Keywords: gems; calibration; drillhole; mineral target.

Estimación de la probabilidad de mineralización de esmeraldas usando algoritmos de aprendizaje automático

Resumen
La investigación propone un modelo de aprendizaje automático para estimar la probabilidad de mineralización de esmeraldas en el Cinturón Esmeraldífero Occidental (CEOC). Se emplearon concentraciones elementales, litología y coordenadas como variables de entrada y la productividad como variable objetivo (176 muestras). Las variables fueron transformadas para ser integradas al modelo. (1) Se recurrió a los métodos Boruta y *backward elimination* para seleccionar las variables. (2) Una regresión logística (LR), una red neuronal de retropropagación (BPNN) y una máquina de vectores de soporte (SVM) fueron entrenadas. (3) Se usó la calibración de Platt y (4) se evaluó su desempeño usando la puntuación Brier y curvas de calibración. El modelo elegido fue una máquina de vectores de soporte calibrada ($C = 0.19$ y $\lambda = 0.1$) que incluyó 17 variables geoquímicas y las coordenadas. Asignar valores de probabilidad permitió jerarquizar los objetivos mineros.

Palabras clave: gemas; calibración; perforación; objetivo minero.

1 Introduction

The global demand for colored gemstones implies higher prices and industry growth [1]. However, Colombian emerald production has declined significantly, from 9.8 million carats in 2004 to approximately 964,000 carats in 2021 [2]. This negative trend indicates the need to establish new mining goals.

The mineral potential of economically viable areas was determined through geometric and geostatistical methods that require significant manual processing [3]. Geometric methods primarily use mean values or weighted averages for estimation in defined blocks, while geostatistical methods estimate mineral resources from the variability and spatial correlation characteristics of the original data [4]. These methods are efficient in early stages of a project, but some authors have pointed out that they perform poorly on very heterogeneous data sets [1].

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Mining recommendations are limited to determining if a rock is an emerald producer. Identifying potential mining sites can be challenging due to variations in mineral association within different rock formations. These discrepancies arise from changes in fluid composition over time and the interaction with the rock's composition [5].

The purpose of this research is to find a ML model applicable to drill data that estimates the probability of emerald mineralization in rocks of the Western Emerald Belt (CEOC). Lithological, geochemical data and coordinates were integrated and processed simultaneously to identify and hierarchize mining targets.

Determining and quantifying the mining potential of an emeraldiferous prospect is a challenging task. Significant amounts of data are available from emerald mines in Colombia due to the long history of exploration. However, no literature was identified regarding the useful of these datasets as training data in ML models for selecting new mining targets.

The absence of previous research of this nature may be attributed to experiments conducted by private companies that remain unpublished. Alternatively, stakeholders in the emerald industry may not be familiar with the use of ML algorithms for gemstone exploration, or there may be uncertainty about the significance of the data and methods.

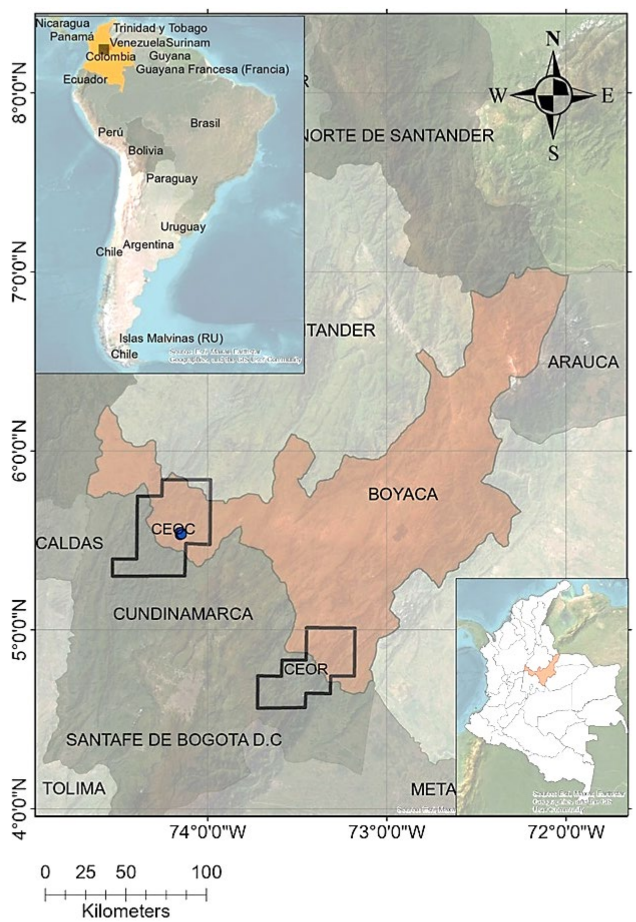


Figure 1. Emerald belts in Colombia - Western belt (CEOC) and Eastern belt (CEOR)
Source: Own elaboration and adapted from [6,7].

Colombian emerald deposits are found in two belts located in the Eastern Cordillera, Boyacá Department. The Western Emerald belt (CEOC) includes the mining districts of Muzo, Coscuez, La Pita, Peñas Blancas, and La Glorieta-Yacopí [7], The Eastern Emerald belt (CEOR) includes Chivor, Gachalá, and Macanal [8], (Fig. 1Figure 1).

Emerald deposits data from projects in the exploitation stage have been collected through various techniques over several decades, resulting in abundant and diverse information that includes lithological, mineralogical, and stratigraphic [9]; hydrothermal alteration, and geochemical [5,10,11] and geophysical data [12].

Giuliani et al., (1999) [10] made an important breakthrough by measuring the number of emerald crystals formed from the amount of beryl leached in five phases of hydrothermal alteration. Starting from the axiom that beryllium (Be) can be mobilized under hydrothermal conditions, they estimated the total gem reserves in the Chivor mines using a methodology developed, evaluated, and validated by Bourlès (1992) [17], to estimate the autigenic potential $^{10}Be/^{9}Be$. The results indicated that 470 kg of beryllium was leached at the Chivor mine, and therefore, it can be concluded that if 100% of the leached beryllium was mobilized, there would be 720,000 emeralds, interpreted as crystals 1 cm in diameter by 5 cm in height.

Niño and Sheng-Rong (2017) [5] analyzed 17 samples belonging to seven mines in the Western Emerald Belt. They used the stable isotopes Oxygen-18 (^{18}O) / Oxygen-16 (^{16}O), and Carbon-12 (^{12}O) / Carbon-13 (^{13}O) as a measure of groundwater-mineral interactions to identify differences between calcite in productive and non-productive veins in the study area. They revealed that although the mineralogy of productive and non-productive veins is similar, it is possible to find variables that separate them using geochemical data; unfortunately, isotopic experiments on emeralds are rare.

1.1. Machine learning in mineral exploration

Machine Learning (ML) for the exploration of geological resources has primarily been restricted to massive and stratiform deposits [13]. Extending these techniques to gemstone deposits poses a challenge due to the discrete nature of gems, each varying in quality, making the estimation of quantity during exploration particularly challenging. The absence of prior scientific publications on using ML in gem exploration emphasizes the significance of this research. However, this does not imply that ML algorithms haven't been utilized in mineral exploration previously.

Zhang et al. (2018) [14] employed Support Vector Machines (SVM) and Artificial Neural Networks (ANN) to assess the prospectivity of a gold deposit in the Hatu region of Xinjiang, northwest China. The researchers compared the predictive results of the ANN and SVM models, demonstrating the superior predictive competence of SVM in this case.

Mohammadi and Hezarkhani (2018) [15] investigated a copper porphyry in the Urumieh-Dokhtar magmatic arc using drill hole data. The 3814 samples collected from 44 drillholes included lithology, alteration type, copper concentration, coordinates, and collar as input variables. This research focuses on a multi-class classification SVM in which the data were separated into four groups - zones (oxidation, leaching, trans, and hypogene zones). The model was trained on 80% of the data and evaluated on 20%; 25% of the area was classified as favorable, containing 78.6% of the known deposits.

Taboada et al., (2007) [16] analyzed data from a shale deposit in an area of low regional metamorphism in Spain using multiclass, ordinal, and regression SVMs with a Gaussian Kernel. The shales in this deposit were divided into three groups: first quality with no aesthetic defects; secondary quality with aesthetic defects, and a third group with no economic value. The input variables included intercalations with sheets or layers of sands, presence of closed or quartz-filled microfractures, planes of schistosity, sulfides affected by oxidation, degree of surface alteration, crenulation, and kink bands.

2 Materials and methods

Data is the core of this research and the most important part of ML. Fig.2, presents the samples from producing projects that were used as the data train for this research. Since the rock samples used as training data come from the Western Emerald Belt (CEOC), the application of the generated model is restricted to this belt.

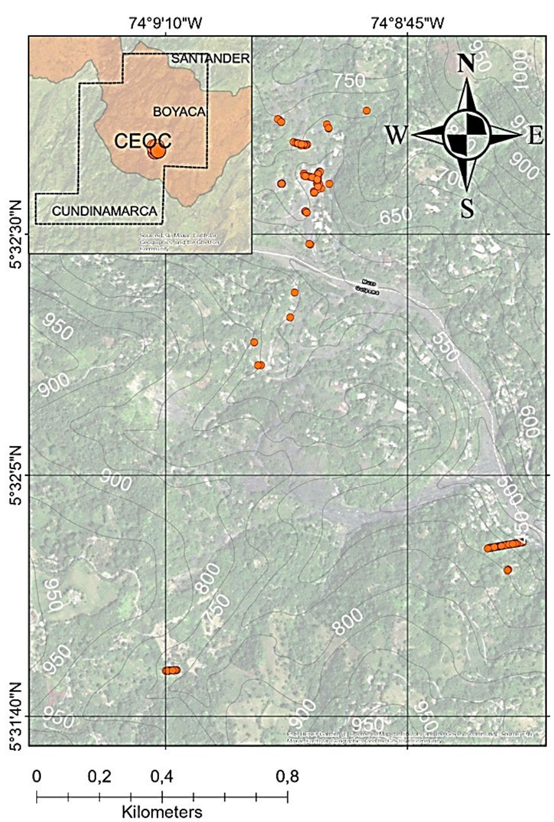


Figure 2 Sample's location
Source: Own elaboration

Table 1. Train samples.

Train samples	Input variables	Output variables	Quantity
Productive	49	1	88
Sterile	49		88
Total			176

Source: The authors

Each of the 176 samples utilized as training examples originates from projects in the production stage, including 49 associated variables. These samples are categorized into either productive (88 samples) or sterile (88 samples) classes. (Table 1). The rock samples were analyzed by inductively coupled plasma mass spectrometry (ICP-MS), which quantifies most of the elements in the periodic table at trace levels; 170 of the 176 samples were prepared by 4-acid digestion and the remainder were prepared by aqua regia.

2.1 Variables

Table 2 presents the input and output variables associated with each example. There are 49 input variables.

The numerical values of latitude, longitude, and elevation describe the location of the samples and thus the relations between geologic bodies. Lithology is a categorical variable that can take three values: mudstone, vein, and breccia.

The elemental concentrations of major elements are determined as percentages and minor elements in parts per million (ppm). The lithology variable includes values such as vain, breccia, and mudstone. One-hot coding and binary codification were employed to convert lithology and productivity into numerical form, given that both represent categorical data.

Table 2.
Input variables description.

Description	Variable	Format	Transformation method
Location (3)	Longitude Latitude Altitude	Numeric (m)	Normalization (Cube 1x1x1)
Type of Rock (1)	Lithology	Categoric (Veins, mudstone, Breccia)	One-hot codification (1-0)
Trace elements (36)	Ag, As, Ba, Be, Bi, Cd, Ce, Co, Cr, Cs, Cu, Ga, Hf, In, La, Li, Mn,Mo, Nb, Ni, Pb, Rb, Sb, Sc, Se, Sr, Ta, Te, Th, Tl, U, V, W,Y, Zn, Zr.	Numeric (ppm)	Z-score
Major elements (9)	Al, Ca, Fe, K, Mg, Na, P, S, Ti.	Numeric (%)	Z-score
Total – Input variables: 49			

Source: The authors

Since ML algorithms are sensitive to the range and distribution of attributes, and outliers can corrupt the training process, all outliers were considered as real observable values and removed by the flooring and capping process. All values below the 1st percentile and above the 99th percentile were replaced by the value of the 1st percentile and the 99th percentile. After the removal of outliers, the data underwent standardization using the z-score. This step was crucial due to the varied reporting of elemental concentrations, with some values expressed in percent and others in parts per million.

According to Colombian Emerald Good Practices Guide [17], the key to calculating resources and reserves is the rigorous delineation of geological bodies. This information was integrated into the model through the coordinates of each sample. Coordinates were transformed into vectors by situating each point within a unit cube with dimensions of 1x1x1. The use of the new unit avoided including parts per million and millions of meters in the same model and ensures the maintenance of spatial relationships. The scale was calculated by dividing 1.0 by the range in which the initial coordinates are found separately for longitude, latitude, and altitude.

2.2 Proposal

The research was divided into two phases: modeling and application (Fig.3). Each step in the process impacts the following one. data selection and classification are essential to calibrate the models.

Since the training values have as output a categorical value "mineralization of emeralds" or "absence of mineralization" and the desired result of this research is a probability, the problem was approached from two angles.

A classification was performed using logistic regression, SVM and ANN to divide the samples into prospective and non-prospective, then the probability of emerald mineralization was determined using the Platt calibration method [18]. This method allows a comparison between the classification into prospective samples and the probability of emerald mineralization, translated as confidence.

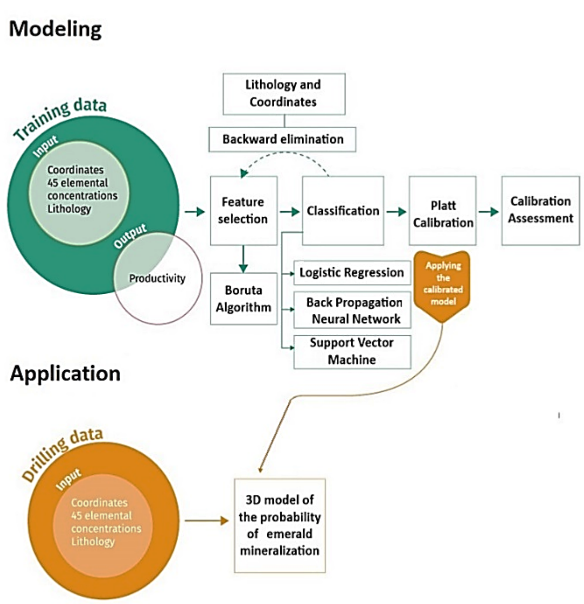


Figure 3 Methodology
Source: Own elaboration

Table 3.
Backward elimination - data sets.

Variables	LR	ANN	SVM	CANN	CSVM
Elemental concentrations latitude, longitude, altitude, lithology	LR1	ANN1	SVM1	CANN1	CSVM1
Elemental concentrations latitude, longitude, altitude	LR2	ANN2	SVM2	CANN2	CSVM2
Elemental concentrations lithology	LR3	ANN3	SVM3	CANN3	CSVM3
Elemental concentrations	LR4	ANN4	SVM4	CANN4	CSVM4

Source: The authors

2.3 Feature selection

Variable selection reduces the model's complexity and eliminates noise in the data; this, in turn, reduces the computational cost of training. Boruta and backward elimination methods were employed to assess the relevance of the variables based on their nature.

2.3.1 Selection of geochemical variables (Boruta Method)

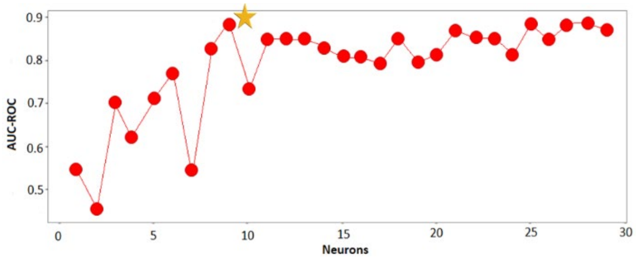
Synthetic variables were created by rearranging the values of the original variables. Subsequently, the significance of each original variable was evaluated by comparing it with its synthetic counterparts in the random forest algorithm. A total of 1000 iterations were performed, leading to two possible outcomes: either the variable exceeded the threshold or it did not. The right tail of the binomial distribution was used to identify variables that consistently met the threshold, categorizing them as significant [19].

2.3.2. Location and lithological variables selection (Backward elimination method)

The influence of the variables in each model (LR, ANN, and SVM) was evaluated through tests in which the input variables were varied to determine which had the greatest influence on classification [20]. The test groups were formed by subtracting coordinates and lithology (Table 3)

2.1 Classification

This problem is limited to two labels or classes (binary classification) because each sample belongs only to the productive or non-productive group. The models used to perform the classification task were logistic regression, back-



propagation neural network and support vector machine.

Figure 4. Hyperparameters selection - Elbow method for ANN.
Source: Own elaboration

The neural network and support vector machine hyperparameters were chosen through grid search with 5-fold cross-validation and evaluated using AUC ROC. Unlike neural networks and support vector machines, it is not necessary to select hyperparameters for logistic regression (LR).

2.4.1. Backpropagation neural network (ANN).

Nine neurons were selected using the elbow method because the model's performance did not significantly improve beyond this point (Fig.4).

The number of layers was limited to one due to the small amount of data; adding more layers would increase the model's complexity. The logistic function was selected as the activation function for its range of 0 to 1, enabling interpretation as probability. An adaptive learning rate was utilized with the gradient descent method.

2.4.2. Support vector machine (SVM).

The values C = 0.19, λ = 0.1 and a RBF kernel was selected. This hyperparameter combination optimized the model's performance according to the area under the ROC curve (Fig. 5).

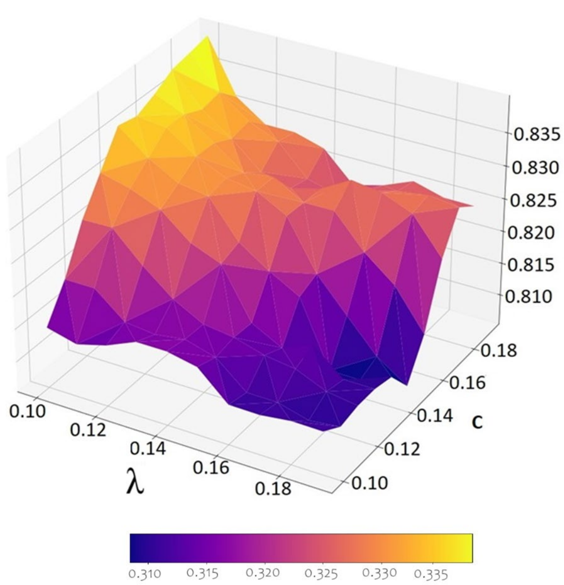


Figure 5. Hyperparameters selection - Gridsearch for SMV.
Source: Own elaboration

2.2 Calibration

The Platt's calibration can be understood as a dual training process. A calibrated algorithm generates true probabilities [21]. Since logistic regression inherently produces well-calibrated probabilities, it is not necessary to calibrate these models.

Neural networks provide probabilities, but because the development of these algorithms has focused on increasing capacity in classification tasks, modern ANNs are poorly calibrated, unlike those of a decade ago [22]. Support vector machines do not provide probabilities natively, so they require a calibration process to provide reliable probabilities [23].

Neural networks and support vector machines were trained, and then, using the estimated probabilities, the values of A and B are calculated to obtain calibrated probabilities [18].

In eq. (1), $P(y = 1|x)$ is the probability of 1 or 0 depending on whether mineralization is present or not; $f(x)$ is the score provided by the support vector machine or neural network; and A and B are parameters learned by the algorithm and were found to obtain calibrated probabilities.

$$P(y = 1|x) = \frac{1}{1 + exp(A\,f\,(x) + B)} \qquad (1)$$

2.3 Calibration assessment

The Brier Score was originally proposed to measure the evaluation of probability forecasts in meteorology [24]; however, its applications have become widespread. The Brier Score for a sample of n binary predictions is given by eq. (*2*), where f_t is the predicted probability of the event occurring, and o_t is 1 or 0, depending on whether the event subsequently occurred or not; lower score values indicate better estimated probabilities [25].

$$BS = \frac{1}{n}\sum_{t=1}^{n} f_t - {o_t}^2 \qquad (2)$$

3 Results

The Boruta algorithm identified seventeen chemical elements in the green zone as variables that enable data division into two classes (productive and non-productive).

Twenty-eight chemical elements were placed in the orange zone, indicating that their characteristics did not meet the threshold to be considered relevant and were therefore disregarded (Fig.6).

The research seeks to obtain probability values using classification as an intermediary process. Nonetheless, an assessment of the capability to classify between productive and non-productive samples was carried out both before and after calibration.

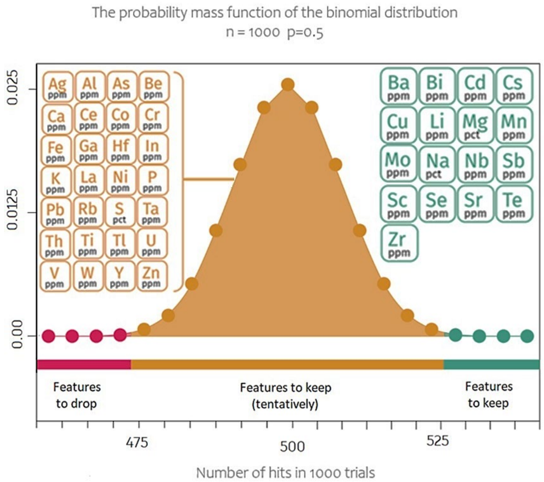


Figure 6. Geochemistry variable selection - Boruta Method.
Source: Own elaboration

The Fig. 7 displays the accuracy, precision, sensitivity, F1 score, specificity, and area under the ROC curve for the three evaluated algorithms and the subsets chosen according to the backward elimination method. The logistic regression algorithm exhibits superior classification performance, achieving better metrics in all scenarios. After calibration, the classification ability of the neural networks decreased, while the classification ability of the support vector machine increased.

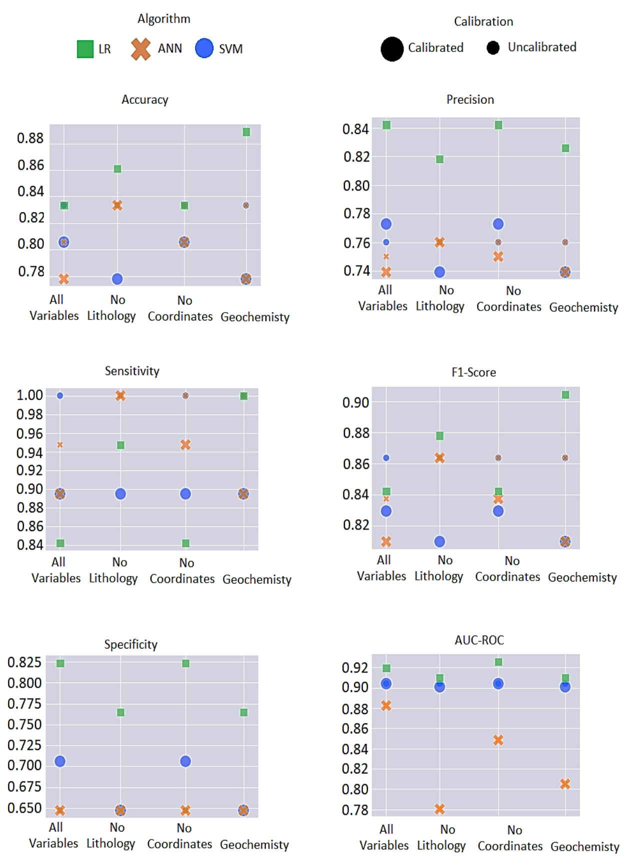


Figure 7. Classification metrics.
Source: Own elaboration

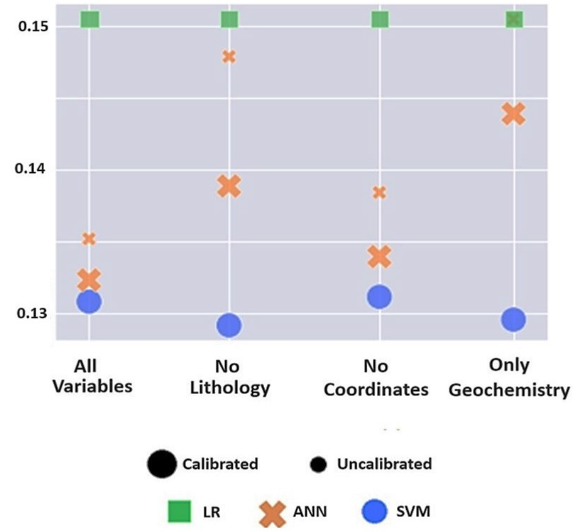


Figure 8. Brier score results.
Source: Own elaboration

The Brier score is negatively oriented, which means that smaller values indicate better forecasts [25]. Since support vector machines do not generate inherent probabilities, there are no blue points in Fig. 8 showing the pre-calibration probability score for this model.

Since it is unnecessary to calibrate the LR model [26], there are no variations observed in the green points pre and post-calibration (Fig. 8) or green calibration curves (Figure 9Figs. 9, 10). The Brier score suggests that the support vector machine without lithology provided the best calibrated estimated probabilities.

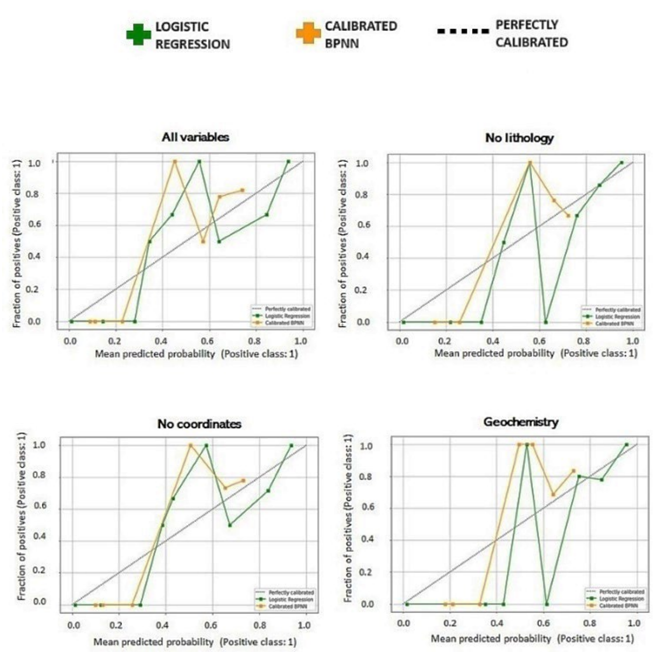


Figure 9. Calibration curves- before Platt calibration
Source: Own elaboration

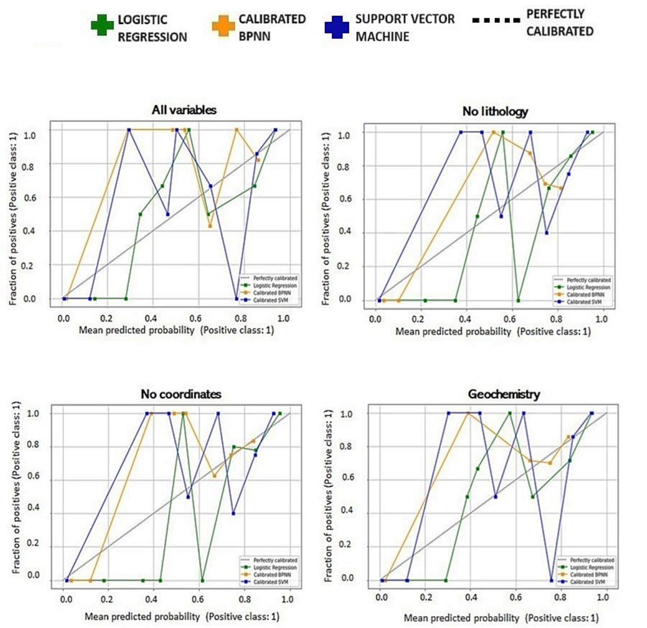


Figure 10. Calibration curves - after Platt Calibration
Source: Own elaboration

4 Discussion

This research used 176 samples; however, 6 were prepared through the aqua regia method instead of the four-acid method, introducing bias to the data that should be avoided. Future experimental designs need to consider the rigor required to apply machine learning models. The collected information must be highly accurate, or the data analysis and application will be unreliable [27].

The wealth of data collected on emeralds over the years must be reinterpreted using ML techniques to provide mining recommendations. It is important to recognize the bias inherent in any data to ensure data quality; this is no small matter, as poor-quality data input leads to unreliable data output.

Studying the geological processes associated with emeralds is essential to identify the data that most efficiently describes the deposits. The use of elemental concentrations may not be the most appropriate descriptor to define such deposits because it does not efficiently incorporate mineralogical information into the models. Partial analysis and isotope data, such as those used by Niño and Sheng-Rong (2017) [5], should be integrated.

This methodology proposes integrating data from various sources, including spatial, geochemical, and lithological variables, and analyzing them simultaneously. Geological body boundaries are important in gemstone exploration; therefore, not only must more training data be integrated, but the spatial density of the data must be high enough to allow the models to integrate the geometry of the geological bodies.

Metrics of ML models should be assessed based on their use and stakeholders' interests. If the classification process is more important, it is essential to evaluate whether the

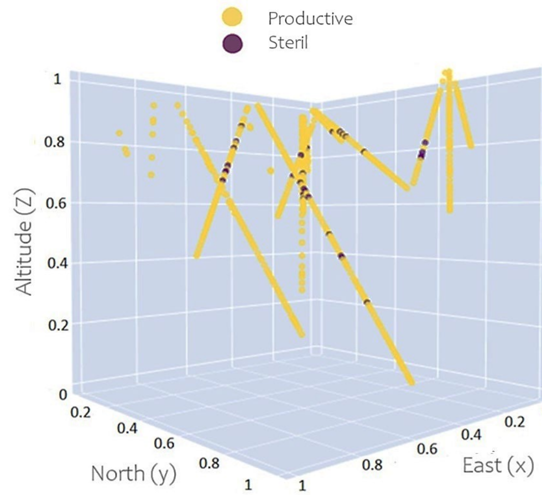


Figure 11. 3D Classification model.
Source: Own elaboration

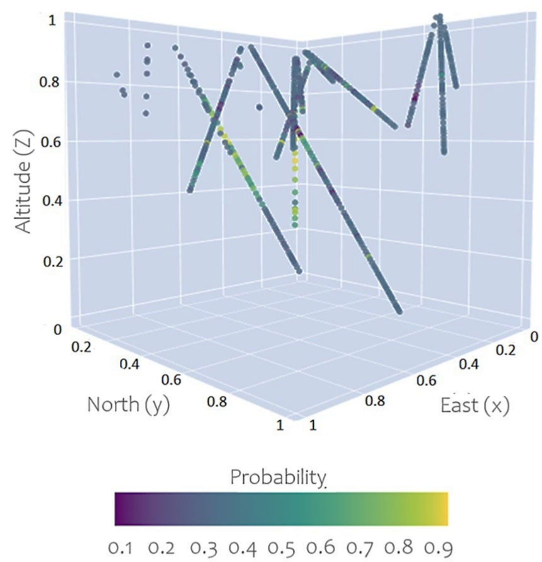


Figure 12. 3D Calibration model.
Source: Own elaboration

business need is to minimize false positives or maximize true positives. The primary aim of these models is to estimate the probability of emerald mineralization for ranking mining targets. Hence, the selection of the best model was based on the calibration performance.

The model CSVM2 achieved the lowest Brier score among the models evaluated. Two intervals have been identified as having the highest probability for emerald mineralization. This model should be used with caution because it overestimates the highest probabilities, suggesting that more data should be integrated.

Emeralds, like other gemstones such as rubies and diamonds, occur as discrete particles in parts per billion. The concentration of emeralds cannot be accurately measured in drill samples, and their value varies from deposit to deposit based on size and quality [28].

The advantages of using calibrated models over classification models (Fig. 11Figure 11) for this application are obvious. Calibrated models hierarchize mining targets by assigning a numerical value, allowing for informed decision-making, without restricting it to the mere occurrence or absence of mineralization. Additionally, utilize free software to present the outcomes in 3D. The Fig. 12 shows two continuous segments with estimated probabilities above 85%.

5 Conclusions

The data from existing emerald exploration and exploitation campaigns should be processed using machine learning techniques. It is imperative to study the characteristics of this ore to determine which are the variables that more accurately describe emerald deposits and to identify the biases that exist in the data.

The model SVM; C = 0.19 and λ = 0.1 calibrated by Platt calibration method (CSVM2) was selected because generate the best calibrated probabilities, as the numerical value associated with the classification is more important in this application than the classification itself; however, the selected model overestimates the highest probabilities, so it should be used with caution.

Presenting the estimated probabilities on a 3D model is extremely useful for mining companies because it allows them to quickly identify the best segments (higher probability) and consider other factors such as access roads and previous mining works.

Geologic models or data with higher spatial density should be integrated to describe geologic unit boundary information more accurately and improve the models' calibration.

Although there are examples of machine learning (ML) applications in mineral exploration, its use in gemstone exploration remains limited. This presents a significant challenge due to the lack of established or measured precedents in this field.

According to Abu-Mostafa et al. (2012) [29], for a problem to be addressed using machine learning methods, it must meet three conditions: (1) there must be a pattern in the data, (2) the problem cannot be explained through a simple mathematical model, and (3) adequate data must be available.

The problem addressed in this research meets these conditions: there is a relationship between emerald mineralization and changes in measured chemical elements. This relationship cannot be explained by a polynomial model, thus requiring data to identify and understand these relationships, and there is sufficient data available to determine the necessary parameters.

Given this, the mining industry must ensure that decision-makers understand the model and its limitations. Additionally, it is crucial to commit to the continuous search for high-quality training data, as the more comprehensive the training data, the better the model will be. Human supervision is also important for interpreting and validating the results.

This research sets out a methodology for gem exploration, however, each of the steps performed from data exploration to calibration is a discipline. Efficient application of these techniques to the gem exploration industry involves ongoing research that evaluates the spectrum of possibilities available.

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Machine learning in industrialization: a bibliometric analysis

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Abstract
Machine learning is currently emerging as one of the most rapidly advancing technologies, with a recent upward trend in its use for process automation across industrial processes. The objective of this study was to conduct a bibliometric analysis to identify research trends in machine learning. The Scopus database was used to identify scientific production. Bibliometric indicators of visibility, impact, and concurrence were analyzed. The analysis of 7,335 documents, involving 22,383 authors, showed a growth rate of 20.86% from 1988 to early 2024. Three dominant research trends were identified: the first based on machine learning applications in industrial processes, the second referring to the human factor and artificial intelligence, and the third related to convolutional neural networks.

Keywords: machine learning; industrialization; bibliometrics; artificial intelligence; supervised learning; unsupervised learning; reinforcement learning.

Aprendizaje automático en la industrialización: un análisis bibliométrico

Resumen:
El machine learning es una de las tecnologías en auge actualmente, en los últimos años se ha observado una tendencia en su uso en la industria para la automatización de procesos. El objetivo de este estudio fue desarrollar un estudio bibliométrico para identificar las tendencias de investigación sobre machine learning en la industrialización. Se utilizó la base de datos Scopus para la identificación de la producción científica. Se analizaron indicadores bibliométricos de visibilidad, impacto y concurrencia. El análisis a partir de 7335 documentos, con la participación de 22383 autores, evidenció un crecimiento con una tasa de 20.86% en el intervalo de tiempo desde 1988 hasta inicios de 2024. Se identificaron tendencias dominantes al tema de investigación: la primera basada en la industria y el machine learning la segunda referida al factor humano y la inteligencia artificial, y la tercera relacionada con las redes neuronales convolucionales.

Palabras clave: aprendizaje automático; industrialización; bibliometría; inteligencia artificial; aprendizaje supervisado; aprendizaje no supervisado; aprendizaje reforzado.

1 Introduction

Artificial intelligence (AI) is defined as the simulation of human intelligence processes by machines, especially computer systems [1].

Regarding their applications in industry, the use of Graph Neural Networks (GNNs) is transforming multiple industrial sectors, particularly in transportation, finance, and telecommunications. In intelligent transportation systems, GNNs model spatial and temporal dependencies, improving traffic prediction and resource optimization [39]. Additionally, GNNs are related to ML as an advanced model within the framework of deep learning [39].

On the other hand, in the financial sector, deep learning processes complex data to predict markets and enhance strategic decision-making, demonstrating the cross-sector versatility of these tools in areas such as logistics [40].

Meanwhile, in telecommunications, GNNs optimize the

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management of complex networks and resources such as spectrum and routing, showcasing their ability to capture advanced dynamics [41].

Within this field, machine learning (ML) stands out as a decisive branch that focuses on developing algorithms and statistical models, enabling computers to learn and make predictions based on data [2].

ML is generally classified into three main categories: Supervised learning (SL), Unsupervised learning (UL), and Reinforcement learning (RL) [3].

SL is one of the categories within ML, based on a model trained with a labeled dataset. In this approach, the model is trained with both input and output data. Once trained, it can be used to predict outputs from new inputs not seen during training [4].

UL, on the other hand, is based on unlabeled data. This approach focuses on identifying inherent patterns or structures in the data, without the explicit guidance of known inputs and outputs during model training [5].

As for RL, the focus is not on labeled or unlabeled datasets. Instead, it concentrates on how an agent can make sequential decisions to maximize some notion of "reward" [6]. Additionally, it can be stated that deep learning, thanks to its multiple applications, can be used in various ways within these three categories: “SL”, “UL” y “RL”. [39]

This field is not only growing in significance but has also become a major catalyst of growth across industrial processes due to its ability to drive efficiency, innovation, and competitiveness. ML has revolutionized numerous sectors by enabling the automation of complex tasks, process optimization, and more informed decision-making. This technology is achieving significant transformations, from healthcare to manufacturing to logistics, providing opportunities to improve quality, reduce costs, and accelerate product and service development [7].

Industrialization is defined as the process by which mass production systems are developed and established to meet society's needs and demands and is paramount in the world of today This process involves adopting advanced technologies, optimizing resources, and efficiently organizing labor for the large-scale manufacture of goods and services [8].

This is a crucial current topic as it contributes to the achievement of the United Nations Sustainable Development Goal 9: "Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation" [9]. Specifically, it supports target 9.2: "Promote inclusive and sustainable industrialization and, by 2030, significantly raise industry's share of employment and gross domestic product, in line with national circumstances, and double its share in least developed countries" [9].

For instance, [36] highlights the extensive growth of AI and ML, illustrating their relevance to each of the Sustainable Development Goals (SDGs) in various ways. These technologies have demonstrated applicability across fields such as industrialization, environmental pollution, and economics. This underscores the expanding reach of ML and AI into numerous domains.

On the other hand, [37] focuses on their application in more specific fields, such as business. It reveals a growing trend in the development and implementation of techniques and methods involving ML and AI, which are rapidly gaining momentum and widespread adoption.

Lastly, [38] showcases the diverse applications of ML, reaffirming its broad scope of study and practical use. As previously discussed, this versatility indicates that ML is a field poised for continued growth and expansion.

The importance of conducting an analysis of this nature lies in the increasing proliferation of specialized articles on ML and AI [36]. Given the rapid generation of data in these fields, it is essential to establish methods for quantifying and organizing this information systematically. Such reviews can play a pivotal role in strengthening the theoretical foundation for future research, enabling the identification of data sources and the extraction of relevant information in a structured manner [36].

In summary, ML emerges as a fundamental tool for improving efficiency, productivity, and sustainability in various industrialization sectors. This position is reflected in the large number of publications on the subject, with a total of 7,335 associated articles as of April 2024 in Scopus. It is therefore appropriate to examine this topic using bibliometric analysis, a widely recognized and rigorous method that allows for the analysis and representation of large volumes of scientific data [10].

This article presents a bibliometric analysis of the application of ML in industrialization, with the objective of analyzing its evolution, trends, and areas of application, as well as identifying relevant actors in this specific topic. It also presents a summary of the 15 most cited research articles in this area of study. It is worth noting that this study represents a novel case that has not been previously conducted.

After this introduction, the article is organized as follows: section 2 presents the methodology used, section 3 the results, and section 4 the discussion and conclusions.

2 Methodology

This study employs a bibliometric analysis to examine the application of ML in industrialization. Data was collected from the Scopus database, providing a comprehensive overview of the field.

The search was conducted on April 26, 2024, using Scopus to identify English-language journal articles on ML in industrialization. The following search equation was used:

(TITLE-ABS-KEY (“ML”) AND TITLE-ABS-KEY (industrial*)) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (LANGUAGE , "English"))

This search yielded 7,335 articles, which formed the basis of our bibliometric analysis. The Bibliometrix library in R Studio [11] was used to analyze the following categories:

- Main data: Including number of sources, authors, and annual growth rates.
- Scientific Production: Annual publication rates.
- Citation analysis: Examination of the 10 most globally cited articles and their annual citation rates.
- Most relevant papers: A summary and categorization of the 15 most relevant research papers, based on the classification proposed by [3].
- Thematic Map: Analysis of niche topics within the research field.
- Co-occurrence Network: Analysis of the most frequent keywords.

- Factor Analysis: Identification of research clusters.
- Scientific affiliations: Analysis of the most prolific institutions.
- Country-level production: Examination of scientific output by country.
- Three-field plot: Analysis of the relationships between authors, references, and keywords.

In general, the analysis provides an overview of the subject under study.

Exclusion criteria were applied to focus the analysis. Only English-language ‘articles’ were considered, excluding other document types. For the in-depth article analysis, additional criteria were applied, such as excluding literature reviews or articles with a generalized treatment of ML that didn't provide specific structural insights.

On the other hand, the article was structured as follows:

In Fig. 1, we can see the structure of this article, which is divided into three sections, each with its specific components. In the introduction section, we will cover everything from the abstract to the introductory part of the article. The second part will analyze the results found through various graphs and tables, and finally, in the conclusion, a discussion will be provided, followed by the references.

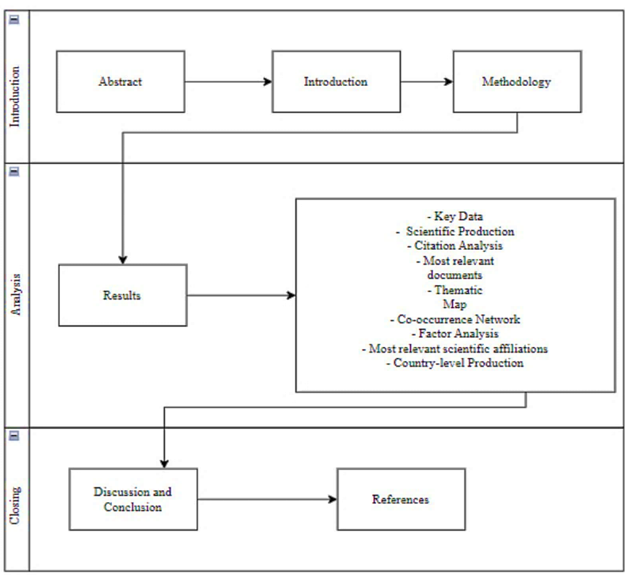

Figure 1. Article Structure Flowchart.
Source: Own elaboration.

The methodology consists of four phases, as illustrated in Fig. 2. Phase 1 involves conducting a search in the Scopus database. Phase 2 focuses on data collection, followed by Phase 3, which is dedicated to analyzing the collected data. Finally, Phase 4 encompasses drawing conclusions and assessing the limitations of the study.

Finally, it is worth noting all tables and figures presented in this study were created by the authors based on the data found.

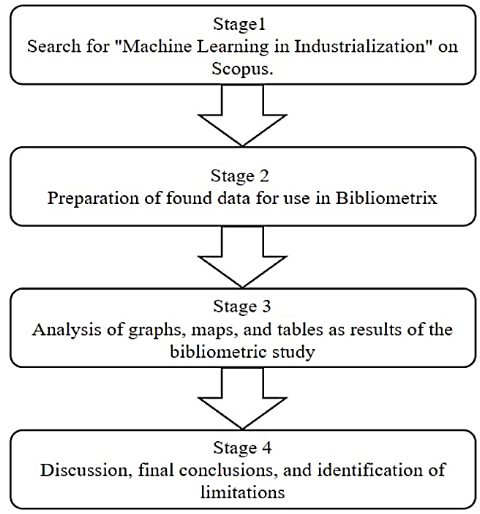

Figure 2. Phases of the methodology
Source: Own elaboration.

3 Results

This section presents the findings from our bibliometric analysis, organized according to the categories outlined in the methodology.

3.1 Key Data

Table 1 presents the overall results of the dataset. The analysis encompassed 2,149 sources published between 1988 and April 2024, with an average annual growth rate of 20.86%. The dataset comprises 7,335 documents. The relatively young average age of the articles (2.89 years) in our sample suggests that this is an emerging field with significant potential for future research.

Table 1.
Summary of most important data

Description	Results
Timespan	1988:2024
Sources (Journals, Books, etc)	2149
Documents	7335
Annual Growth Rate %	20.86
Document Average Age	2.89
Average citations per doc	19.3
References	335959
Documents Content	
Keywords Plus (ID)	34231
Author's Keywords (DE)	17960
Authors	
Authors	22383
Authors of single-authored docs	272
Authors Collaboration	
Single-authored docs	284
Co-Authors per Doc	4.62
International co-authorships %	30.47
Document Types	
Article	7335

Source: Own elaboration.

3.2 Scientific Production

Fig. 3 illustrates the annual scientific production trend. Publications are distributed across 2,149 different sources, involving 22,383 authors. The analysis reveals a clear upward trend, particularly pronounced from 2015 onwards, and significantly more than the single document published in 1988. The peak was reached in 2023 with 1,916 publications. As of April 26, 2024, 916 papers have already been published this year. If this trend continues, it is possible to project a 30% increase in publications by the end of 2024 compared to 2023.

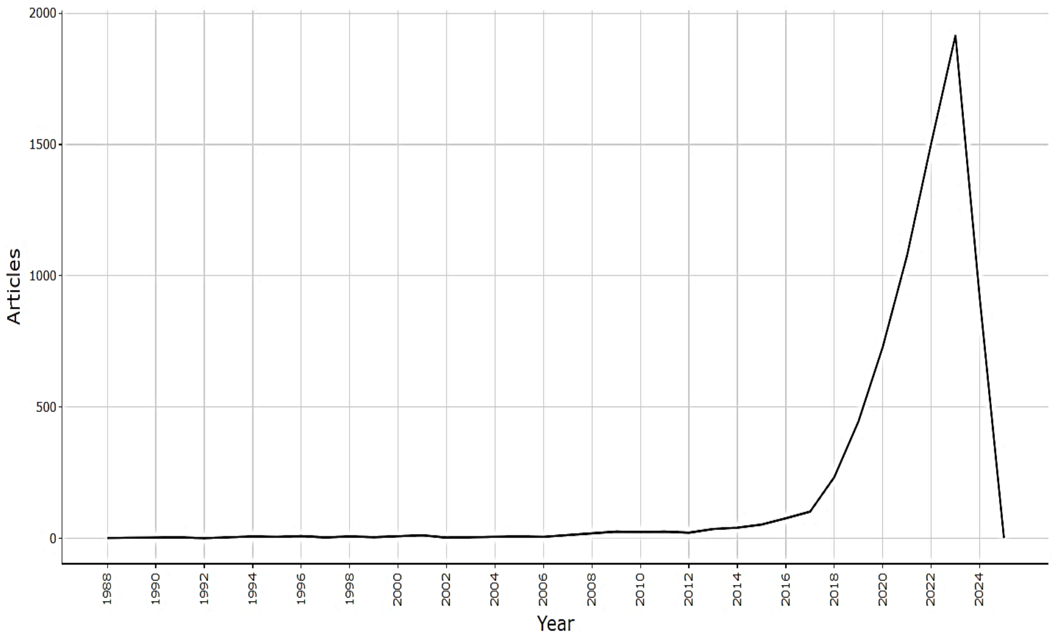

Figure 3. Annual Scientific Production.
Source: Own elaboration.

3.1 Citation Analysis

Table 2 shows the annual citation counts for the top ten highly cited scientific articles. The highest counts suggest considerable impact in their respective fields of research. For example, article [12] has the highest annual average of 393.29 citations, indicating significant and continuing influence. Other notable articles include [13] with 267.75 citations and [14] with 213.20 citations. In contrast, some articles, such as [15] with 71.44 citations per year, the lowest count, show a moderate annual average, which may suggest a lower influence or a decrease in their impact over time.

It is important to note that these articles, except for [14], were not considered among the sample. This is because many of these focus on literature reviews, such as [12], which discusses Explainable AI (XAI), and [16], which reviews fault detection and diagnosis methods. Others like [15] and [17], although they address artificial intelligence-related issues, do not present direct applications of ML in their studies. [15] focuses on authorship attribution, while [17] deals with Digital Twin. Finally, [18] and [19], although they include ML components, focus mainly on optimization frameworks and secure data exchange architecture, respectively.

Table 2.
Total number of citations of the most globally cited documents per year

Paper	Title	TC per Year
[12]	Peeking Inside the Black-Box: A Survey on Explainable Artificial Intelligence (XAI)	393.29
[16]	Survey on data-driven industrial process monitoring and diagnosis	93.38
[15]	A survey of modern authorship attribution methods	71.44
[20]	Deep learning for smart manufacturing: Methods and applications	158.86
[13]	Artificial Intelligence (AI): Multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy	267.75
[14]	On hyperparameter optimization of ML algorithms: Theory and practice	213.20
[21]	A deep convolutional neural network with new training methods for bearing fault diagnosis under noisy environment and different working load	144.86
[17]	Digital Twin: Enabling Technologies, Challenges and Open Research	191.60
[18]	Pymoo: Multi-Objective Optimization in Python	158.60
[19]	Blockchain and Federated Learning for Privacy-Preserved Data Sharing in Industrial IoT	139.40

Source: Own elaboration.

3.2 Most relevant documents

In this section, Table 3 summarizes the 15 most relevant scientific articles according to Scopus, selected from the total 7,335. Each article is briefly summarized and categorized according to the classification proposed by [3], highlighting whether it focuses on SL, UL, or RL.

3.3 Thematic Map

Fig. 4 illustrates the thematic map of ML in industrialization. Topics such as 'Internet of Things', 'network security', and 'anomaly detection' show high development but low relevance marking them as niche topics. There are no topics that can be labeled as emerging or declining, nor as driving themes, which would be those of high relevance and development. In the core topic quadrant, key topics such as 'ML', 'forecasting', and 'AI' demonstrate high relevance but lower development, suggesting areas ripe for further research. The chart also includes the terms 'article', 'human', and 'algorithm', positioned relative to the axes, indicating a cross-cutting theme or specific focus in the analysis.

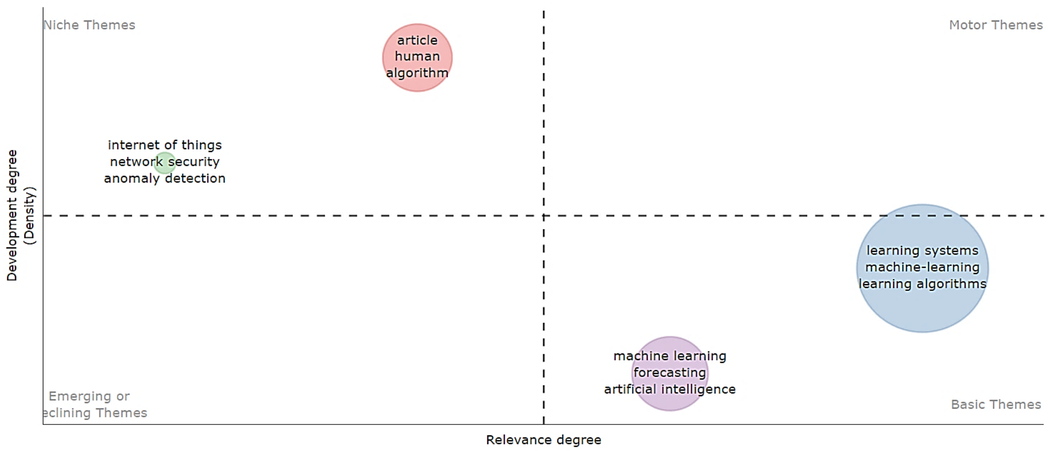

Figure 4. Thematic Map
Source: Own elaboration.

Table 3.
Most relevant articles

Art.	Summary	Type
[22]	Proposes an autonomous platform designed to automate ML processes based on specific levels of autonomy for various industries, including information management and smart cities.	SL
[23]	Explores the application of ML techniques on the Internet of Things (IoT) field to improve connectivity and communication in the smart city industry.	SL
[24]	Addresses the application of ML techniques to predict and improve the efficiency of corrosion inhibitors in metals. It is mainly applied to the materials industry.	SL, UL, RL
[25]	Describes how ML is applied to predict the reliability of manufacturing components compared to traditional approaches, targeting the manufacturing industry.	SL
[26]	Analyzes the use of ML to classify plant leaf diseases, with applications in the agricultural industry.	UL
[27]	Addresses the use of statistical and ML models to predict failures in manufacturing robotic arms. This work applies to the automation and robotics industry.	SL
[28]	Discusses how ML accelerates the development of quantum dots, which are crucial nanometer materials for advanced photonics technology. This work is primarily applicable to the materials science industry and photonic device engineering.	SL, UL
[14]	Discusses techniques for hyperparameter optimization in ML algorithms, such as Bayesian optimization and metaheuristic algorithms. It is relevant to the ML and AI industry.	SL, UL
[29]	Discusses how ML and AI are transforming various industries by providing insights into how ML techniques are applied to fields such as engineering, life sciences, finance, and sports analytics.	SL, UL, RL
[30]	Investigates the use of ML-based models to improve timber allocation planning in sawmills. Applies to the forest industry, specifically in the forest products supply chain.	SL
[31]	Presents a hybrid ML (HML) model for complex manufacturing information systems. This work is relevant to the manufacturing and production control industry.	UL
[32]	Describes the implementation of courses that integrate ML concepts into the operations research curriculum. This initiative is relevant to the education sector, specifically in the training of engineers and professionals in analytics and optimization.	UL
[33]	Focuses on the reliability assessment of WC-Co-based cemented carbides using ML. It is relevant to the manufacturing industry.	UL
[34]	Addresses the use of ML methods to develop customized models of the human neuromusculoskeletal system. The industry to which it is mainly applied is biomedical, orthopedic, and rehabilitation technology.	SL
[35]	Focuses on predicting the success of startups using an ML approach. A model is proposed that considers both internal conditions of startups and industry characteristics to make accurate predictions. This study is applicable to the business and entrepreneurship industry.	UL

Source: Own elaboration.

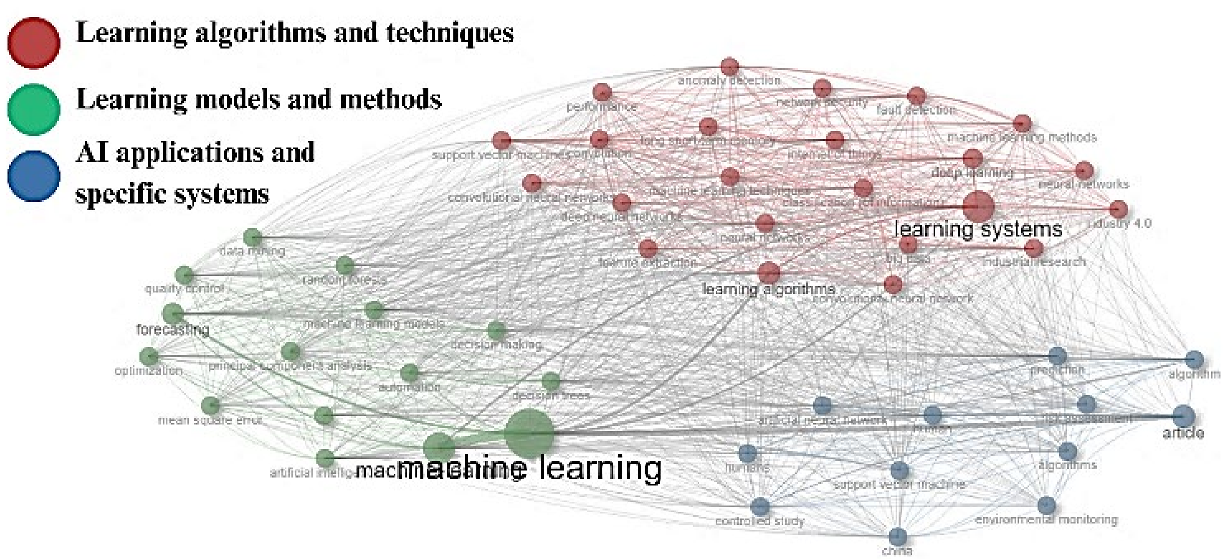

Figure 5. Co-occurrence Network
Source: Own elaboration.

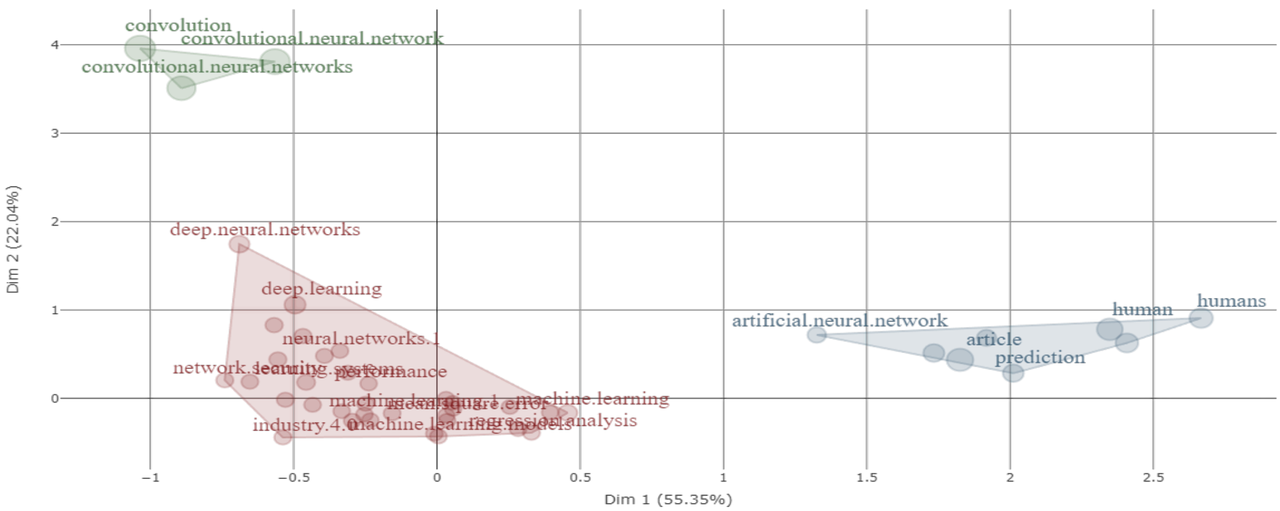

Figure 6. Factor analysis.
Source: Own elaboration.

3.1 Co-occurrence Network

Fig. 5 illustrates the co-occurrence network of keywords, generated using a bibliometric network construction and visualization tool. The terms with the highest frequency are ‘ML’, ‘industry’, ‘innovation’, and ‘infrastructures’. The analysis revealed three main clusters: green, blue and red.

The green cluster contains terms related to AI techniques and models, such as ‘ML techniques’, ‘random forests’, ‘learning algorithms’, ‘ML models’, ‘automation decision’, and ‘artificial neural network’. These terms suggest that the network focuses on various ML approaches and models.

The blue cluster is primarily centered around neural network including terms such as ‘neural networks’, ‘convolution’, ‘convolutional neural networks’, ‘information classification’, and ‘feature extraction’ indicating the network is particularly interested in the applications of neural networks to feature extraction, classification, and evaluation.

Finally, the red cluster focuses on learning systems and ML techniques as it includes terms such as ‘learning systems’, ‘ML’, ‘SL’, ‘UL’, ‘RL’, 'classification', ‘prediction’, ‘control’, ‘learning algorithms’, ‘forecasting’, ‘set theory’, and ‘machine’.

3.2 Factor Analysis

Fig. 6 presents a factor analysis based on multiple correspondence analysis. In the graph, each color represents a group of words that address a specific theme or subfield. The analysis identified three dominant clusters with respect to the research topic. The first (green), although the least relevant, addresses factor convolution. The second (red), and the most relevant, groups terms aligned with ML such as deep learning and neural networks. Finally, the last subgroup (blue) brings together human-related terms such as 'humans' and 'article', among others.

3.3 Most relevant scientific affiliations

We identified 1,589 different affiliations, with Zhejiang University (274 articles) being the most prolific, followed by University of California (188 articles), Northeastern University (171 articles), University of Science and Technology Beijing (163 articles), Tsinghua University (160 articles), Huazhong University of Science and Technology (144 articles), Central South University (131 articles), Beijing (129 articles), Shanghai Jiao Tong University (106 articles), and 123 papers affiliated to others institutions.

3.4 Country-level Production

Fig. 7 illustrates the global distribution of scientific production in a range of blues, where the most intense blue indicates the regions with the highest number of scientific

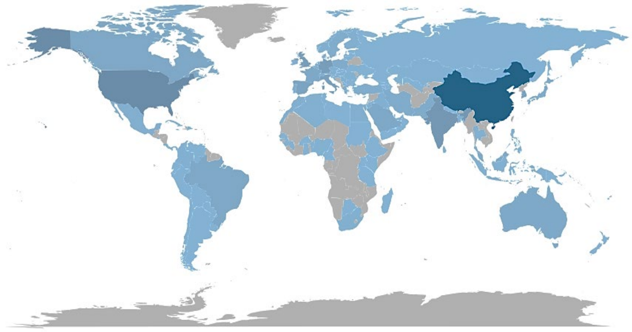

Figure 7. Scientific production by country
Source: Own elaboration.

affiliations, while the gray color indicates the absence of scientific production in this topic. China (8,562 articles) and the United States (3,492 articles) lead in contributions followed by India (2,224 articles), United Kingdom (1,609 articles), Germany (1,602 articles), Italy (1,392 articles), Spain (1,054 articles), South Korea (1,037 articles), Canada (772 articles), and Brazil (770 articles). Brazil stands out as the Latin American country with the most publications on the subject.

3.5 Three-field Plot

Fig. 8 establishes a relationship between authors, keywords, and references.

The left column shows important references with a high level of relationship with ML and deep learning. Some authors that stand out are Breiman, LeCun, Bengio & Hinton, and Kingma & Ba.

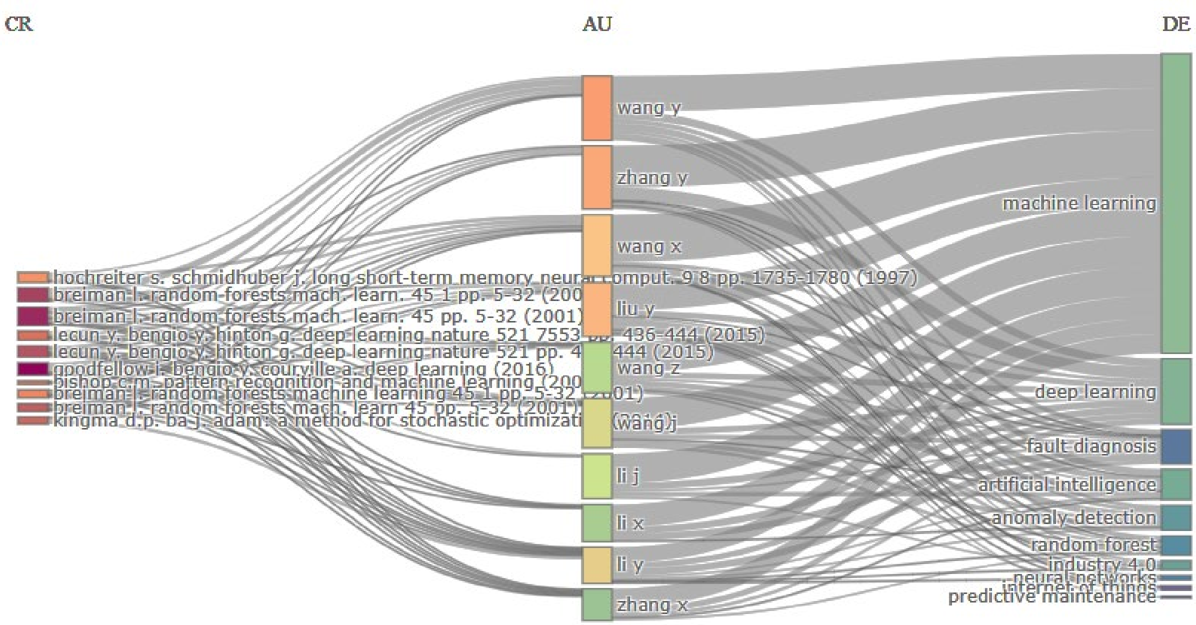

Figure 8. Three-field plot of authors, references and keywords
Source: Own elaboration.

The middle column shows authors such as Wang Y, Zhang Y, and Wang X, who display a connection to multiple references and keywords.

The column on the right shows the keywords associated with the articles of these authors, the most relevant words being ‘ML’, ‘deep learning’, ‘fault diagnosis’, ‘AI’, ‘anomaly detection’, ‘random forest’, ‘long short-term memory (LSTM)’, ‘industry 4.0’, ‘neural networks’, and ‘predictive maintenance’.

The relationships between CR (Cited References), AU (Authors), and DE (Keywords) show a dense network of interconnections where fundamental references in ML and deep learning significantly influence the research of several leading authors, who in turn work on a variety of key applications and technologies in these fields.

1 Discussion and Conclusion

The bibliometric analysis conducted on the application of ML in industrialization has revealed several significant trends and findings.

As of April 2024, 7,335 articles have been identified in Scopus. According to Fig. 3, scientific production in the field of ML applied to industrialization began to show significant growth starting in 2015. This growth became especially pronounced from 2019 onwards, peaking around 2023. Put in numbers the growth experienced since 2015 to April 2024 is 20.86%. This remarkable increase in the production of scientific papers may indicate a growing interest and investment in the application of ML techniques across industrial processes, as well as their adoption and application of ML methods, reflecting a continued expansion and growing interest in this area of research. There seems to be a deep interest of the scientific and technological community.

The Three Field Plot analysis identified Wang Y. and Zhang Y. as particularly influential authors who have published widely cited works. Additionally, methodologies such as ‘Long Short-Term Memory (LSTM)’, ‘random forests’, and ‘deep learning’ emerged as crucial in this field.

The thematic map highlighted ‘learning systems’ and ‘learning algorithms’ as fundamental yet underdeveloped areas, suggesting significant opportunities for future research.

As for the factor analysis, three relevant subthemes could be identified: ML, AI, and convolutional neural networks. The first of these subthemes is the most relevant due to the high frequency of associated words in the graph. In addition, the field covered by convolutional neural networks has the fewest synonyms of the three, while the field covered by ML has the most.

Regarding the production of scientific articles by country, there was a low presence of research in Latin America. Although Brazil's presence among the most outstanding countries was evident it is in the last position with 770 scientific articles.

Regarding the limitations of the present analysis, three main aspects were identified. First, only articles indexed in Scopus were included due to lack of access to other databases, which restricted the scope of the review. Secondly, the language selected was a limitation, as only articles in English were considered, excluding publications in other languages that could have provided relevant information. Finally, the exclusive use of articles as a data source also represents a limitation, since other types of documents that could have enriched the analysis were omitted. These three factors limited the breadth and diversity of our sample.

In conclusion, we can say that ML has contributed significantly to industrialization and, over time, will automate more processes and handle larger amounts of data. Industries will have to adapt to these advances, conducting more tests and collecting larger amounts of data to achieve greater accuracy and improve their contributions. However, the lack of empirical studies and long-term evaluations of the proposed applications represents a notable opportunity for improvement, as most of the techniques and applications described appear to be in experimental or proof-of-concept phases, without sufficient evidence of their effectiveness and sustainability in real and long-term scenarios. Knowledge and familiarity with key concepts such as IoT, neural networks, learning systems, and forecasting will allow industries to better manage their data and achieve greater efficiency, since over time there will be greater changes and it will be necessary to adapt to and understand these advances.

In addition, it is recommended to implement studies such as Systematic Literature Review (SLR) and State of the Art Systematic Review (SotA) to obtain a comprehensive and up-to-date view. In addition, Systematic Mapping Review (SMR) and Scoping Review will categorize and explore the breadth of research, consolidating existing knowledge and guiding future research.

It is suggested to analyze articles from other repositories such as Web of Science (WOS) and SciELO, among others, to obtain a broader and more diverse perspective of the literature. It is also recommended to conduct specific studies on topics identified as emerging or insufficiently explored during the review, such as specific applications of RL, IoT and ML integration, and the impact of ML on industrial sustainability, to deepen knowledge and potential practical applications.

In the context of ML applied to industrialization, various challenges and opportunities are identified that outline future lines of research. Many applications described in the literature are in experimental or proof-of-concept stages, which limits their validation in real scenarios. In addition, ML methodologies face difficulties in adapting to the variability of data and operating environments characteristic of industrial contexts, which poses the challenge of generalizing solutions and ensuring their integration with existing technologies.

For example [43], highlights 2 challenges. First, many algorithms have been validated mainly through simulations with synthetic data, which makes it difficult to consolidate them in practical environments. Second, deep learning-based algorithms often require large volumes of data for training, which represents an obstacle for organizations that do not have sufficiently large and representative data sets.

On the other hand, there are significant opportunities for the development of ML in industrialization. These include the expansion of applications in emerging sectors, such as industrial sustainability, energy efficiency, and waste management. In addition, the integration of ML with the IoT could improve automation and real-time monitoring, while CNN offer great potential for specific applications, as seen in factor analysis.[42]

Finally, the expansion of research in less explored regions represents an opportunity to generate unique perspectives tailored to local needs. In Latin America, for example, Brazil leads in scientific production, which underlines the importance of promoting similar studies in other countries in the region. In conclusion, overcoming these barriers and taking advantage of these opportunities could significantly contribute to technological progress and competitiveness in various industrial sectors.

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Influence of quenching and annealing heat treatments on the strain hardening properties of AISI steels: a statistical approach

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Abstract
The knowledge of the stress-strain curve is of great interest due to the different parameters, conditions, and applications to which materials are exposed in different industrial sectors. This statistical study aims to analyze the strain-hardening behavior of two AISI-grade materials (1045 and 304). The ASTM E-8 standard procedure guidelines were considered for different hardening percentages due to plastic deformation (20% and 40%), following an experimental design of 45 tests, including repetitions. The results revealed an improvement in the material's mechanical properties corresponding to the hardening percentage, which was also correlated with the heat treatment process. Finally, response surface methodology plots were generated, depicting predictive equations governing the behavior of the response variables (stress, yield, load, and strain) with a confidence level of 98% in the results.

Keywords: strain hardening; statistical analysis; prediction; RSM

Influencia de los tratamientos térmicos de temple y recocido en las propiedades de endurecimiento por deformación de los aceros AISI: un enfoque estadístico

Resumen
El conocimiento de la curva esfuerzo-deformación es de gran interés debido a los diversos parámetros, condiciones y aplicaciones a las que se ven expuestos los materiales en diferentes sectores industriales. Este estudio estadístico tiene como objetivo analizar el comportamiento de endurecimiento por deformación de dos materiales grado AISI (1045 y 304). Se consideraron los lineamientos de procedimiento de la norma ASTM E-8 para diferentes porcentajes de endurecimiento por deformación plástica (20% y 40%), siguiendo un diseño experimental de 45 ensayos, incluyendo repeticiones. Los resultados revelaron una mejora en las propiedades mecánicas del material correspondiente al porcentaje de endurecimiento, el cual también se correlacionó con el proceso de tratamiento térmico. Finalmente, se generaron gráficos de la metodología de superficie de respuesta, representando ecuaciones predictivas que gobiernan el comportamiento de las variables de respuesta (esfuerzo, fluencia, carga y deformación) con un nivel de confianza del 98% en los resultados.

Palabras clave: endurecimiento por deformación; análisis estadístico; predicción; RSM.

1 Introduction

The machine elements design relies heavily on a comprehensive understanding of materials' mechanical and microstructural behavior. During both manufacturing and operational use, materials are exposed to different factors, such as temperature fluctuations and mechanical loads. These conditions induce stresses that can significantly modify the materials' mechanical and physical properties [1]. Strain hardening is a critical phenomenon for many industrial alloys. It occurs when a material is subjected to plastic deformation, increasing its resistance to further deformation. This property is especially

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important in industries that manufacture parts and components subject to high stress, as it can enhance durability and performance [2].

Patiño-Perez *et al.* [3] evaluated the AISI 1006 alloy using different suppliers to determine its elongation and thinning properties according to ASTM standards. Salman [4] explored the microstructure and mechanical properties of AISI 1018 low-carbon steel subjected to a cold rolling process. Dimatteo *et al.* [5] developed a prediction model for strain-hardening behavior in multiphase steels. Bounezour *et al.* [6] investigated the effects of strain hardening on the mechanical properties of two metallic materials (XC38 steel and aluminum alloy).

Using simulations and experiments, Eom et al. [7] compared the plastic deformation behavior of pre-heat-treated steel (PHTS) and SCM435 steel. PHTS exhibited a high initial yield strength and negligible strain-hardening capacity, while SCM435 exhibited good strain-hardening behavior under the experimental conditions evaluated. Pérez *et al.* [8] analyzed the conditions of quenching and annealing heat treatments and their impact on the mechanical properties of hardness, toughness, and mechanical strength of 5160H steel. Lorenzo *et al.* [9] investigated the mechanical behavior of two different steels under cyclic loading, focusing on the Bauschinger effect and hardening rule, which better represent the material's plastic behavior. Using analysis of variance, Soria Aguilar et al. [10] studied the impact of two cycles on the microstructure and mechanical properties of API-5CT-J55 welded steel.

Considering the above, this study addresses a significant gap in the current literature by investigating the effects of thermal annealing treatments, specifically quenching and annealing, on AISI 1045 and 304 steels subjected to different strain-hardening conditions, with the aim to analyze the influence of treatment parameters and response variables statistically. While previous research has examined various heat treatments and their impact on mechanical properties, detailed insights into how these treatments affect strain-hardening behavior and corresponding mechanical performance across different geometries remain limited. The scientific challenge lies in accurately modeling and predicting the mechanical behavior of these steels under the combined effects of strain hardening and heat treatment [2].

2 Materials and methods

The methodology developed in this research is shown in Fig. 1, based on 5 steps. Initially, circular bar samples of hot-rolled AISI 1045 and 304 steel were selected, considering the guidelines of the ASTM E-8. These materials were in the hot-rolled state, which introduces anisotropy due to the rolling process.

2.1 Experimental design

Initially, for the factorial design, it was necessary to consider the parameters (input variables) and the response variables (output), as shown in Table 1. The factorial design type used was the fractional Box-Behnken design, which allows for evaluating a fraction of all possible combinations (3^3 design). This approach involves selecting a subset of the combinations and conducting experiments only with those combinations, optimizing the study of the variables' effects efficiently. Note that a total of 45 samples of both materials were used.

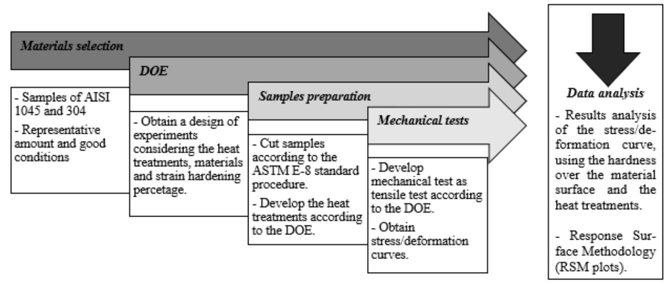

Figure 1. Methodology applied to this work. Note: DOE, design of experiments.
Source: The authors.

Table 1.
Specification of parameters and response variables

Parameters	ID	Level	Response variables	ID
Steel	AISI 1045	27 samples	Yield strength	YS
	AISI 304	18 samples	Tensile strength	UTS
Heat treatment (HT)	Original-O	-1	Unit strain	Unit def.
	Quenched-T	0	Maximum load	CM
	Annealed - R	1	Strain hardening capacity	SHc
Strain hardening percentage (SH%)	0%	-1	---	---
	20%	0	---	---
	40%	1	---	---

Source: The authors.

2.2 Quenching and Annealing heat treatments

For AISI 1045 steel in the quenching treatment, the steel was preheated to a temperature of 850°C for 30 min and then cooled in water. For the annealing treatment, the steel was heated to a temperature of 850°C for 60 min and then slowly cooled in the muffle furnace (Pinzuar equipment). Similarly, AISI 304 steel in the annealing treatment was heated at a temperature of 1,100°C for 30 min, followed by rapid cooling in water. As mentioned, due to the similar phase transformation during quenching and annealing, only annealing was carried out for the AISI 304 steel samples [11]. Annealing is a heat treatment process in which the material is heated to a temperature that "transforms into austenite and is then slowly cooled (down to 500°C)". As a result, the austenite transforms into coarse-grained pearlite and ferrite and then air-cooled [12].

2.3 Tensile test

The tensile tests were conducted using a Pinzuar/50K Universal Testing Machine in uniaxial direction along the sample longitudinal axis (Y-axis), which corresponds to the rolling direction of the hot-rolled steel bars, at a room temperature of 23°C and 49% relative humidity, following the specifications (dimensions and geometry) of the ASTM-E8M standard procedure [13]. The sample machining precision and consistent cross-sectional dimensions are critical factors in obtaining reliable mechanical properties. Variations in these factors can significantly impact the tensile test results and other mechanical evaluations. The geometric data of the samples suggested for the tensile test were input into the equipment's software considering a calibrated length of 187.5 mm, a diameter of 12.5 mm, and a total length (300 mm). Note that the steel samples were machined using a machining center to guarantee the same circular geometry, where G: Calibrated length = 62.5 mm, D: Diameter = 12.5 mm, R: Fillet radius = 10 mm, and A: Reduced section length = 172.7 mm.

2.4 Strain hardening percentages (SH%)

In this process, the stresses and strains in the strain-hardening region were estimated to evaluate the different steels in their original state. The required stresses were obtained from [14]. Notably, hardness and yield strength increase more than tensile strength, especially in the initial deformation stage (10%) [15]. Also, the strain hardening capacity (SHc) can be estimated using Eq. 1, which was proposed by [16], taking into account the material mechanical parameters such as ultimate tensile strength (σ_{ult}) and yield strength (σ_{y}).

$$\mathrm{SHc} = \frac{\sigma_{\mathrm{ult}}}{\sigma_{\mathrm{y}}} - 1 \quad (1)$$

2.5 Response surface methodology (RSM)

The statistical approximation of the wear test parameters such as steel (S), heat treatment (HT), and strain hardening percentage (%SH) on the response variables, which are yield strength (YS), tensile strength (UTS), unit deformation, maximum load and strain hardening capacity (SHc) were estimated. As a product of the combination of factors S, HT, and SH with 2 and 3 levels each one, respectively, 45 tests were developed for each steel in a Completely Randomized Design (CRD) with 3 replicate tests to guarantee the statistical dispersion of the results. These experiments aim to represent many factors and levels primarily responsible for the differences in the response. These contours showed a range of colors where blue is the minimum value and red is the maximum value for each plot obtained for the response variables using *Statgraphics* statistical software [17].

Response surface methodology (RSM) is a statistical technique to develop, improve, and optimize processes. It uses quantitative data from appropriate experiments to determine regression model equations and operating conditions [18]. The goal is to identify the relationships between response and input variables. Analyzing the surfaces can determine the optimal conditions for achieving desired mechanical properties in materials to facilitate better design and process control in material engineering.

2.6 Analysis of variance (ANOVA or AV)

An analysis of variance was performed on the evaluated parameters and response variables on the strain hardening behavior using the Statgraphics statistical software for the sources of variation (M, HT, and %SH) and their interactions [19]. AV is a statistical technique that analyzes the variation on the experimental results of a particular design, decomposing it into independent sources of variation attributable to each of the effects (variables) that constitute the experimental design [20]. In this statistical analysis, the factor's effects were analyzed, allowing the comparison of more than two levels simultaneously and determining whether there is a relationship between them and, thus, the positive or negative significance of the response variables. The significant or non-significant model terms were identified through the P index values, existing a significant effect between the factors, with P values equal to or less than 0.05 ($P \leq 0.05$).

3 Results and discussions

3.1 Experimental results for the RSM

Table 2 presents the mechanical properties of average values and their behavior, analyzed from the stress-strain curves obtained in the tensile tests for the entire experimental set (original samples). However, SHc was calculated using Eq. 1. Fig. 2 was obtained from both materials' tensile tests (stress-strain curves) based on the developed heat treatments.

The mechanical properties behavior of AISI 1045 and AISI 304 stainless steels after heat treatments and variations in strain hardening (SH) are according to the technical literature [21]. For AISI 1045, the quenching heat treatment (T-HT) significantly increases the yield strength (YS) and ultimate tensile strength (UTS), reaching up to 830.14 MPa and 1,055.26 MPa, respectively, for 40% SH. This steel also decreases maximum unit deformation and maximum load, making it more material brittle but stronger [22]. For the annealed heat treatment (R-HT) AISI 1045, the yield strength and ultimate tensile strength are lower than quenched samples but still higher

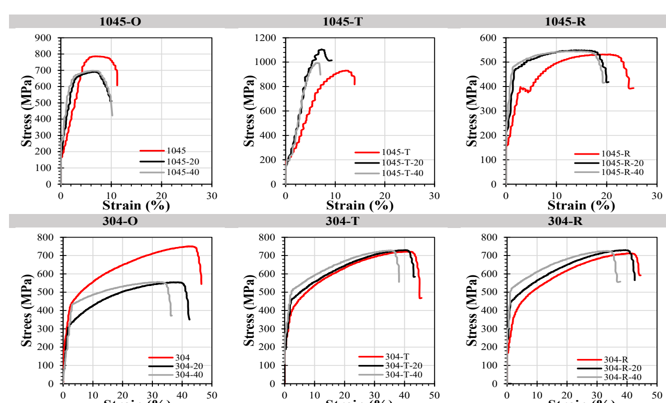

Figure 2. Stress-strain curves of AISI grade steels (1045-304).
Source: The authors.

Table 2.
Average mechanical properties analyzed from the stress-strain curves of AISI 1045 grade steels (O, T, and R) and AISI 304 (O and R), along with their corresponding SH variations (20 and 40%).

Parameters			Response variables				
Steel	HT	SH (%)	YS (MPa)	UTS (MPa)	Unit deformation (mm)	Max Load (kN)	SHc
AISI 1045	O	0	376.18	673.07	10.12	97.20	0.789
		20	563.09	698.75	9.213	86.03	0.241
		40	607.89	724.64	8.481	85.10	0.192
	T	0	700.00	943.22	13.22	122.90	0.347
		20	750.70	964.40	7.227	118.35	0.285
		40	830.14	1,055.26	6.893	115.16	0.271
	R	0	398.00	533.01	23.30	71.16	0.339
		20	493.55	563.2	19.60	62.23	0.141
		40	452.24	541.08	18.75	66.40	0.196
AISI 304	O	0	230.01	504.58	49.06	72.98	1.194
		20	302.17	538.36	42.33	66.06	0.782
		40	385.08	557.20	34.37	64.51	0.447
	R	0	220.62	444.16	53.74	61.61	1.013
		20	391.03	482.50	42.82	59.55	0.234
		40	386.46	478.34	39.39	52.98	0.238

Note: Where, SH is the strain hardening, and SHc is the strain hardening capacity.
Source: The authors.

than the original state (O), reflecting a more ductile and relaxed structure due to the formation of larger grains. Variations in SH% also show a decreasing trend in strain hardening capacity (SHc), with values decreasing from 0.339 in the original state to 0.196 at 40% SH, which aligns with greater energy absorption capacity and increased ductility. In AISI 304 stainless steel, strain hardening significantly increases the yield strength and ultimate tensile strength, with YS reaching 385.08 MPa and UTS reaching 557.20 MPa for 40% SH in the original state. This behavior is typical of austenitic steels exhibiting a high strain-hardening capacity. The annealing treatment (R) also improves ductility, but the increases in YS and UTS are less pronounced than in AISI 1045, reflecting its more ductile and tough nature [23].

3.1 Statistical results

3.2.1 **ANOVA results**

The response variables behavior of YS, UTS, Unit Def., Max. Load, and SHc were evaluated for both materials using the results in Table 4. The sum of squares (SS), F factor, and P values were also used to interpret statistical significance. Furthermore, the correlation coefficients R^2, MAE (Mean Absolute Error), and the Durbin-Watson statistic were used to assess the quality of the models, as shown in Tables 7 and 8 for the two steels.

Table 3 shows that, for the AISI 1045 analysis, heat treatment (HT) significantly impacts the properties of UTS and Max. Load, with P-values of 0.0119 and 0.0009, respectively, indicating strong statistical significance. It also affects Unit Def. with a P-value of 0.0023, suggesting strong significance. However, YS and SHc are unaffected (P-values of 0.0846 and 0.1690, respectively). Strain hardening (SH) significantly affects the response variables YS, Unit Def., and Max. Load, with P-values of 0.0138, 0.0363, and 0.0164, respectively, indicating strong statistical significance. However, the effects on UTS and SHc are insignificant (P-values of 0.1326 and 0.0740, respectively). This behavior indicates that strain hardening has a major impact on these properties.

Notice that AA interaction significantly affects all response variables except SHc, with extremely low P-values for YS, UTS, Unit Def., and Max. Load (0.0012, 0.0006, 0.0102, and 0.0001, respectively). This interaction does not significantly affect SHc (P-value of 0.8719). For AB Interaction, no significant effects were observed on any of the response variables, with high P-values across the board (all P-values > 0.1). However, BB interaction shows a trend towards significance for Max. Load with a P-value of 0.0659, while other variables are not significantly affected (P-values > 0.1). For model quality assessment, high R^2 values (YS: 98.44%, UTS: 98.87%, Unit Def.: 97.97%, Max. Load: 99.70%, SHc: 84.42%) indicate a good fit of the models to the data, suggesting that the variations in response variables are well-explained by the factors considered [23].

Pareto plots show the percentage contribution of each factor to the total variation in the mechanical properties, as was observed in Fig. 3.

Table 4 shows that for the AISI 304 analysis, HT significantly affects UTS and Max. Load, with P-values of 0.0010 and 0.0080, respectively, indicating strong statistical significance. It also affects SHc with a P-value of 0.0669, suggesting a trend toward significance. However, YS and Unit Def. are unaffected (P-values of 0.4244 and 0.0895). SH significantly affects all response variables. YS, UTS, Unit Def., Max. Load and SHc show strong statistical significance with P-values of 0.0115, 0.0040, 0.0018, 0.0117, and 0.0062, respectively. This behavior indicates that strain hardening has a major impact on these mechanical properties [24].

Table 3.
Analysis of Variance for AISI 1045.

Fuente	DOF	YS			UTS			Unit Def.			Max. Load			SHc		
		SS	F	P-Value	SS	F	P-Value	SS	F	P-Value	SS	F	P-Value	SS	F	P-Value
A:HT	1	6893.23	6.46	0.0846	35139.5	30.11	0.0119	190.812	95.57	0.0023	782.955	185.67	0.0009	0.049686	3.25	0.1690
B:SH	1	28855.1	27.04	0.0138	4912.34	4.21	0.1326	26.1084	13.08	0.0363	100.86	23.92	0.0164	0.110976	7.27	0.0740
AA	1	155074	145.31	0.0012	266939	228.71	0.0006	67.2181	33.67	0.0102	3326.56	788.84	0.0001	0.000470	0.03	0.8719
AB	1	7873.90	7.38	0.0728	473.062	0.41	0.5696	2.11848	1.06	0.3788	13.4689	3.19	0.1719	0.051529	3.37	0.1635
BB	1	3478.61	3.26	0.1688	17.1698	0.01	0.9111	4.18955	2.10	0.2433	33.8939	8.04	0.0659	0.035555	2.33	0.2244
Error total	3	3201.61	---	---	1167.16	---	---	1.99657	---	---	4.217	---	---	0.015269	---	---
Total (corr.)	8	205377	---	---	310983	---	---	296.437	---	---	4270.39	---	---	0.294026	---	---
R^2	-	98.44%			98.87%			97.97%			99.70%			84.42%		
MAE	-	16.61			16.90			0.68			1.01			0.06		
Durbin-Watson	-	3.46091 (P=0.9091)			2.04502 (P=0.2033)			2.19018 (P=0.2608)			3.4441 (P=0.9028)			2.08344 (P=0.2177)		

Where: SS, sum of squares, DOF, degrees of freedom.
Source: The authors.

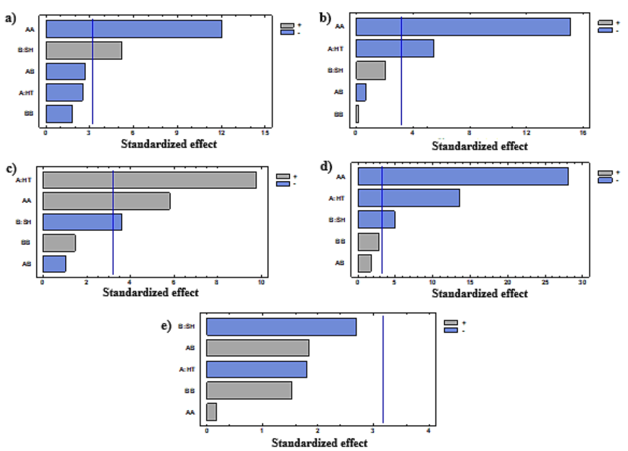

Figure 3. Pareto plots of AISI 1045 for (a) YS, (b) UTS, (c) Unit Def., (d) Max. Load, and (e) SHc.
Source: The authors.

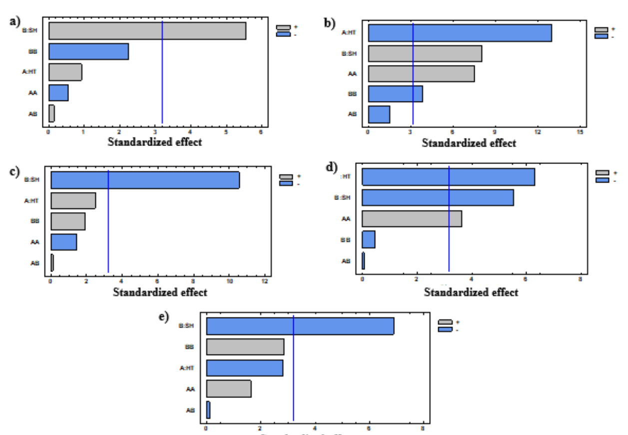

Figure 4. Pareto plots of AISI 304 for (a) YS, (b) UTS, (c) Unit Def., (d) Max. Load, and (e) SHc.
Source: The authors.

Notice that AA interaction shows significant effects on UTS and Max. Load with extremely low P-values (0.0049 and 0.0356 respectively). This interaction also affects SHc (P-value of 0.2024), suggesting some influence. However, the effects on YS and Unit Def. are insignificant (P-values of 0.6313 and 0.2480, respectively). For AB interaction, no significant effects were observed on any of the response variables, with high P-values across the board (all P-values > 0.2). However, BB interaction significantly affects UTS and SHc with P-values of 0.0311 and 0.0652, respectively. Other variables are not significantly affected (P-values > 0.1) [25]. For model quality assessment, high R2 values for most variables (YS: 92.50%, UTS: 97.26%, Unit Def.: 96.54%, Max. Load: 95.67%) indicate a good fit of the models to the data, suggesting that the variations in response variables are well-explained by the factors considered. However, the R2 value for UTS (9.03%) suggests that the model does not explain much of the variability in this response variable.

Pareto charts show that the variables B:SH and A:HT are the most frequent for all analyzed variables, as is shown in Fig. 4.

3.2.2. RSM plots

Fig. 5 shows the RSM plots for the AISI 1045 response variables, according to the statistical statements made in Table 3. Notice that YS increases significantly with higher levels of SH (Fig. 5a).

At the highest SH values (around 1 on the scale), YS reaches values close to 770 MPa. The influence of HT is also notable, with an intermediate level of HT contributing to higher YS values. However, high or low HT levels do not reach the maximum YS. From Fig. 5b, UTS shows a steady increase with HT and SH. Higher levels of SH (approaching 1) and higher HT levels result in UTS values near 1,120 MPa. This behavior suggests that both parameters should be optimized to maximize ultimate strength. Unit Def. behavior decreases as SH

Table 4.
Analysis of Variance for AISI 304.

Fuente	DOF	YS			UTS			Unit Def.			Max. Load			SHc		
		SS	F	P-Value	SS	F	P-Value	SS	F	P-Value	SS	F	P-Value	SS	F	P-Value
A:HT	1	1089.45	0.85	0.4244	6346.60	168.90	0.0010	17.3060	6.14	0.0895	144.158	39.87	0.0080	0.146641	7.93	0.0669
B:SH	1	39487.6	30.83	0.0115	2439.36	64.92	0.0040	313.782	111.29	0.0018	110.339	30.51	0.0117	0.879368	47.58	0.0062
AA	1	363.151	0.28	0.6313	2115.53	56.30	0.0049	5.76867	2.05	0.2480	48.0527	13.29	0.0356	0.048880	2.64	0.2024
AB	1	28.9982	0.02	0.8899	85.0084	2.260	0.2296	0.02890	0.01	0.9257	0.00641	0.00	0.9691	0.000196	0.01	0.9245
BB	1	6392.41	4.99	0.1116	554.889	14.77	0.0311	10.5035	3.73	0.1491	0.74013	0.20	0.6817	0.149969	8.11	0.0652
Error total	3	1280.84	---	---	37.577	---	---	2.81945	---	---	3.61606	---	---	0.018482	---	---
Total (corr.)	8	51204.1	---	---	11654.1	---	---	355.847	---	---	314.144	---	---	1.2805	---	---
R^2	-	92.50%			9.03%			97.26%			96.54%			95.67%		
MAE	-	18.34			3.06			0.86			0.97			0.069		
Durbin-Watson	-	3.21647 (P=0.7769)			3.03962 (P=0.6737)			3.26739 (P=0.8046)			3.25774 (P=0.7994)			3.22803 (P=0.7833)		

Where: SS, sum of squares, DOF, degrees of freedom, and MAE, Mean absolute error.
Source: The authors.

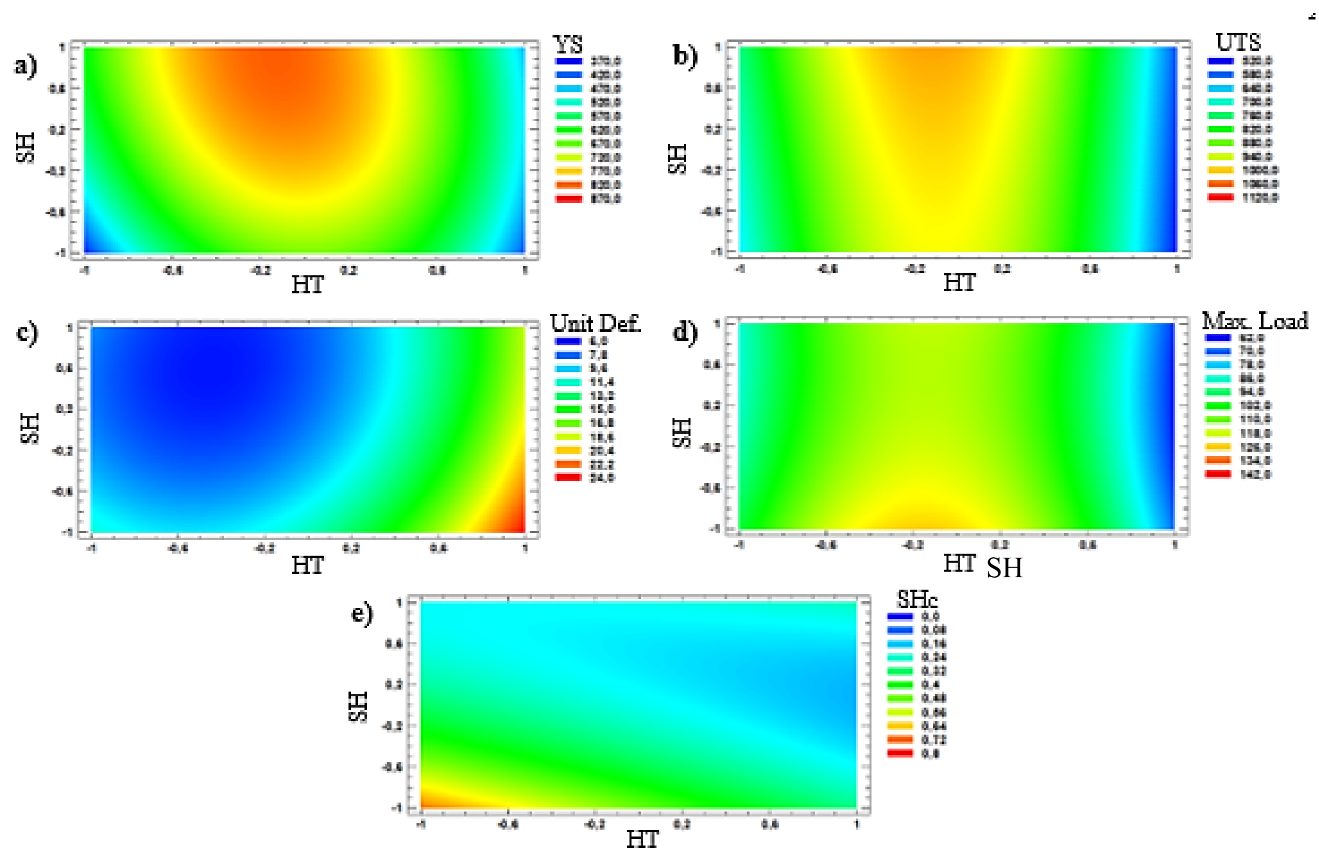

Figure 5. RSM plots for the AISI 1045 response variables.
Source: The authors.

increases, as shown in Fig. 5c. Note that the lowest deformation (around 8 mm) occurs at the highest SH levels. HT has a minimal impact compared to SH. These results indicate that increasing SH is more effective for reducing unit deformation. HT and SH influence the maximum load capacity, but SH has a more pronounced effect (See Fig. 5d). The highest maximum load (around 142 kN) is achieved with high SH and intermediate HT levels. Like YS, very high or low HT levels are less effective than moderate levels. Finally, in Fig. 5e the strain-hardening capacity (SHc) increases significantly with higher SH levels, reaching values close to 0.86. HT has a lesser impact on SHc. Therefore, increasing SHc is crucial to enhance SHc.

Fig. 6 response surfaces include a detailed interpretation of each response surface about the color scale and corresponding numerical values. Fig. 6a for YS indicates that increasing %SH positively impacts the yield strength. The highest values of YS (440 MPa) are observed when %SH is around 1 and HT is between -0.6 to 0.4. Conversely, the lowest values of YS (200 MPa) are found at lower %SH and HT values near -1. This behavior suggests that heat treatment and strain hardening contribute significantly to increasing yield strength, with strain hardening having a more pronounced effect. The UTS response surface in Fig. 6b shows a moderate increase in ultimate tensile strength with increasing %SH and HT. The maximum value (680 MPa) is achieved at %SH around -0.2 and HT near 0.8. The minimum value (400 MPa) is observed at low %SH and HT values, which indicates a combined effect of HT and %SH on ultimate tensile strength, where optimized conditions can substantially enhance UTS. The response surface for Unit Def. illustrates that higher %SH and intermediate HT levels decrease unit deformation, with the minimum value (34 mm) appearing at %SH around 1 and HT at 0.6 as is shown in Fig. 6c. The maximum deformation (64 mm) is seen at low %SH and HT values. This behavior implies that strain hardening reduces unit deformation, improving material ductility. For the case of the Max. Load (See Fig. 6d), the response surface reveals that both %SH and HT positively influence the maximum load capacity. The highest load (77.6 kN) is observed at %SH near 1 and HT around 0.4. The lowest load (54.4 kN) is found at low %SH and HT values, which suggests that enhancing %SH and applying suitable heat treatment can significantly increase the material's load-bearing capacity. Finally, in Fig. 6e, the SHc response surface indicates that %SH strongly affects the strain hardening coefficient. The maximum SHc value (1.6) is achieved at %SH near 1 and HT around -0.4. The minimum SHc value (0.5) is seen as a low %SH and HT values. This result highlights that strain hardening predominantly influences the strain hardening coefficient, with heat treatment playing a secondary role.

Equations 2 to 6 describe the behavior of YS, UTS, unit def., max. load, and SHc under different experimental conditions for AISI 1045 steel. For AISI 304 steel, these properties are represented by equations 7 to 11. These equations enable the determination of specific values on the response surface about the material's mechanical properties.

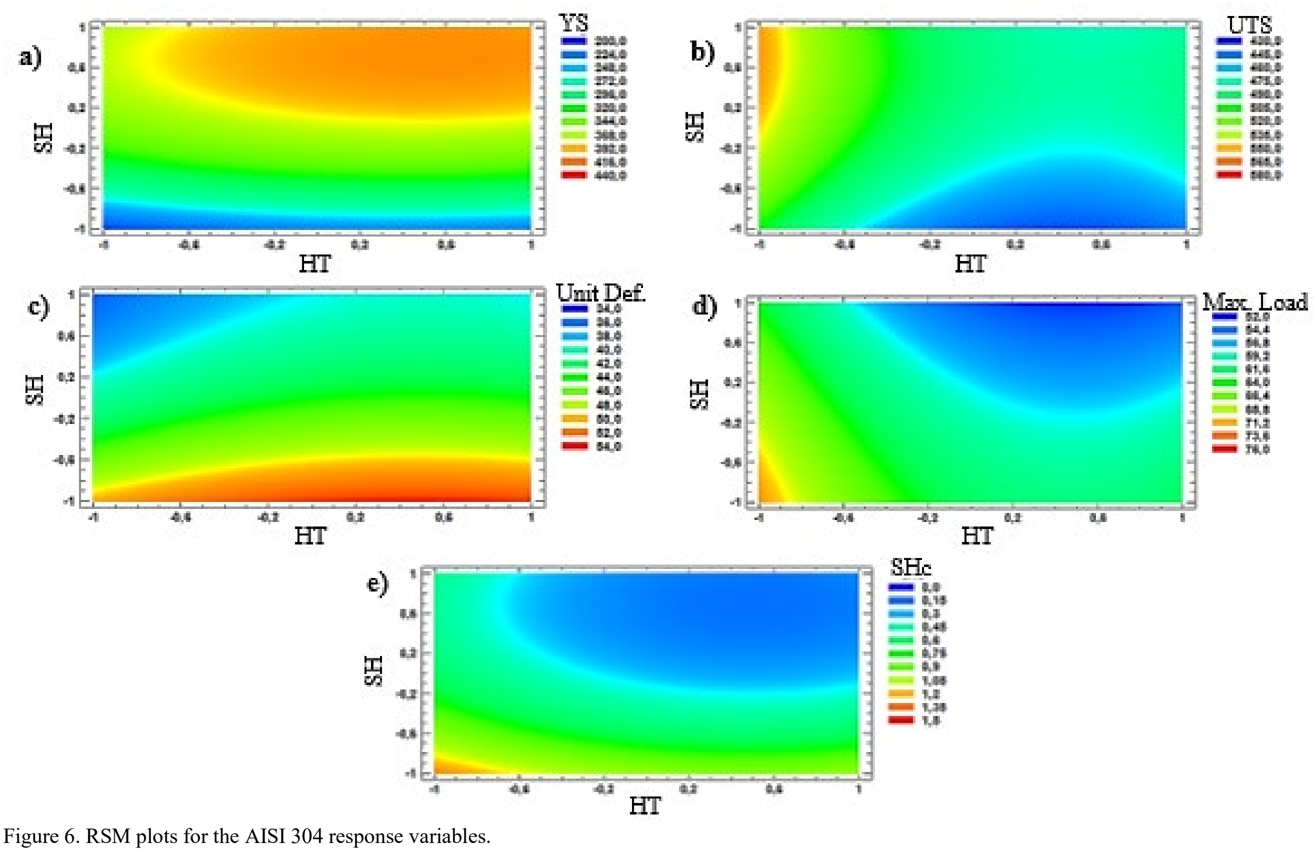

Figure 6. RSM plots for the AISI 304 response variables.
Source: The authors.

$$YS = 788.083 - (33.895 \times HT) + (69.3483 \times SH) - (278.455 \times HT^2) - (44.3675 \times HT \times SH) - (41.705 \times SH^2) \quad \text{Eq. 2}$$

$$UTS = 985.673 - (76.5283 \times HT) + (28.6133 \times SH) - (365.335 \times HT^2) - (10.875 \times HT \times SH) + (2.93 \times SH^2) \quad \text{Eq. 3}$$

$$\text{Unit Def.} = 8.14844 + (5.63933 \times HT) - (2.086 \times SH) + (5.79733 \times HT^2) - (0.72775 \times HT \times SH) + (1.44733 \times SH^2) \quad \text{Eq. 4}$$

$$\text{Max. Load} = 116.059 - (11.4233 \times HT) - (4.1 \times SH) - (40.7833 \times HT^2) + (1.835 \times HT \times SH) + (4.11667 \times SH^2) \quad \text{Eq. 5}$$

$$SHc = 0.212111 - (0.091 \times HT) - (0.136 \times SH) + (0.0153333 \times HT^2) + (0.1135 \times HT \times SH) + (0.133333 \times SH^2) \quad \text{Eq. 6}$$

$$YS = 370.393 + (13.475 \times HT) + (81.125 \times SH) - (13.475 \times HT^2) + (2.6925 \times HT \times SH) - (56.535 \times SH^2) \quad \text{Eq. 7}$$

$$UTS = 479.438 - (32.5233 \times HT) + (20.1633 \times SH) + (32.5233 \times HT^2) - (4.61 \times HT \times SH) - (16.6567 \times SH^2) \quad \text{Eq. 8}$$

$$\text{Unit Def.} = 43.7889 + (1.69833 \times HT) - (7.23167 \times SH) - (1.69833 \times HT^2) + (0.085 \times HT \times SH) + (2.29167 \times SH^2) \quad \text{Eq. 9}$$

$$\text{Max. Load} = 58.4522 - (4.90167 \times HT) - (4.28833 \times SH) + (4.90167 \times HT^2) - (0.04 \times HT \times SH) - (0.608333 \times SH^2) \quad \text{Eq. 10}$$

$$SHc = 0.312444 - (0.156333 \times HT) - (0.382833 \times SH) + (0.156333 \times HT^2) - (0.007 \times HT \times SH) + (0.273833 \times SH^2) \quad \text{Eq. 11}$$

Fig. 7 shows good agreement between the measured data and the values predicted by the statistical model's equations (Equations 2 to 11 for both materials). While correlation coefficients exceed 97% for most variables, the specific wear rate exhibits a lower value (R^2 = 84.4%). This weaker correlation for SHc can be attributed to the material chemical composition, superficial roughness, mechanical preparation, or the heat treatment applied.

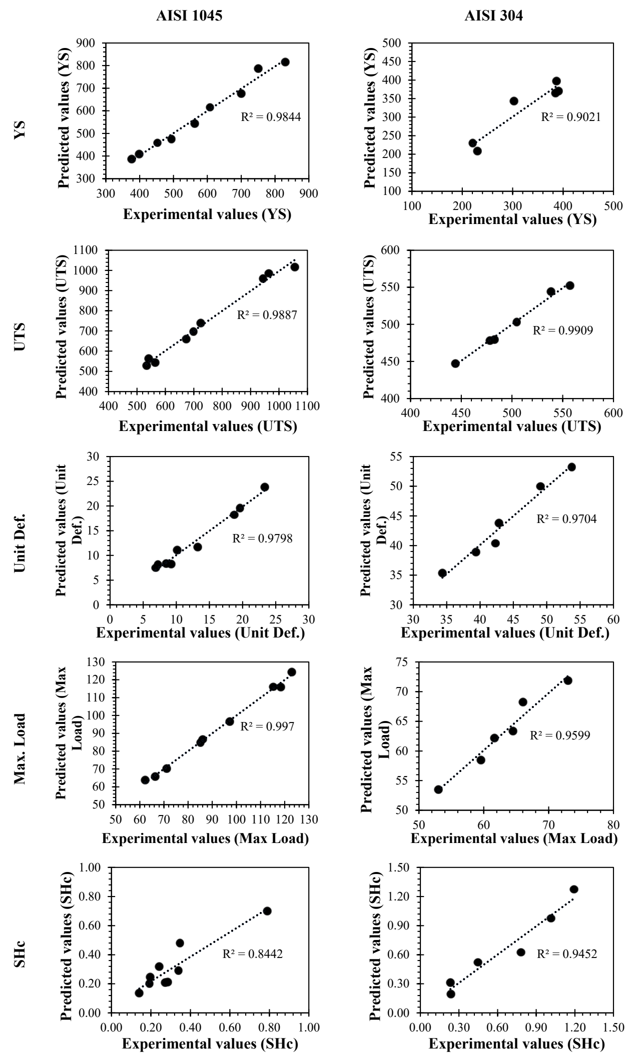

Figure 7. Estimation of calculated and measured values for both materials.
Source: The authors.

1 Conclusions

Heat treatments significantly influence the mechanical properties of AISI 1045 and AISI 304 steels. Quenching AISI 1045 increases hardness by 71.9% and the stress required for strain hardening by 60.1% for 20% and 40% SH, respectively, due to martensite formation. Annealing reduces these stresses by 2.4% and 8.7% for 20% and 40% SH, respectively, allowing for stress relaxation and grain growth, which enhances ductility. In contrast, AISI 304 shows minor variations in mechanical properties after annealing, with changes of -6.9% for 20% SH and +4.4% for 40% SH, consistent with its austenitic nature.

The high R^2 values (above 0.97) for the RSM equations indicate that the predictive models are generally accurate, particularly for UTS and maximum load in AISI 304. However, the slightly lower R^2 for the SHc suggests that this property is more challenging to predict, likely due to experimental data variability or the material behavior's complexity.

The observed changes in the mechanical properties of AISI 1045 and AISI 304 after heat treatments and variations in strain hardening are consistent with the literature, showing significant increases in strength and hardness after quenching and greater ductility and energy absorption capacity after annealing. Also, strain hardening increases the yield strength of the materials by increasing dislocation accumulation, promoting the formation of new crystalline structures, and restricting the mobility of dislocations.

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Monitoring of environmental variables in greenhouse crops through an IoT wireless sensor network

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Abstract
Agricultural cultivation in the Amazon region is vital for local farmers. Monitoring environmental variables in greenhouses is crucial for the quantity and quality of the harvest. The objective was to propose a wireless sensor network with open-source hardware and software. The client nodes, based on ESP8266, acquire data in real time from various transducers and transmit them to the server node (ESP32) through WebSockets. A webpage embedded in the ESP32 displays the environmental variables. The data is transmitted to a broker using MQTT (Message Queuing Telemetry Transport), processed with Node-RED, stored in InfluxDB, and displayed on a Grafana dashboard. The results show that the use of open-source software and hardware for wireless sensor networks is efficient, reliable, economical, and applicable in various covered plantations.

Keywords: grafana; interface; MQTT.

Monitoreó de variables ambientales en cultivos bajo invernadero mediante una red inalámbrica de sensores IoT

Resumen
El cultivo agrícola en la región amazónica es vital para los agricultores locales. Monitorear las variables ambientales en invernaderos es crucial para la cantidad y calidad de la cosecha. El objetivo fue proponer una red de sensores inalámbricos con hardware y software de código abierto. Los nodos clientes, basados en ESP8266, adquieren datos en tiempo real de transductores diversos y los transmiten al nodo servidor (ESP32) a través de WebSockets. Una página web embebida en el ESP32 muestra las variables ambientales. Los datos se transmiten a un Broker mediante MQTT (Message Queuing Telemetry Transport), se procesan con Node-RED, se almacenan en InfluxDB y se visualizan en un dashboard de Grafana. La investigación demuestra que el uso de software y hardware de código abierto para redes de sensores inalámbricos es eficiente, confiable y económico, aplicable en diversas plantaciones bajo cubierta.

Palabras claves: grafana; interface; MQTT.

1 Introduction

Global agriculture is being affected by the impacts of climate change (rising temperatures, droughts, floods, and storms, among others). These events can cause crop losses and physical damage to fields, resulting in decreased productivity and crop quality [1].

The decrease in agricultural production as a result of climate effects has raised concerns about the possibility of ensuring food security [2], and it also leads to a reduction in farmers' incomes [3]. As a response to this challenge, various alternatives to conventional crops have emerged as potential solutions.

One option is the implementation of greenhouses as a form of physical protection for crops, making them capable of isolating certain climatic factors while also enabling the creation of optimal environmental conditions for plant

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growth [4]. This is achieved through monitoring and controlling agroecological variables, such as soil moisture, relative humidity, ambient temperature, and sunlight [5].

One of the most important benefits of greenhouses is their ability to create a controlled environment for plants. This allows for the adjustment and control of factors such as temperature, humidity, light, soil quality, irrigation, and plant nutrition, which promote the optimal growth and development of crops [6]. Additionally, greenhouses provide protection against extreme weather conditions, including frost, hail, strong winds, and high temperatures, thereby reducing the risk of crop losses.

Another important advantage of greenhouses is the possibility of growing crops throughout the year, regardless of the season. This allows greater flexibility in agricultural production and the possibility of offering products out of season, which can have a positive impact on farm profitability [7]. Additionally, greenhouses can help reduce the use of pesticides and fertilizers since the controlled environment allows for more precise and efficient management of these inputs, which can have both economic and environmental benefits.

According to [8], in Ecuador, approximately 3,000 hectares are devoted to the cultivation of *Solanum lycopersicum*, with 2,000 hectares cultivated under greenhouses. This type of greenhouse cultivation is increasing due to the advantages it offers for plant development, as well as the reduction in maintenance costs due to the reduced use of agrochemicals. Authors such as [2] state that photosynthesis depends largely on humidity since if the plant loses large amounts of water, its stomata will close and this will stop the photosynthesis process. Meanwhile, when an excessive amount of water is supplied, plant growth is negatively affected, resulting in fewer flowers and fruits as well as poor growth in general [9].

Globally, efforts have been made to develop wireless technologies with smaller, more economical, and energy-efficient devices that allow the monitoring of various variables through sensors, making the data collection process more continuous and efficient, whether in greenhouses or open fields [10]. This facilitates decision-making to improve cultivation and harvesting processes.

[11] developed a network of low-cost wireless sensors for monitoring agroecological variables (temperature, soil humidity, and luminosity) in greenhouse crops. The information from the sensors was displayed locally on a screen, wirelessly from a cell phone via Bluetooth, and remotely through the ThingSpeak Internet of Things (IoT) platform.

The work of [12] mentions the implementation of a web system for monitoring and controlling a greenhouse. They used low-cost technologies that allow the remote monitoring of temperature and humidity (soil and air). The goal was that farmers would be able to more efficiently identify any threat that may affect their production and make a decision from wherever they are, avoiding production losses and saving time and travel costs.

At Finca Pozo located in the El Triunfo canton in Guayas province, a drip irrigation system with IoT technology was implemented for bell pepper greenhouses. This system is based on the ESP8266 device and uses FC-28 sensors to measure soil moisture and the DHT22 sensor to measure temperature and relative humidity in the environment. These data are used by solenoid valves to regulate water flow according to the specific needs of the crop. Through a web application, users can monitor in real time the values of these variables in the greenhouse [13].

Authors such as [14] propose applying IoT technology and Artificial Intelligence (AI) techniques in greenhouse control methodology. The network of sensors implemented allows temperature and soil humidity to be monitored. The data obtained were analyzed using Machine Learning algorithms, such as K-Means, with the aim of proposing an automatic control system for the greenhouse.

The mentioned cases serve as a reference for the development of similar projects in the Amazon region. This is because the Amazon is characterized by presenting humid-tropical and humid-rainy climatic conditions that are not suitable for the cultivation of certain types of legumes and vegetables endemic to a dry climate. Problems in the Amazon include low soil fertility and high exposure of crops to fertilizers and fungicides with negative health impacts. For these reasons, it has been suggested that new forms of production system management must be introduced [15].

By having a technological tool that allows automation in greenhouses and at the same time the acquisition, adaptation, and transmission of information on environmental variables, such as ambient temperature, relative humidity, and soil, to a base station, users will have access locally and through the cloud in order to visualize and analyze the information collected by the network. Furthermore, it will be possible to promote crop growth and production efficiency, which are challenges of precision agriculture since it has been shown that the use of wireless sensor networks contributes to this benefit [12].

The implementation of a greenhouse will allow for the use of the most appropriate techniques at each stage of the cultivation processes to supervise and optimize agricultural production methods and offer efficient and sustainable management of the necessary resources and inputs. Wireless sensor networks in precision agriculture are used to improve crop growth and production efficiency [16].

For all these reasons, the purpose of this research was to design a wireless monitoring system using embedded systems and the IoT to be implemented in greenhouses in the Amazon region.

2 Methodology

2.1 Network topology

Properly selecting the network topology that best fits specific requirements is crucial, as the choice of how network nodes are physically connected affects not only economic costs but also the overall performance of the network.

There are four basic topologies that can be used in wireless networks [17] and which can be combined to create more complex networks. The implemented sensor network is based on the star topology [18] since the communication between the main node and the secondary nodes is direct, which results in less time in data exchange.

Table 1.
Technical characteristics of the ESP8266 and ESP32 modules

Characteristics	ESP8266	ESP32
Processor	LX106 32-bit at 80MHz	LX6 32-bit at 160MHz
RAM Memory	80 KB (40 KB available) 520 KB	520 KB
Flash Memory	Up to 4MB	Up to 16MB
Power Supply	3.0v to 3.6v	2.2v to 3.6v
Temperature Range	-40°C to 125°C	-40°C to 125°C
Current Consumption	80 mA (average)	225 mA
Deep Sleep Consumption	20uA (RTC + RTC memory)	2.5uA (RTC + RTC memory)
Wi-Fi	802.11 b/g/n (up to +20dBm)	802.11 b/g/n (up to +20dBm)
Soft-AP Support	Yes	Yes
UART Ports	2 ports	3 ports
I2C Interfaces	1 interface	2 interfaces
GPIO Pins	32 pins	11 pins

Source: Authors' own creation.

2.2 Data transport medium between server and clients

The OSI (Open Systems Interconnection) model [19] is the conceptual reference used to describe and understand how data communication networks function. The physical layer of the OSI model establishes the electrical, mechanical, procedural, and functional standards necessary for the activation, maintenance, and deactivation of the physical connection between the end systems of the communication network.

Various media and technologies allow the transport of digital data. Due to the technical and mechanical characteristics of the greenhouses, Wi-Fi technology based on the IEEE 802.11 b/g/n [20] standard at 2.4GHz was chosen to implement the sensor network architecture in a star topology. Table 1 shows the technical characteristics of two modules that feature integrated Wi-Fi functionality.

2.3 Data communication protocol

The communication protocol defines the rules that establish how data should be transmitted, received, and processed between two or more entities in the wireless sensor network.

HTTP (Hypertext Transfer Protocol) allows the exchange of data between one or more clients and a server [21]. HTTP operates on a request and response model, where a client sends a request to the server, which responds with the requested information, and the communication is closed.

The WebSockets protocol [22] enables the establishment of a bidirectional and real-time communication session between the client and the server, implying the ability to transmit data from both the client to the server and vice versa at any time during the communication session.

The WebSockets protocol was used to implement the wireless sensor network because it is characterized by presenting more efficient and faster communication than HTTP. With WebSockets, the client sends simple data frames

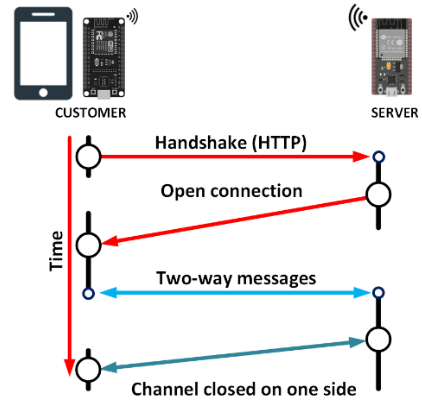

Figure 1. WebSockets Protocol, Client – Server.
Source: Authors' own creation.

to the server, which processes the data and sends the response, making WebSockets more suitable for real-time applications compared to HTTP.

As shown in Fig. 1, the client initiates a WebSocket connection with the server through the Handshake binding process, which starts with an HTTP request/response. This allows servers to handle both HTTP and WebSocket connections on the same port. Once the connection is established, the client and server can exchange data in full-duplex mode via WebSocket. This also allows for periodically sending information to the web browser and constantly updating the data displayed on the web interface.

2.4 Client node

Two types of client nodes can be connected to the sensor network architecture: those affiliated with the network and those not affiliated.

The client node affiliated with the network (NAN) is based on the ESP8266 module and is responsible for acquiring the variables of ambient temperature, soil humidity, relative humidity, luminosity, and UV radiation present in the greenhouse through sensors. The data is transmitted to the server (ESP32) via the WebSockets protocol.

The NAN stores a unique identification value (ID) in its memory, which is validated when WebSocket communication starts. The client sends a data frame that includes its ID, and the server verifies that the ID is registered in its memory. If the ID is validated, the server processes the data frame, backs up the information in the data logger, and updates the web interface. If the ID is not validated, the server discards the data frame.

For measuring ambient temperature and relative humidity (RH), the SHT71 sensor was used. According to Veldscholte & de Beer [23], the SHT71 sensor features I2C communication, an RH measurement range between 0 and 100%, a linear output, stable measurements over time, a small absolute deviation in its measurements, high repeatability, and an RMS dispersion around the fitting line of 2% RH. The SHT71 sensor has a temperature

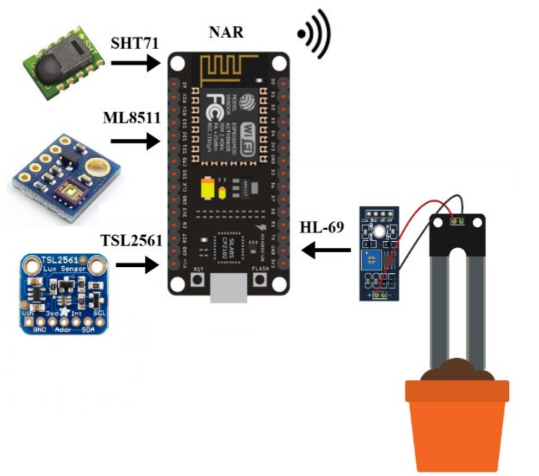

Figure 2. Sensor Connection to the Node Affiliated with the Network.
Source: Authors' own creation.

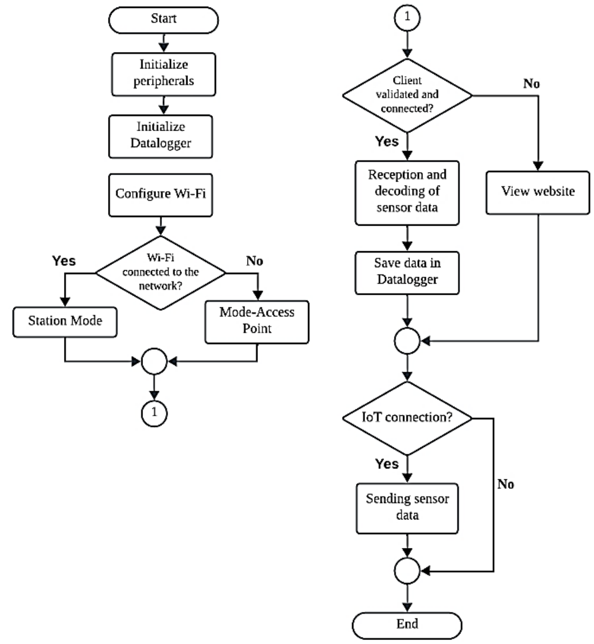

Figure 3. Heuristic Diagram of the Server Node.
Source: Authors' own creation.

measurement range between -40 and 123.8ºC, linear output that responds accurately to temperature changes, greater thermal stability, and repeatability with a variation of 0.1ºC.

Soil humidity was measured using the HL-69 sensor [24], which uses water conductivity to determine the amount of liquid in a substrate (e.g., soil). This sensor features an electronic conditioning circuit that processes the signal from the sensor and transmits it to the ESP8266 module.

The ML8511 sensor [25] provides an analog signal that varies based on the amount of ultraviolet (UV radiation in the environment. This sensor can detect light with a wavelength of 280 to 390 nm (nanometers) and operates in environments with temperatures between -20 and 70ºC.

The intensity of light in the greenhouse was measured using the TSL2561 sensor [26], selected for its ability to measure visible and infrared light from 0.1–40,000 lux in real time, with an operating temperature range of between -30 and 80ºC.

Fig. 2 shows the connection of the different sensors used in the instrumentation system with the ESP8266 module affiliated with the network.

The node not affiliated with the network (NNAN) makes a WebSocket request to access information from the webpage embedded in the ESP32 server. Through a web browser, the user can visualize real-time data from various sensors. NNAN devices are typically smart devices (computers, smartphones, etc.). Unlike NANs, NNANs do not have a registered ID in the server's memory.

2.5 Server node

The web server node is responsible for processing, visualizing, and storing the data emitted by the sensors, as well as responding to client requests. It also has the fundamental task of storing the files associated with the webpage, through which sensor data is visualized in real time. These files are accessed by users through a web browser.

For hardware, the ESP32 module was used to function as the server. It is part of the ESP (Espressif Systems Platform) microcontroller family, known for its low cost, low power consumption, up to 16MB of flash memory, and various communication ports.

The WLAN (Wireless Local Area Network) connection of the ESP32 server module is configured to work in two modes within the sensor network:

Station mode: The ESP32 web server connects to a Wi-Fi network provided by a router.

Access Point mode: If the ESP32 web server cannot connect to a Wi-Fi network, it acts as a router and generates a Wi-Fi network to which client devices will connect.

In both operation modes, the ESP32 server presents a static IP address.

The web server based on the ESP32 module performs the following functions: validating the connection of client nodes affiliated with the network (the web server only receives data frames from nodes with IDs registered in its memory); receiving the data frame with the sensor values from validated client nodes; establishing a connection with clients who need to access the webpage displaying sensor data through the TCP (Transmission Control Protocol) [27] data logger [28] of sensor data; managing the web page; and communicating with the IoT platform [29].

Fig. 3 shows the heuristic diagram of the operation of the web server in the wireless sensor network.

2.6 Web interface

The web interface [30], also known as user interface or GUI (graphical user interface) [31], is the structure designed in a web application that allows users to access various

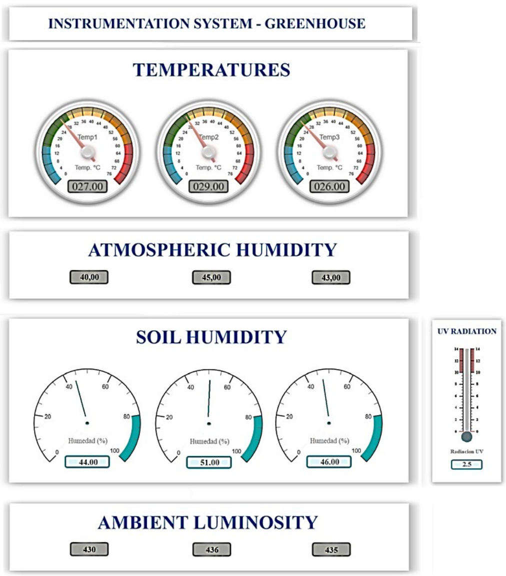

Figure 4. Web Interface– Greenhouse Instrumentation System.
Source: Authors' own creation.

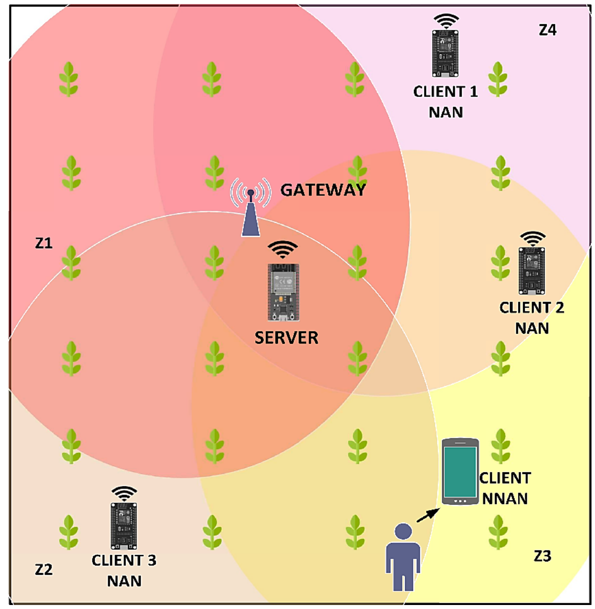

Figure 5. Sensor Network Architecture– Greenhouse.
Source: Authors' own creation.

contents of the server. The web interface of the sensor network uses visual components, such as numerical displays and gauge-type elements, to represent the information from each of the data provided by the sensors of the client nodes affiliated with the network.

Fig. 4 shows the web interface that allows the user to monitor [32] the ambient temperature, soil humidity, and ambient relative humidity at three different locations in the greenhouse. It also displays the light intensity and existing UV solar radiation inside the greenhouse. Depending on the area of the greenhouse or crop to be instrumented, a greater number of sensors can be added to the network with a greater diversity of functionalities.

2.7 Data logger

The implemented data logger allows for the collection and recording of data from various sensors at regular time intervals or specific events.

The data logger [33] has the ability to locally store variables using a Micro SD memory card. The data is stored in a plain text file that does not have any formatting or markup code, making it ideal for storing information that only needs to be readable in its most basic form. Additionally, this type of file is compatible with various operating systems and applications, making it easy to exchange and share between different platforms [34].

The information provided in the data logger will be used for:

Data analysis and processing: The recorded data can be analyzed and processed to extract relevant information.

Monitoring and tracking: Monitoring and tracking the measured variables.

Decision-making: Supporting decision-making processes.

Research and study: The data can be used in studies to propose new research and generate digital controllers, among other uses.

2.8 Sensor Network Architecture

The sensor network consists of a server module, a gateway for internet access, three client NANs, and various client NNANs, which are distributed throughout the greenhouse as per Fig. 5.

The Gateway provides the sensor network with IoT connectivity, through which data is transmitted to a broker using the Message Queuing Telemetry Transport (MQTT protocol [35], processed using Node-RED [36], stored in the InfluxDB database [37], and visualized using Grafana [38].

The ESP32 server node's hardware structure includes a 2.4GHz data transmission block with an average power of +20.5 dBm (113.24mW) [39], which complies with the IEEE 802.11b standard. If the Gateway device is damaged or turned off, the ESP32 server is reconfigured to operate in Access Point mode, generating a Wi-Fi signal with a coverage of up to 65 meters within the greenhouse.

The Gateway device and the ESP32 server node were installed in the center of the greenhouse because a star topology was used for the sensor network. The NAN client nodes were distributed across three sections of the greenhouse, while the NNAN nodes can be positioned anywhere in the greenhouse.

Fig. 5 identifies the coverage areas of the different nodes of the sensor network. The Gateway or web server generates a Wi-Fi signal that covers the entire greenhouse area (zone Z1). NAN Client 1 has a coverage area denoted by Z4, Z3 is the coverage area of Client 2, while NAN Client 3 has the coverage area denoted by Z2. Identifying these zones is essential for the network to cover a larger area using a tree topology [40].

2.9 IoT Platform

The IoT enables the interconnection of physical devices with electronic components capable of collecting and sharing data in real time with other devices through a common platform [35].

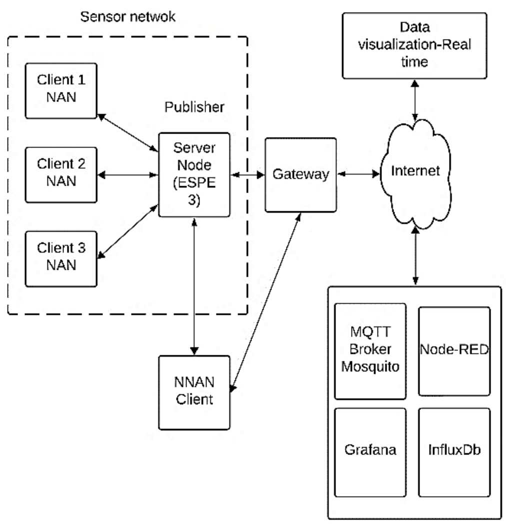

Figure 6. Integration of Sensor Network and IoT Platform.
Source: Authors' own creation.

IoT platforms facilitate the capture of information collected by sensors, real-time data transmission, and remote device management. They also provide an interface to access their resources using internet protocols, allowing interaction with high-level programming languages to process data and remotely control devices [10].

Several experts have presented different architectures for the IoT, although the most common are the three- and five-layer architectures, which are widely analyzed by [41]. Regardless of the IoT architecture applied, it is essential to have communication. To achieve this, IoT technologies make use of the four layers of the TCP/IP model [42].

There are various protocols for communication and data transfer between IoT devices. For data transfer between the Web Server node (ESP32) of the sensor network and the IoT broker, the MQTT protocol was used because it is lightweight and compatible with devices and applications with limited resources (low bandwidth, limited computational power, low memory, etc.) [43].

An MQTT client is a hardware and/or software component that exchanges data by connecting to a broker [44]. The web server node of the sensor network (client) sends data to the broker (server). In an IoT platform using the MQTT protocol, there is a "Publish-Subscribe" mechanism, where the client is called the publisher, and the process is called publication. The action of receiving data from the broker (server) by a client (subscriber) is known as a subscription. Subscribers have graphical access to sensor network data using the Grafana software.

It is important to note that a broker can serve multiple subscribers and publishers, depending on the hardware capacity of the machine on which it runs. A client can play the role of both publisher and subscriber.

The MQTT protocol employs three levels of Quality of Service (QoS) to ensure message delivery. [45] used QoS 2, which is the highest level of service in MQTT and ensures that each message is received by the recipient.

The Eclipse Mosquitto broker acts as an MQTT intermediary and supports QoS levels 0 (at most once), 1 (at least once), and 2 (exactly once) [46]. These characteristics make MQTT reliable for IoT applications. The Eclipse Mosquitto IoT server, along with the Node-RED programming tool, the InfluxDB database, and the Grafana application, is hosted on an IBM System x3250 M2 server running Ubuntu 18.04.

The data from the sensor network is stored using the InfluxDB database [47]. The Grafana application allows connection to various data sources, monitoring services, and metric systems to collect information and display it graphically to the user. The dashboard developed in the Grafana application permits users to visualize the data from the publishing devices in real time.

3 Results and discussion

The instrumentation system developed for monitoring environmental variables in greenhouses was subjected to a set of tests in different controlled and real conditions. Initially, it was validated in a controlled environment to ensure the accuracy of the measurements and the stability of the hardware and firmware. Subsequently, it was implemented in a real environment, where its performance was evaluated over a period of 21 hours. Variables similar to those studied by [48] were monitored, including ambient temperature, soil moisture, UV radiation, illumination and relative humidity, with 10-minute intervals between each measurement. These data allowed the identification of stable patterns and critical behaviors related to the greenhouse microclimate.

Fig. 7 shows two representative graphs of the measurements taken in the developed system. In the upper graph (Node 1), it is observed that the ambient temperature varies between 26.4 and 27.4 °C, with thermal peaks around noon due to maximum solar radiation. This daytime pattern suggests the need to adjust the greenhouse ventilation during the hottest hours. The lower graph (Node 2) shows soil moisture, which presents a stable behavior with slight increases in the cooler hours due to reduced evaporation. Around 2:00 pm, a slight decrease in humidity is recorded, reflecting the impact of the increase in ambient temperature. These results highlight the system's ability to monitor soil conditions in real time, informing irrigation-related decisions.

Fig. 8 shows a control panel developed in Grafana that integrates multiple variables measured at Node 3 over three days. The upper graph shows temperature fluctuations between 20 and 30 °C, with daytime highs and nighttime lows.

The indicators show the levels of illumination (988 lux) and UV radiation (index of 5.9). These figures allow us to evaluate the impact of sunlight on the crops. Fig. 8 shows soil humidity, which varies significantly throughout the day, reaching peaks close to 80% at times of low temperature and dips to 50% during the hottest hours. This analysis capacity makes it possible to optimize irrigation, avoiding problems such as root asphyxia due to excess water or dehydration due to a lack of water.

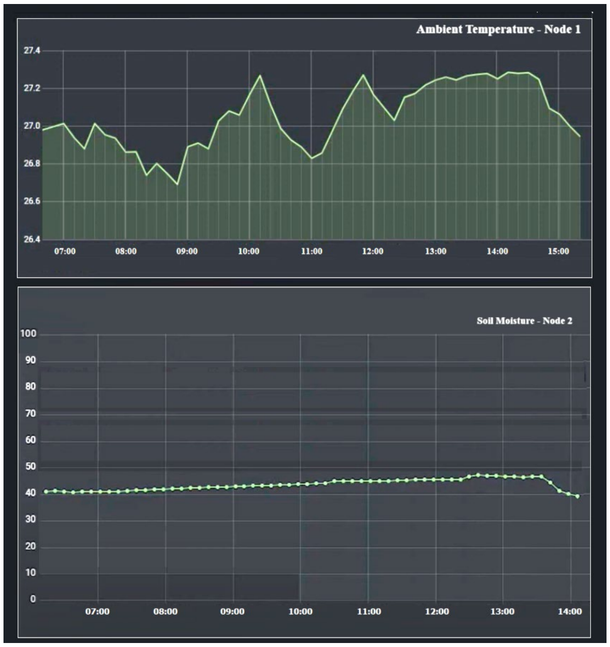

Figure 7. Graphs depicting ambient temperature and soil humidity data.
Source: Author's own creation.

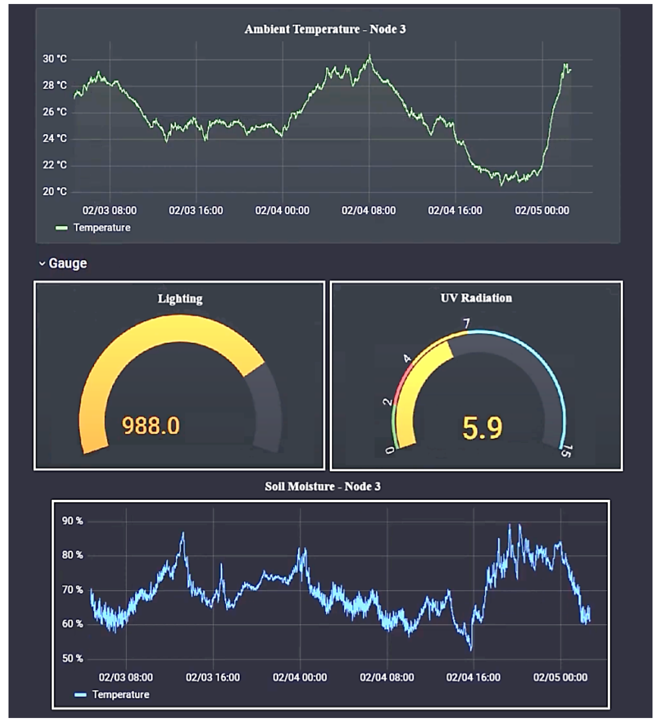

Figure 8. Graphs depicting the ultraviolet radiation index.
Source: Author's own creation.

In comparison with studies such as [49], which designed a modular system based on Xbee technology to monitor basic variables in greenhouses using a GUI developed in Matlab software, the proposed system incorporates a wider range of sensors, Wi-Fi technology, and a user interface based on the Grafana tool. The Matlab software, although robust, involves costs in license acquisition, and it is complex to deliver applications in an accessible way. In contrast, Grafana is open-source software, allowing greater flexibility, customization, web deployment, and native integration with databases such as InfluxDB. Limitations have been identified in the use of industrial HMI screens for data visualization due to the cost of acquiring equipment and licenses [50], whereas our study overcomes this by employing Grafana, open-source software, which allows real-time data visualization through interactive dashboards accessible from smart devices, significantly reducing costs and facilitating the scalability of the system.

Likewise, [51] used LoRaWAN technologies for data collection over long distances, demonstrating their energy efficiency and coverage. However, they did not address the integration of real-time graphical interfaces for the user to visualize the data nor the possibility of scaling the system to new sensors, as mentioned by [52]. In contrast, our study allows a more interactive and accessible experience for end users since the dashboard presented in Fig. 8 allows real-time data visualization from any end device with network access. The developed hardware platform allows the integration of a larger number of sensors according to the needs of the application environment.

This instrumentation system contributes to information collection by combining low-cost hardware with open-source software, eliminating economic barriers for small-scale farmers. The data collected and visualized in real time mean that transfer functions can be established to optimize ventilation and irrigation in greenhouses. This represents an advance over research projects such as [53], which highlighted the importance of integrating IoT in monitoring systems but limited its scope to data collection and storage, without addressing specific applications that allow immediate and automated action on agricultural systems. It did not explore critical functions, such as automatic control of irrigation and ventilation, which are essential in maintaining optimal crop conditions and maximizing resource use efficiency. Our proposal not only collects and visualizes data in real time but also lays the groundwork for integrating automated processes, representing a more comprehensive and practical approach to precision agriculture.

In Fig. 7, the graphs demonstrate the system's ability to monitor temperature and humidity variations in real time, providing reliable data to identify critical weather patterns within the greenhouse. This information provides a solid basis for designing and implementing more effective climate management strategies. In addition, the clarity of the graphic representation and the stability of the data collected prove the system's robustness. This facilitates its scalability and integration in larger greenhouses or with specific monitoring requirements adapted to different types of crops and environmental conditions.

The implementation of this system in a greenhouse provides farmers with a tool to access real-time information, facilitating strategic decision-making based on accurate and up-to-date information. The ability to integrate key measurements, such as UV radiation and lighting levels, allows operators to adjust critical environmental variables, such as shading or artificial lighting, quickly and efficiently.

This is particularly important in sensitive crops, where even small variations in environmental conditions can significantly impact yields. By minimizing unnecessary energy use through data-driven adjustments, the system helps reduce operating costs, making it especially valuable for growers with limited resources. Optimizing the use of natural and artificial light not only improves crop productivity but also promotes sustainable farming practices by reducing the energy footprint.

Compared to traditional monitoring methods, which often rely on manual inspections or expensive and less accessible tools, this system offers a more economical, scalable, and adaptable solution to the needs of different types of crops and environments. The clear and understandable visualization of these variables, as shown in Fig. 8, allows growers to easily interpret the data and respond in a timely manner, maximizing productivity and ensuring crop quality.

Moreover, by monitoring soil moisture, both dehydration and over-irrigation, problems identified by [54] concerning smart irrigation systems, can be avoided.

The use of open-source technologies significantly reduces initial implementation costs and eliminates dependence on proprietary licenses, making them accessible to small and medium-scale farmers. Furthermore, their modular and scalable nature allows the integration of new sensors and functionalities adapted to the specific needs of each crop or region. This not only fosters local innovation and technological customization but also democratizes precision agriculture by making these tools accessible to rural communities. Thus, it promotes a more inclusive, sustainable, and efficient agriculture, capable of meeting global challenges like food security and climate change.

Although the system proved to be functional and stable, limitations were identified. For instance, the modules' outer casings are not airtight, which could affect their durability in very humid conditions. Additionally, the integration of new sensors requires advanced technical skills, limiting their adoption by farmers with less access to technical training.

In future developments, it is advisable to improve the casing design to protect the electronic components better, as well as to implement artificial intelligence to automate decision-making based on data patterns. These improvements will further align the system with the practical needs of modern, sustainable agriculture.

This study is notable for implementing a low-cost platform that monitors environmental variables in real time and facilitates their interpretation through an interactive and accessible system. This allows resources to be used well and accurate decisions to be taken, overcoming the limitations of previous systems that did not integrate open-source tools or provide practical scalability for different agricultural contexts.

4 Conclusions

Climate change has led farmers to devise strategies to minimize possible crop damage. As a result, greenhouses have emerged as an option to isolate plantations and create an optimal environment for crop growth. Farmers often control environmental variables within greenhouses, manually and experimentally, which could lead to crop damage.

For this reason, a wireless sensor network connected to the IoT based on ESP32 and ESP8266 modules was created to monitor environmental variables in crops under greenhouses. This allowed users to know in real time, locally or remotely, all the environmental variables that affect the crop through the data collected by the sensors. The information is represented on a dashboard consisting of various graphs that help the user to make decisions.

The sensor network structure in star topology consists of a server node and three client nodes attached to the network. These nodes are in constant communication to acquire the various environmental variables inside the greenhouse. Each of the nodes presents a hardware and software element (firmware) that was subjected to various operation tests in controlled and real environments.

The use of MQTT in a wireless sensor network offered an efficient and reliable solution for data transfer to the Eclipse Mosquitto broker. Thanks to its low bandwidth consumption, ability to maintain persistent connections, and adjustable quality of service levels, MQTT has become a useful protocol for transmitting data through the IoT. Using the InfluxDB database, the information was backed up, and software such as Node-RED and Grafana enabled the development of a dashboard that visualizes the variables in real time within the greenhouse.

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Approach to model the influence of faults in a geothermal reservoir

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Abstract
Two hydrogeological numerical models (2D and 3D) for the geothermal area located to the West of the Nevado del Ruiz volcanic complex (Colombia) are presented here. They are built with the software HydroGeoSphere using data collected in the field, as well as hydraulic and thermal properties measured on rock samples in previous laboratory studies. The purpose of this modeling work is to analyze the influence of faults aperture and depth on groundwater flow circulation and heat transfer in the geothermal reservoir. The 2D model illustrates the relation between fault aperture and temperature distribution. The 3D model shows the behavior of a potential production well located in the Botero-Londoño area that withdraws hot water from a depth of 2600 m. The results highlight the usefulness and limitations of this approach, providing guidelines for future numerical models of this site and for the initial modeling work for any fractured geothermal reservoir.

Keywords: geothermal reservoir; production well; faults; HydroGeoSphere; Nevado del Ruiz.

Acercamiento a la modelación de la influencia de las fallas en un reservorio geotérmico

Resumen
Se presentan aquí dos modelos numéricos hidrogeológicos (2D y 3D) para el área geotérmica situada al oeste del complejo volcánico Nevado del Ruiz (Colombia). Están construidos con el software HydroGeoSphere utilizando datos recolectados en campo, así como propiedades hidráulicas y térmicas medidas en muestras de roca en laboratorio, en estudios previos. El propósito de este trabajo de modelación es analizar la influencia de la apertura y profundidad de las fallas sobre la circulación del flujo de agua subterránea y la transferencia de calor en el reservorio geotérmico. El modelo 2D ilustra la relación entre la apertura de la falla y la distribución de la temperatura. El modelo 3D muestra el comportamiento de un pozo de producción potencial situado en la zona de Botero-Londoño que extrae agua caliente desde una profundidad de 2600 m. Los resultados demuestran la utilidad y las limitaciones de este estudio, proporcionando pautas para futuros modelos numéricos de este sitio y para las etapas iniciales de modelación de cualquier reservorio geotérmico fracturado.

Palabras clave: reservorio geotérmico; pozo de producción; fallas; HydroGeoSphere; Nevado del Ruiz.

1 Introduction

The growing use of renewable technologies is illustrated in Latin America by the generation of 210 GW of low-carbon energy through hydropower, biomass, solar, wind, and geothermal [1]. The latter provides baseload energy with a lower environmental impact compared to other power generation methods [2,3].

To improve the sustainable use of geothermal resources, numerical simulations can be used to update conceptual models and to understand and predict heat transfer and fluid flow in geothermal reservoirs [4-7]. Here, faults can also directly affect geothermal fluid circulation. Their impact has been studied with experimental investigations [8], structural and kinematic data [9], and numerical modeling [10,11].

This paper presents the results of field characterization and numerical simulations of fluid flow and heat transfer in the geothermal system associated with the Nevado del Ruiz Volcano (NRV) in Colombia. The numerical simulator HydroGeoSphere (HGS) [12] uses the Discrete Fractured Models approach to represent regional faults embedded in a low-permeability porous

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rock matrix. The geothermal fluid is assumed to be in its liquid phase, before it flashes. [13] and [11] have simulated 2D heat transfer at the reservoir scale in the NRV with the numerical simulator OpenGeoSys In contrast, this work focuses on a specific zone located at the intersection of three faults (Samaná Sur, Santa Rosa, and El Billar) that defines an area of special interest for geothermal development and presents a 3D model. The influence of these faults on the local fluid circulation and a hypothetical geothermal production scenario are analyzed here, and they have not been presented before.

2 Geological setting

The study area is located to the West of the NRV complex, in the Nereidas sector. The geological units in thiszone area: the Cajamarca Complex (Pes), the Quebradagrande Complex (Ksc and Kvc), and the Quaternary eruptive and superficial deposits (Fig. 1).

The Cajamarca Complex comprises metamorphic rocks forming the nucleus of the Colombian Central Mountain Range [14]. It contains pelitic mica and quartz-sericite schists (Pes in Fig. 1), formed through regional metamorphic events and local thermal or dynamic effects of varying intensity.

The Quebradagrande complex is found between the San Jerónimo and Silvia Pijao faults (Fig. 1). It is an interrelation of volcanic (volcanic flows and pyroclastic layers) and sedimentary rocks [15]. The volcanic member (Kvc) consists of basalts and diabases with toleitic characteristics, some debris flow breccias, and tuff. The sedimentary member (Ksc) is predominantly recognized as carbonaceous lutite, graywacke, feldspathic arenite, limolithes, lidites, and local limestone layers [15].

The quaternary eruptive and superficial deposits are the result of the interaction and evolution of the volcanic processes that have marked the history of the zone. The PRE-Ruiz lavas (CL-PRE) form a homogeneous, dense, and eroded unit with the presence of bands that vary from light gray to white. The Río Claro Ignimbrite Eruptive Unit (UE-IRC) is divided into the Inferior Deposit Unit (UE-IRCi), which is massive, partially altered, poorly selected, and matrix supported. The Superior Deposit Unit (UE-IRCs) is massive, well sorted, crumbly, with medium to fine grain sizes, and very altered. The other deposits are the Playa Larga avalanche debris deposits (DA-PL), Los Alpes eruptive units (UE-LA), Río Claro avalanche debris deposits (DA-RC), and Moraine deposits (M) [16].

Structural geology is an important aspect for the study area since it contains several faults that generate both upward groundwater flow (evidenced by the presence of superficial hot springs) and downward groundwater flow (allowing reservoir recharge) [17]. The Silvia Pijao fault belongs to the Romeral fault system and is classified as a regional tectonic feature with N-S to NNE orientation and dextral reverse behavior [18]. [19] defined the Manizales-Aranzazu fault, called here the Manizales fault, with dextral reverse behavior. [16] defined the San Jeronimo fault with sinistral reverse behavior and NNE-SSW tendency. Moving towards the East, the Samaná Sur fault system (hereafter simply referred to as fault) is described with sinistral normal behavior and N-S to N20E orientation. Then, the Nereidas Fault presents a sinistral movement with normal behavior [16] with a dip between 50 to 60° NE [20]. The Santa Rosa Fault is defined by [21] with reverse dextral behavior, while the El Billar fault has sinistral normal behavior and a dip of S70W approximately. The Quebrada Negra fault presents normal behavior and a N20-40W dip [16]. Finally, the La Tosca- El Descanso is the easternmost fault crossing the AA' trace (Fig. 1) and it is catalogued as the most recent in the study area, with a dextral behavior [20].

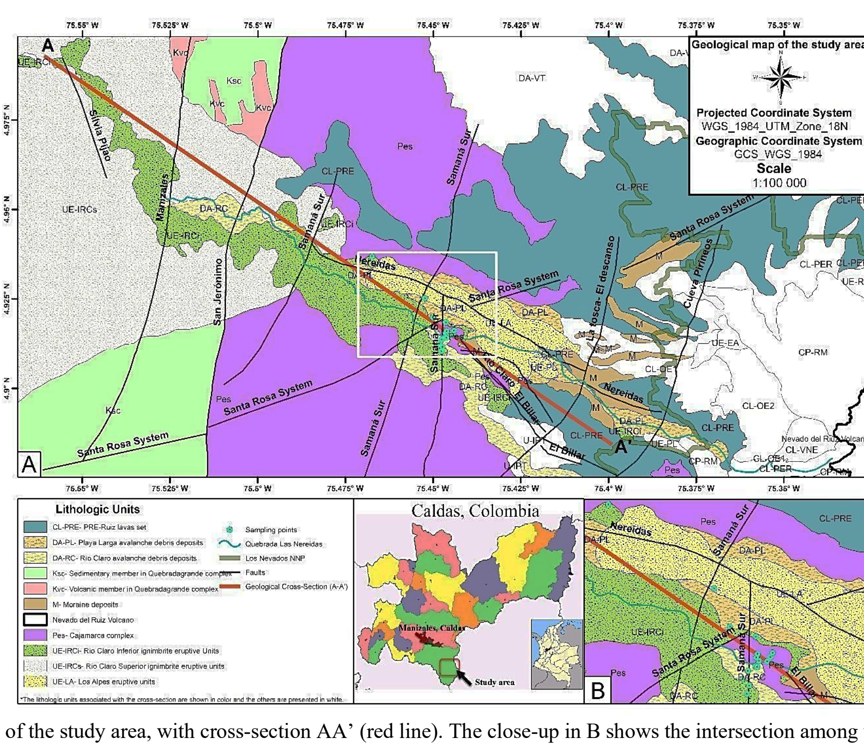

Figure 1. Geological map of the study area, with cross-section AA' (red line). The close-up in B shows the intersection among the Samaná Sur fault system with the Santa Rosa and El Billar faults.
Source: the authors, modified from [15] and [16].

1 Field characterization

In the Botero Londoño area (4.915°N 75.45°W, WGS_1984_UTM_Zone_18N), the outcrop of the Cajamarca complex (Pes) underlying the Río Claro Inferior ignimbrite eruptive unit (UE-IRCi) was identified, in a valley containing several hot spring manifestations along Las Nereidas stream (Fig. 2). The schists of Pes (Fig. 3) have foliated nature, and their discontinuities (joints, random fractures, and faults) allow a fast circulation of hydrothermal fluids [20].

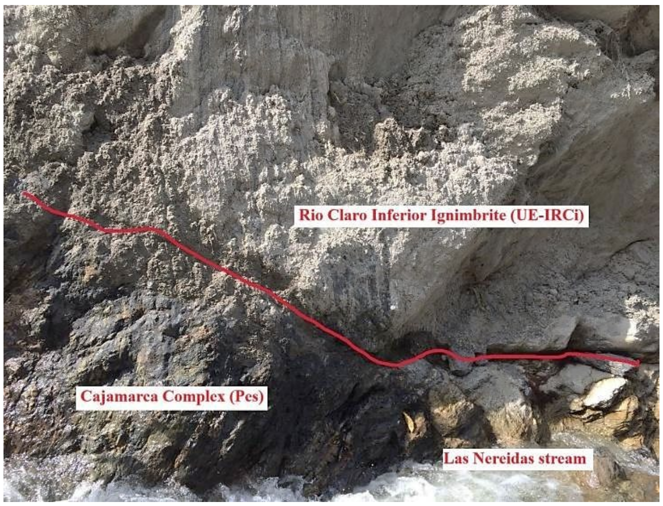

Figure 2. Lithological contact between the Cajamarca complex (Pes) and the Río Claro Inferior ignimbrite (UE-IRCi) identified in the field.
Source: The authors.

Figure 3. Schists of the Cajamarca complex observed in the field in the Botero-Londoño area.
Source: The authors.

2 Hydrogeological numerical model

Cross-section A-A' shows the main geological units in the study area, as well as the faults and geological contacts (Fig. 4). Its actual orientation is northwest – southeast (Fig. 1). A small correction should be applied to the orientation of the faults, but it is neglected here considering the uncertainty that still exists about their orientation and their continuity at depth [11].

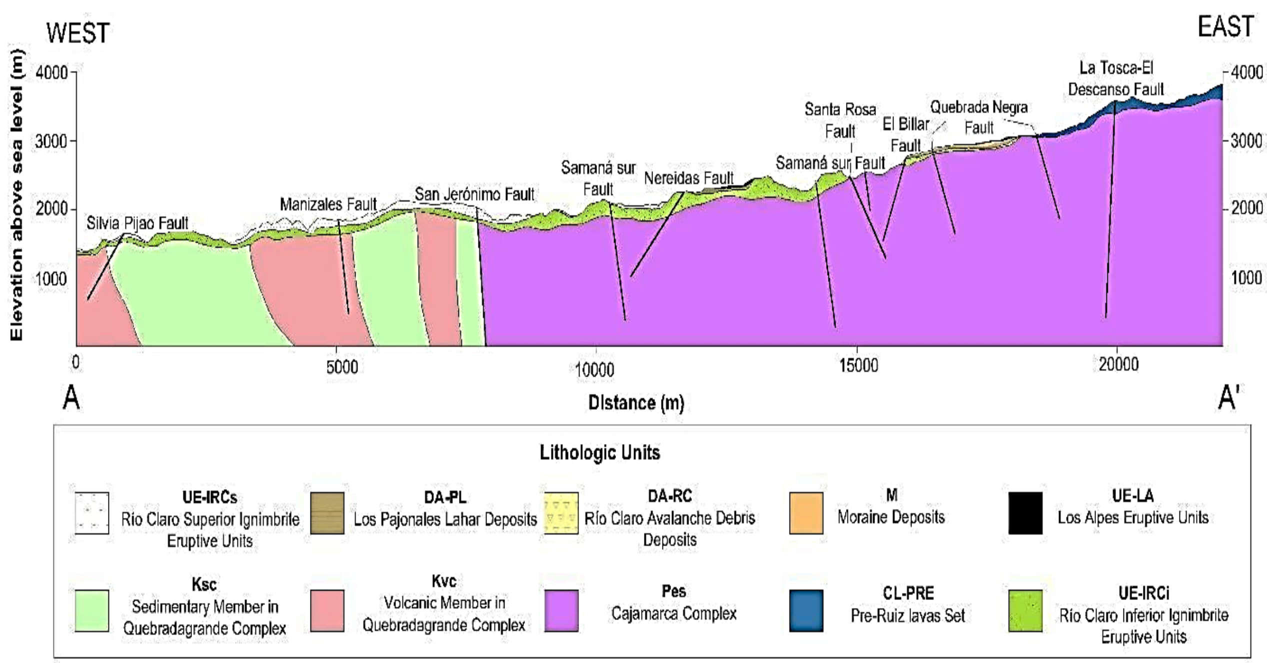

Figure 4. Geological cross-section A-A'. The lithologic units shown here are grouped into the three hydrogeological units listed in Table 1.
Source: The authors

Table 1.
Properties of the three hydrogeological units defined in the model (data from 11, 13, 22).

Properties	Pes	Kvc & Ksc	Superficial deposits
Hydraulic conductivity (m s^{-1})	$8.4x10^{-11}$	$9.8x10^{-11}$	$2.0x10^{-10}$
Specific storage (m^{-1})	$1x10^{-4}$	$1x10^{-4}$	$1x10^{-4}$
Porosity	$1x10^{-2}$	0.1	0.1
Longitudinal dispersivity (m)	100	100	100
Transversal and vertical dispersivity (m)	10	10	10
Tortuosity	0.25	0.25	0.25
Thermal conductivity of solids (W m^{-1} K^{-1})	4.94	1.92	1.22
Bulk density (kg m^{-3})	2697	2654	2660
Specific heat capacity of solids (J kg^{-1} K^{-1})	910	822	815

Source: The authors.

Considering the hydraulic properties and spatial extension, three hydrogeological units are defined, and they are listed in Table 1) the Quebradagrande complex (Kvc and Ksc) that may act as an aquitard, 2) the Cajamarca complex (Pes), an aquitard that locally acts as a fractured aquifer hosting the geothermal reservoir, where the rock is highly fractured close to the faults, and 3) the superficial deposits that combine all quaternary units with limited thickness. The properties of each hydrogeological unit required for the numerical simulations are listed in Table 1.

Faults are modeled as 2D planes, where groundwater velocity is defined from Darcy's law and the fault hydraulic conductivity is calculated according to the parallel plate conceptual model:

$$K_f = \left(\frac{\gamma \cdot (2b)^2}{12\mu}\right) \quad (1)$$

where 2b (m) is the fracture aperture, γ (N m-3) and μ (Pa s) are the specific gravity and the dynamic viscosity of water, respectively.

2.1 2D model

The 2D numerical model (Fig. 5) is based on the geological cross-section (Fig. 4). The mesh is generated with AlgoMesh [23] using 5409 nodes and 10194 triangular elements, whose maximum and minimum areas were 146842 m2 and 4 m2, respectively. The mesh is refined close to the ground surface and near faults, to properly capture their geometry. Since HGS always uses 3D elements to discretize the subsurface, the 2D mesh is duplicated in the direction perpendicular to the cross-section to form 3D triangular prisms (6-node elements). Therefore, the resulting 3D mesh has a unit thickness in the direction perpendicular to the cross-section.

For groundwater flow, the upper and lateral boundaries are assigned hydraulic head values equal to ground surface elevation and the bottom is considered impermeable. For heat transfer simulations, adiabatic conditions are set to the left and right boundaries, while a constant average surface temperature of 15°C is assigned to the top. A

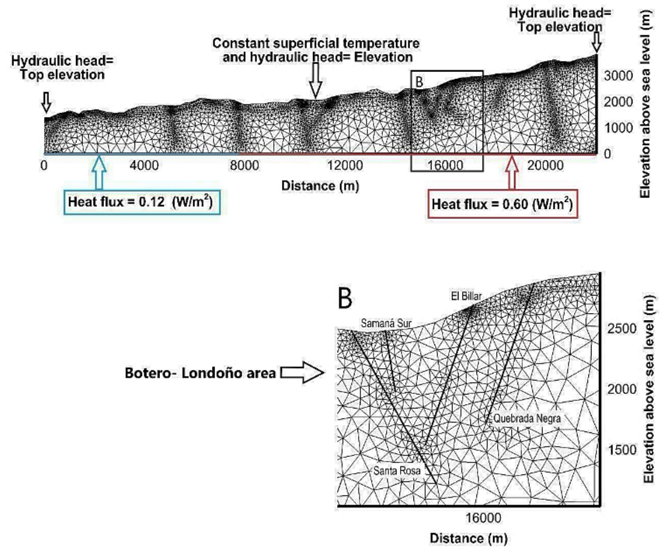

Figure 5. 2D model setup: geometry, mesh, and boundary conditions.
Source: The authors.

spatially variable initial temperature distribution is applied to the model. The values were calculated with the local heat flux and thermal conductivities of the Pes and Kvc-Ksc formations shown in Table 1. A spatially variable heat flux is applied to the bottom of the model to represent the heat released by the magmatic chamber of the NRV. Two different heat flux values are assigned, according to the thermal properties of the Quebradagrande (Kvc and Ksc) and Cajamarca (Pes) complexes. The Kvc and Ksc complexes are assigned a heat flux equal to 0.12 W m^{-2}, which is the smallest value according to the Colombian heat flux map of the region [24]. The assigned heat flux for the Pes complex is 0.6 W m^{-2} and it was calculated with Fourier's law and the geothermal gradient of about 140°C/km reported for the Nereidas well [25]. For transient heat transfer, the total simulated time is 10 million years, while groundwater flow is simulated in steady-state conditions.

For modeling purposes, all superficial deposits are considered as a single hydrogeological unit with average hydraulic and thermal properties (Table 1) since their thickness is not significant when compared to the model dimensions. Finally, all faults are represented as discrete fractures, represented as two-dimensional planes with uniform apertures. Since the faults are poorly characterized because of difficult access in this remote area, a sensitivity analysis of fault aperture is conducted using values equal to $1x10^{-1}$ m (Case A), $1x10^{-3}$ m (Case B), and $1x10^{-5}$ m (Case C), as listed in Table 2. The value of 1 mm (Case B) represents a base case, and the other two values are defined by increasing and decreasing the base case value by two orders of magnitude, to generate a significant difference between the three scenarios. The main purpose of the sensitivity analysis is to assess the impact of the fault apertures on groundwater velocity. These scenarios also show how the fluid mass balance changes depending on fault aperture.

2.2 3D model

The 3D numerical model represents a hypothetical geothermal production vertical well that would intersect the Samaná Sur, Santa Rosa, and El Billar faults shown in Fig. 5B. The objective is to simulate hydraulic head and temperature variations that might result from 30 years of geothermal production. The model dimensions are 3000 m, 3000 m and 4000 m in x, y, and z directions, respectively (Fig. 6). The production well is located in the center of the domain, at x = 1500 m and y = 1500 m. It is open and connected to the subsurface between elevations 1400 m and 1800 m to represent the location of the well screen in the production zone. The depth of the model is defined considering the average temperature simulated in previous studies conducted in areas close to Botero-Londoño. According to results presented by [11] and [13], two kilometers would be an appropriate depth for electric generation since the simulated temperature in this zone is above 150 °C. A total depth of 4 km is thus considered here to keep the bottom of the well far enough from the model boundary. Similarly, in the x and y directions, it is assumed that the boundaries are far enough from the well.

Two porous medium zones are defined: the reservoir zone (Cajamarca complex) extends from the bottom up to an elevation of 2500 m and it is overlain by the caprock, which consists of eruptive and superficial deposits and extends to the top of the model at an elevation of 4000 m. The hydraulic and thermal properties are listed in Table 1.

The depth of the three faults (Samaná Sur, Santa Rosa, and El Billar) is unknown. To analyze the impact of the intersection of faults with the production well on the cone of depression generated during withdrawal, three scenarios are defined. In Case 1, the production well only intersects the Santa Rosa fault, in Case 2 it intersects both Santa Rosa and El Billar faults, and, finally, in Case 3, the Santa Rosa and El Billar faults are intersected by the well, and there is an intersection between Samaná Sur and Santa Rosa faults. All three faults have the same aperture of 1 mm.

The mesh is generated by HGS, and it consists of 343914 nodes and 327936 block elements, which are refined near the faults and the pumping well. The internal diagonals or the sides of the 3D blocks are automatically selected by the HGS 2D fracture generation algorithm. Those 2D elements are selected using the three points that identify the fracture plane that must be entered by the user. Later, fracture properties are assigned to those 2D elements. Therefore, the resulting faults are represented by a staircase profile in the mesh (Fig. 9) and their angle with the well axis depends on the size of the block elements crossing the faults. A specific head of 4000 m is applied to the lateral and upper boundaries, while the bottom is assumed impermeable. Along the well screen located in the production zone, a hydraulic head of 2700 m is assigned to represent the pressure drawdown due to fluid flow through the reservoir, when production starts. The node at the top of the well has the same hydraulic head of 4000 m preventing the fluid above the well from migrating towards it, due to its high permeability. For heat transfer, an average temperature of 15°C is applied to the top, as done in the 2D model, while the bottom heat flux is 0.6 W m^{-2}, which corresponds to the flux for the Cajamarca complex that forms the rock basement in the Botero-Londoño area. The lateral heat boundaries are assigned to a temperature that decreases from the bottom to the top of the model along four different zones with a thickness of 1000 m. The temperature for each zone is calculated from the average heat flux (0.6 W m^{-2}). The temperatures assigned are, from bottom to top, 435°C, 345°C, 240°C, and 87.5°C (Fig. 6). The initial temperature in the model is assigned by using the mean air temperature at the top of the model and increasing temperature with depth based on the geothermal gradient observed at the Nereidas well [25]. This model does not include superficial deposits since the Cajamarca complex is the main outcropping unit in the Botero-Londoño area and deposits are rarely observed.

3 Results and discussion

3.1 2D Model

The fluid mass balance calculated by HGS indicates that the volume of water entering and leaving the model changes depending on the fault aperture, highlighting its importance in the circulation of fluid in fractured geothermal reservoirs (Table 2).

Fig. 7 shows the results for the three scenarios listed in Table 2. The figure focuses on the three faults located in the Botero-Londoño area. The x-component of the velocity vector, which is the most significant considering the main direction of regional-scale groundwater flow in the model, is shown.

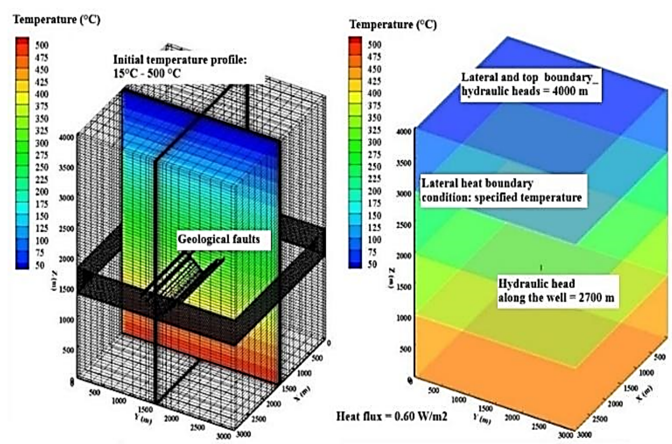

Figure 6. 3D model setup: geometry, mesh, and boundary conditions. Source: The authors.

Table 2.
Impact of fault apertures on fracture hydraulic conductivity and fluid mass balance for the 2D steady-state groundwater model.

	Fault aperture 2b (m)	Temperature (°C)	Fracture hydraulic conductivity K_f (m s^{-1})	Fluid balance (m^3 s^{-1})	
				in	out
Case A	1x10^{-1}	202	7270	1.3x10^{-6}	3.2x10^{-6}
Case B	1x10^{-3}	178	0.7270	5.4x10^{-7}	5.4x10^{-7}
Case C	1x10^{-5}	178	7.2706	3.7x10^{-7}	3.7x10^{-7}

Source: The authors.

In Case A, where the aperture is 0.1 m, the velocity reaches a maximum of 10^{-5} m s^{-1} along the Santa Rosa fault, while velocity for the other faults is on the order of 10-6 m s^{-1}. In the Santa Rosa fault, the highest velocity occurs close to the surface and velocity decreases with depth to a minimum value of 10^{-6} m s^{-1}. In Case B, with an aperture of $1x10^{-3}$ m, a velocity of 10^{-5} m s^{-1} is simulated along the Santa Rosa, El Billar, and Quebrada Negra faults. Case C, with a fracture aperture of 1x10-5 m, shows a velocity on the order of 10-6 m s-1 along all faults.

The Santa Rosa fault is selected to compare Cases A and B, since it is the fault with the largest simulated groundwater velocity. The difference between the simulated hydraulic heads at the fault extremities is approximately 0.1 m for Case B, and it is less than 0.001 m for Case A. This difference depends on the head at the lower extremity of the fault, because the head applied at its upper extremity coincides with ground surface, where a first-type flow boundary condition is applied. As expected, the increase in hydraulic conductivity is directly related to fault aperture, but groundwater flow velocity is not necessarily greater with larger aperture, since it depends on the hydraulic gradient along the fault plane, highlighting the influence of the assigned boundary conditions.

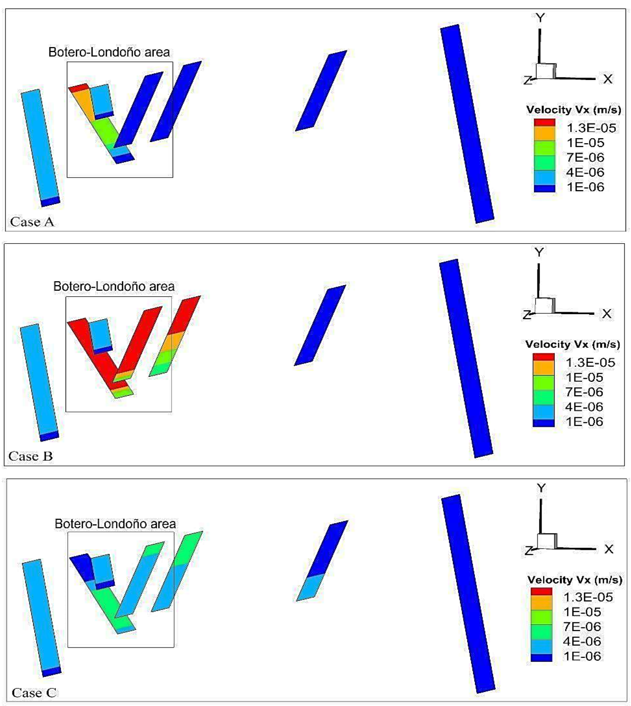

Figure 7. Comparison of x-component of groundwater velocity for three different scenarios of fault aperture in the Botero-Londoño area (2D regional scale model).
Source: The authors.

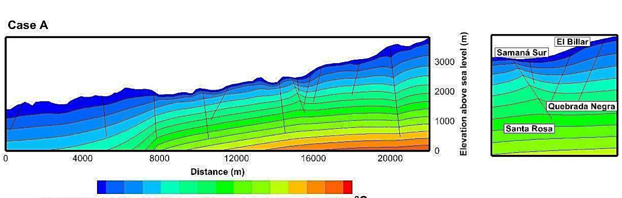

Figure 8. Influence of the faults on the temperature distribution for Case A of the 2D regional scale model.
Source: The authors.

Fault aperture has also an effect on the distribution of simulated temperature since groundwater can flow upward along a fault plane because of hydraulic head gradients (Fig. 8). In Case A, the temperature increases around the Santa Rosa fault while no significant impact is observed along the Quebrada Negra fault. This result is coherent with the work presented by [11], who analyzed the relation between the inclination of the fault and the direction of groundwater flow. Cases B and C, with narrower faults, show a higher temperature at the bottom of the model (438°C for case B and 439°C for case C), which is approximately 50°C greater than Case A.

3.2 3D Model

Fig. 9 shows the hydraulic heads simulated in the 3D model. Three different geometric configurations are considered (Case 1, Case 2, and Case 3) varying the mutual intersection between the production well and the three faults, Santa Rosa, El Billar, and Quebrada Negra.

Case 1, where only the Santa Rosa fault intersects the well, is characterized by the smallest cone of depression. In Case 2 and Case 3, its extension increases, since the number of intersections between faults and production well increases too, creating a larger network of permeable structures. The three scenarios show that the faults allow withdrawing the fluid from a larger area.

To quantify how the simulated temperature may change depending on the mutual intersection between the faults and the geothermal production well, an observation point is located at a depth of 2590 m, close to the bottom of the well (Fig. 10). The network of permeable structures increases in size from Case 1 to Case 3, because of more intersections between faults and production well (Table 3). Therefore, in Case 2 and 3, the cone of depression is larger (Fig. 9), such that more superficial, and therefore colder, water can migrate to the well. This behavior explains why during the first years of the simulation a small drop in the temperature is observed (Fig. 11), but it is not considered significant to affect the enthalpy of the resource, since it remains in the same temperature range.

In Case 1, the average initial temperature around the well is 329°C and increases over time to a maximum value of 345°C, which would increase the geothermal potential. This result depends on the boundary and initial conditions applied. In Case 2 the temperature starts at 329°C, decreases until 323°C in the first 2.7 years, and starts increasing, until it reaches a value of 333°C, which is 16.5°C less than Case 1. In Case 3, the temperature follows the same trend as Case 2, with a small difference of 2°C at the beginning of the simulation, and 7°C at its end.

The analysis of both groundwater flow and heat transfer indicates that Case 2 and 3 scenarios have a similar behavior, which is slightly different from that of Case 1. Scenarios 2 and 3 have a larger cone of depression than Case 1, since the mutual intersections create a larger network of permeable elements (faults and well). This aspect is important to assess the volume of the reservoir that is affected by the extraction of fluids, which is required to identify the proper location of the reinjection well, for example.

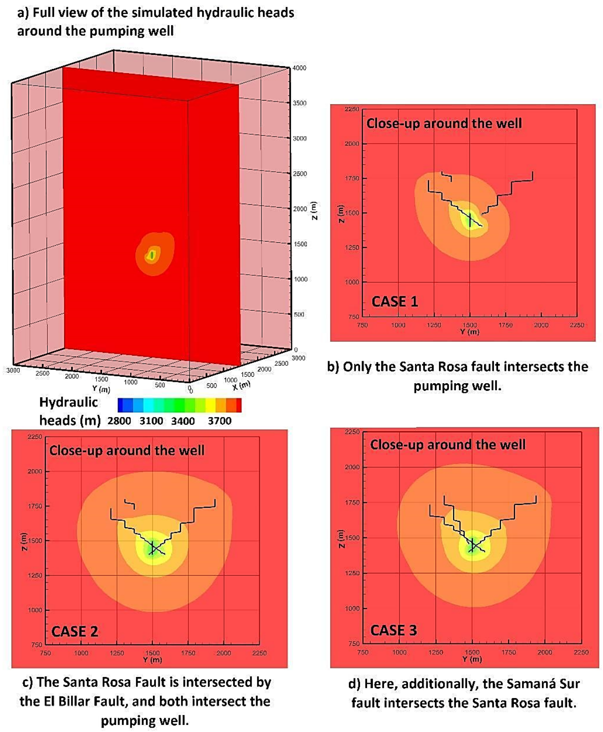

Figure 9. Hydraulic heads simulated for three hypothetical scenarios of different fault-well intersections.
Source: The authors.

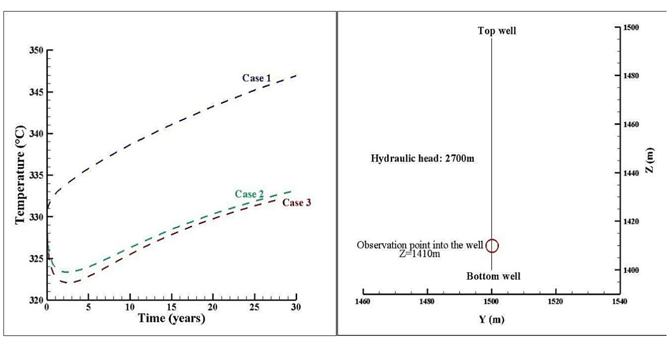

Figure 10. Location of the observation point at the hypothetical geothermal production well and temperature variation during 30-year geothermal development, for the defined boundary conditions.
Source: The authors.

The results have shown that the hydraulic and thermal properties, as well as the geometry of the main structures, faults and well, significantly affect the physical processes evaluated. The 2D model shows that the superficial deposits in the zone do not have a representative thickness to affect the assessment of temperature at depth.

The faults in both models are assumed to be open and continuous structures, such that groundwater can flow freely and unrestrictedly by their high hydraulic conductivity. This hypothesis is made because there are no studies about their spatial continuity at depth.

The 3D model was built for the Botero-Londoño zone for two main reasons. First, the faults (Santa Rosa, Samaná Sur, and El Billar) in this zone that are less than 1220 m apart creating a greater fracturing and allowing groundwater to ascend with less restriction, since several hot spring manifestations are observed along Las Nereidas stream. Second, this area is a valley, such that it would be a suitable location for geothermal well drilling, since it would not be necessary to drill across the quaternary eruptive and superficial deposits. It is therefore appropriate to provide new knowledge and insights about subsurface flow and heat transfer mechanisms in this study area, considering that it can also be applied to other regions with analogous geological context.

Table 3.
Description of the 3D simulation scenarios and calculated temperature at geothermal production well.

	Simulated temperature in the well (°C)	Description of the geometry
Case 1	345	Santa Rosa fault intersects the well
Case 2	333	Santa Rosa and Quebrada Negra faults intersect the well
Case 3	333	Santa Rosa and Quebrada Negra faults intersect the well and El Billar Fault intersects Santa Rosa Fault

Source: The authors.

A limitation of this study is that the variations of water density and viscosity with temperature are neglected, and the fluid is in the liquid phase only. However, the hydrothermal reservoir associated with the NRV is expected to be a liquid dominant reservoir, with a water-steam mixture. Therefore, a more realistic representation should consider two-phase fluid flow (liquid and vapor) and temperature-dependent water properties. However, numerical modeling is generally performed in successive stages, increasing the degree of complexity during time, and this study offers an initial insight into the importance of the intersection between faults and production well. Further modeling tasks can use these results and gradually increase the complexity of the model, to assess the impact of simulating more detailed physical processes. Moreover, considering the numerous available numerical codes, new models may focus on the analysis of different geometrical representations of fractures, using different meshing algorithms. Since a 3D hydrogeological numerical model of this area has not been reported in the literature yet, this study provides useful guidelines to model the available geothermal resources.

4 Conclusions and recommendations

This work presents two numerical hydrogeological models of groundwater flow and heat transfer of the geothermal reservoir of the Nevado del Ruiz Volcano (Colombia). The models focus on the intersection between the faults Samaná Sur, Santa Rosa and El Billar, in the zone called Botero-Londoño.

The results of the 2D model illustrate the impact of fault aperture on the fluid mass balance, as well as on the temperature distribution.

The results of the 3D model show that the spatial distribution of faults has a considerable impact with respect to the cone of depression around a hypothetical production well. Three scenarios with different networks created by the intersection between faults and well, show a relation between the size of this network and the cone of depression associated with withdrawal from the reservoir. The cone of depression explains the temperature observed at the pumping well.

It is recommended to perform geochemical exploration studies coupled to hydrogeological modeling, to define the origin and age of the water and identify the main circulation systems, either deep systems associated with the NRV magmatic chamber or shallow waters. Moreover, geophysical studies can help to improve the understanding of structural geology to better characterize the faults, since their depth, extension, and aperture play an important role for heat transfer and groundwater flow.

With respect to numerical modeling, considering two-phase flow is also recommended for further studies, since it is one of the most important characteristics of a liquid-dominated reservoir, as should be the case in the NRV geothermal system. Two-phase flow modeling would be required once the type of geothermal resources have been confirmed through deep exploratory wells. At that time, it is also recommended to model the geothermal doublet, both production and injection well, to simulate the whole cycle of geothermal resource utilization, to suggest a suitable withdrawal rate to ensure its renewal.

Geothermal energy is a renewable energy if and only if the initial conditions of the hydrothermal system are preserved over time. It should be mentioned that geothermal fluids could present a great diversity of dissolved and precipitated minerals that are neglected in this study, since hydrogeochemical aspects are not simulated. Those minerals are important because, due to changes of temperature and pressure, they can precipitate and cause clogging in wells and pipes of power plants. This phenomenon is another aspect that should be considered and could be analyzed through numerical simulations. Finally, it is recommended to use the 2D models available for this study area to build or update existing 3D conceptual models [17] with the purpose of creating a regional numerical model of the NRV, which can be used to simulate different scenarios of geothermal development.

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Effect of solid fermentation with *Rhizopus oryzae* on coffee pulp to obtain a food product

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Abstract
Coffee pulp is one of the most voluminous by-products in the wet processing of coffee beans. To maximize the use of this by-product, we conducted a solid-state fermentation (SSF) process with *Rhizopus oryzae* (MUCL 28168). In the SSF process, the effect of pH and carbon source on the content of nutritional compounds and condensed tannins was evaluated. Applying a factorial design revealed a significant ($p < 0.05$) interaction of factors affecting protein content, sugars, and condensed tannins, while phenol content and antioxidant capacity were only impacted by pH. The optimum conditions for the fermentation process were pH 6, 75% carbon source, temperature of 32 °C, and 28 h of processing. A coffee pulp infusion with sweet, honey, and woody notes was obtained. The SSF process reduced condensed tannins in coffee pulp by up to 60%, indicating its effectiveness in releasing functional compounds and reducing anti-nutritional factors.

Keywords: by-product utilization; solid state fermentation; coffee pulp; *Rhizopus oryzae*.

Efecto de la fermentación sólida con *Rhizopus oryzae* en pulpa de café para obtención de un producto alimentario

Resumen
La pulpa de café es uno de los subproductos más voluminoso en el tratamiento húmedo del grano. Con el propósito de dar un mejor aprovechamiento de este subproducto, se le realizó un proceso de fermentación en estado sólido (FES) con *Rhizopus oryzae* (MUCL 28168). En el proceso de FES se evaluó el efecto del pH y la fuente de carbono sobre el contenido de compuestos nutricionales y taninos condensados. Aplicando un diseño factorial, se encontró que la interacción de los factores tuvo un efecto significativo ($p < 0,05$) sobre el contenido de proteínas, azúcares y taninos condensados, mientras que el contenido de fenoles y la capacidad antioxidante se vio afectada únicamente por el pH. Las condiciones óptimas para el proceso de fermentación fueron pH 6, fuente de carbono del 75%, temperatura de 32 °C y 28 h de proceso. Se logró obtener una infusión de pulpa de café con notas dulces, a miel y madera. El proceso SSF redujo los taninos condensados en la pulpa de café hasta en un 60%, lo que indica su eficacia en la liberación de compuestos funcionales y la reducción de factores antinutricionales.

Palabras clave: Aprovechamiento de subproductos; Fermentación en estado sólido; Pulpa de café; *Rhizopus oryzae*.

1 Introducción

Coffee is one of Colombia's main export products, making it the third largest producer in the world with an annual production of 11.1 million 60 kg bags of green coffee in 2022 [1]. Despite increasing demand, the coffee sector faces significant challenges because only 5% of the harvested coffee cherries are used to produce the beverage [2]. The remaining 95% results in by-products such as pulp, mucilage, cisco, pasilla, borage, and coffee stalks [2].

Coffee pulp, a major by-product of wet coffee processing, accounts for 42% of the fruit's weight on a wet basis, as noted by Acevedo & Penaloza [3]. Traditional disposal methods that involve water lead to severe environmental issues,

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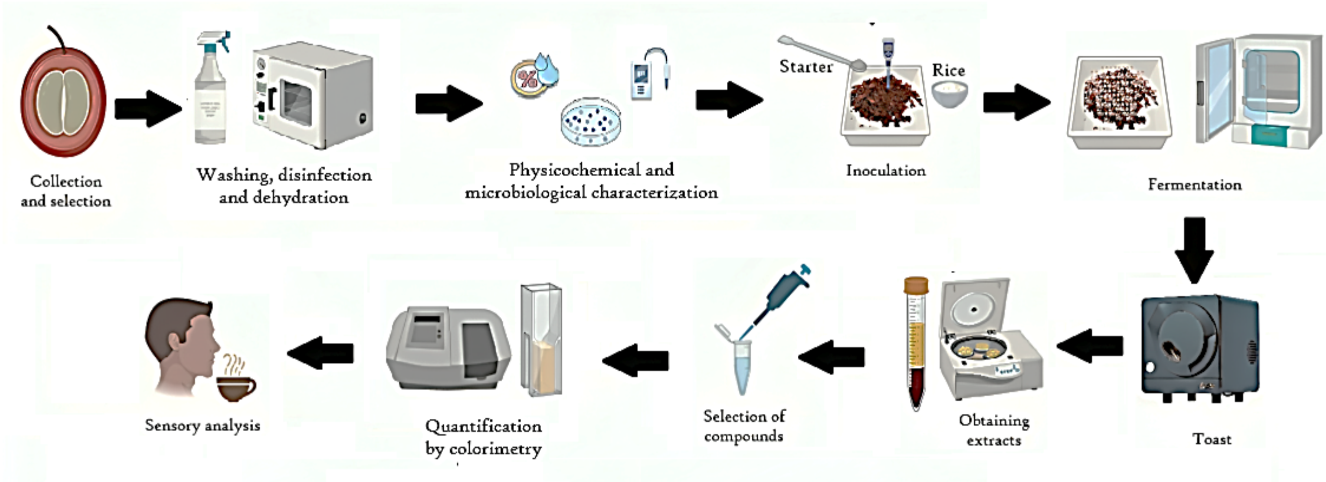

Figure 1. Graphic Summary.
Source: Author made

including contamination of nearby water sources, ecosystem imbalances, and adverse impacts on human health, as well as on local flora and fauna [4,5]. To mitigate these effects, covered pits have been implemented for pulp disposal; however, their effectiveness is limited due to the large volume of pulp produced.

Developing countries often lack the necessary technology and expertise to effectively utilize coffee residues. Consequently, various alternatives have been explored to valorize coffee residues, including their use in composting, animal feed, mushroom substrates, and the production of specialized beverages and infusions. These practices have somewhat increased the market value of coffee residues [6]. However, their application in the food industry is limited by the presence of anti-nutritional compounds such as condensed tannins [7]. Biotechnological processes, such as solid fermentation, are recommended to reduce these compounds to acceptable levels and to release high-value nutritional compounds.

In this context, the fungus *Rhizopus oryzae*, which is recognized as safe (GRAS), has been chosen for its tannase enzyme that hydrolyzes condensed tannins from coffee pulp, thereby improving the bioavailability of nutritional compounds [8,11]. Therefore, this research aims to develop a food product using fermented coffee residues from Coffea arabica var. Castillo with *Rhizopus oryzae* (MUCL 28168) (Fig. 1). This approach offers an environmentally sustainable solution and creates new economic opportunities for coffee farmers.

2 Materials and methods

2.1 Raw material

Coffee pulp from Coffea arabica var. Castillo, sourced from the north of Valle del Cauca, was utilized in this research. The samples were collected immediately after the pulping process and transported under controlled conditions to the Microbiology and Applied Biotechnology Laboratory (MIBIA) at Universidad del Valle. At the laboratory, the pulp was cleaned, sorted, and disinfected with 2% chlorinated water for 30 seconds. The samples were then dehydrated at 60°C until a moisture content of 12% was achieved, to minimize physicochemical and microbiological deterioration.

2.2 Physical and chemical characterization of coffee pulp

2.2.1 Determination of the initial moisture content

The initial moisture content of the coffee pulp was determined by applying the NTC 2558:2000 standard [12], which involves measuring the weight difference as described in eq. (1).

$$\%\,\textbf{Moisture} = \left(\frac{\textbf{Mass of water}}{\textbf{\textit{Total mass}}}\right)\cdot \mathbf{100} \qquad (1)$$

2.2.2 Water Activity (Aw) and pH determination

Water activity was measured using an AQUALAB SERIES 4TE device with 1 gram of the dry sample. For pH determination, 1 gram of the product was weighed, suspended in 10 mL of distilled water for 30 minutes, and the pH was then measured using a sensitive pH-meter electrode (Thermo Scientific) until a stable reading was achieved [13].

2.2.3 Determination of Wáter Absorption Capacity (WAI)

The methodology employed was that developed by Londono [8], where 1.25 g of the sample was suspended in 15 mL of distilled water and agitated continuously for 10 minutes. Afterward, the samples were centrifuged at 3000 rpm for 10 minutes; the supernatant was decanted, and the weight of the resulting gel was recorded. Eq. (2) was used to calculate the water retention capacity:

$$\boldsymbol{WAI} = \left(\frac{\textbf{Weight of the gel}}{\textbf{Weight of the dry sample}}\right) \qquad (2)$$

2.2.4 Microbiological characterization of unfermented coffee pulps

Microbiological analyses were conducted on the coffee pulp following collection, sanitization, and dehydration processes. These analyses adhered to the methodologies outlined in standards NTC 4491-1 [14], 5034 [15], 4516 [16], 5733 [17], and 5698-1 [18], covering material preparation, and counts of lactic acid bacteria, total coliforms, enterobacteria, and yeasts.

2.3 Solid State Fermentation (SSF)

2.3.1 Reactivation and Verification of the Purity of the Filamentous Fungus Rhizopus Oryzae

Dried spores from the MIBIA group's culture collection were used to reactivate *Rhizopus oryzae* (MUCL 28168). These spores were centrally placed on Petri dishes containing Potato Dextrose Agar (PDA) as the stock culture medium. The dishes were incubated at 28°C until complete sporulation was observed. The purity of the cultures was verified using a stereoscope, and their morphological characteristics were examined under a microscope at 40X magnification.

2.3.2 Preparation of inoculum

The inoculum was prepared using the Tane-Koji method as described by Londoño [19]. This method involved inoculating cooked brown rice with a spore suspension of the fungus *Rhizopus oryzae,* extracted from test tubes previously seeded with the strain. The rice-filled containers were incubated for 75 hours to allow complete sporulation of the microorganism. Afterward, the rice was dried at 45°C for 24 hours until it reached a moisture content of 12%. The dried product was then ground using a blade mill, stored in sterile containers at 28°C, and spore counts were conducted using a Neubauer chamber.

2.3.3 Experimental design

A 2x3 factorial design was employed to determine the ideal process conditions, assessing the impact of pH and the percentage of carbon source (CS) on various response variables (Table 1). A total of 27 treatments were evaluated. Data analysis was performed using ANOVA and Tukey's test via Minitab 19.

Table 1.
Experimental design.

Independent Variables	Levels			Response Variable
pH	4	5	6	Content of tannins, total phenols, and caffeine present in coffee pulp
Carbon source (%)	25	50	75	

Source: Author made

2.3.4 Evaluation of fermentation conditions

Solid-state fermentation was conducted in sterile aluminum boxes at 32°C for 40 hours, maintaining substrate humidity at 65% and an inoculum density of 1 x 10^7 spores per gram. The initial pH of the substrate was adjusted using buffered solutions of NaOH and H2SO4. After fermentation, the samples were dehydrated at 60°C for 24 hours, sieved, and then roasted at 140°C for 1 minute and 20 seconds.

2.4 Quantification of Compounds of interest present in coffee pulp

The quantification of the study compounds was performed using aqueous solutions of coffee pulp samples across three stages: unfermented and unroasted (PST), unfermented with roasting (PCT), and fermented with roasting. Water was used for analyzing nutritional compounds and 80% methanol for condensed tannins. One gram of pulp was placed in centrifuge tubes with 10 mL of the respective solvent and subjected to ultrasonic extraction for 45 minutes at 40°C. The samples were then centrifuged at 3000 rpm for 15 minutes, the extract was filtered and stored at 4°C until analysis.

Soluble proteins were quantified using the modified Lowry method [20]. Total sugars were quantified using the Antrona method [21], and the content of reducing sugars was determined by the DNS method [22]. Total phenols were quantified following the methodology described by Londono [8]. Antioxidant capacity was evaluated using the DPPH (1,1-diphenyl-2-picryl-hydrazyl) technique as described by Medina et al. [23]. The quantification of condensed tannins followed the method established in NTC 602 [24].

2.5 Fermented product selection and design

Product selection and design were conducted using the "Response Optimization" feature in the statistical software Minitab 19. The objective was to minimize the levels of tannins and sugars while increasing the protein content, phenols, and antioxidant capacity. The qualitative sensory profile was evaluated by a panel of experts from Agricola Himalaya S.A., who assessed the aroma, flavor, and appearance in aqueous solutions of both the control sample (PCT) and the selected product.

3 Results and discussion

3.1. Physicochemical characterization of unfermented dry pulp

Following the methodologies outlined earlier in this document, the physicochemical analysis of the unfermented dry pulp was performed, and the results are recorded in Table 2.

Table 2.
Physicochemical characterization of coffee pulp.

Analysis	Methodology	Results
Initial Moisture Content	NTC 2558:2000	88.5±0.9
Final moisture content	NTC 2558:2000	11.5±1.5
WIA	Londoño (2015)	8.3±0.2
pH	Londoño (2015)	4.3±0.2
Aw	-	0.49±0.03

Source: Author made

Table 3.
Microbiological characterization of fresh and dehydrated pulp

Parameter	Fresh Pulp	Dry Pulp
Mesophilic Aerobes - PCA (UFC/g)	$4.9*10^6$	<3
Fungi and yeasts - PDA (UFC/g)	$1.2*10^7$	<3
Enterobacteriaceae count - VRBA (UFC/g)	$1.8*10^6$	<36
Lactic Bacteria's -MRS (UFC/g)	$3.7*10^6$	<30
Total Coliforms (NMP/g)	1000	0

Source: Author made

Coffee pulp is a solid by-product with a high moisture content, making it susceptible to microbial growth as well as changes in size, color, and odor [25]. After the drying process, the coffee pulp was found to have an average moisture content of 88.5%. Although several studies indicate that the moisture content of coffee pulp varies between 74% and 88% [25-27], the results obtained in this study are slightly higher. This increase could be attributed to the exudate released during the thawing process, which increased the free water content of the sample, facilitated by the concavity of the pulp.

The water activity of the material after drying was measured at 0.49 ± 0.003, very similar to those found by other researchers [8,28]. This confirms the microbiological and enzymatic stability of the coffee pulp after dehydration, given that the water activity of fresh premium material was reported to be 0.6 [29]. The water absorption capacity of the coffee pulp was recorded at 8.3, significantly exceeding the values reported by Londoño [8]. This indicates a higher hydration capacity of the dry coffee pulp, ensuring effective retention of water added during rehydration and achieving an optimal moisture level (60-70%) for microbial growth. Table 2 shows that the pH of the coffee pulp is 4.3 ± 0.2. Previous studies have shown that the pH of coffee pulp can vary between 3.92 and 5.63 [8,26,30]. This variability is attributed to factors such as geographical location, growing conditions, coffee variety, altitude, degree of fruit ripening, and production methods [8,31].

3.2. Microbiological characterization of the unfermented coffee pulp

Table 3 presents the results of the microbiological analyses performed on both the fresh and dehydrated coffee pulp.

As shown in Table 3, the high load of microorganisms in the fresh pulp was attributed to processing, product handling, and machinery. This is evident in the mesophilic microorganism count, as a higher presence of these microorganisms indicates deficiencies in sanitation practices and possible contamination during production [32]. Puerta et al. [32] reported that reducing two stages of the wet coffee processing method—sorting and sieving—resulted in a significant decrease in the count of mesophilic microorganisms, directly associated with product handling.

Fungal and yeast counts also showed elevated amounts, although they were within the range reported by several authors (1.4 × 10^5 to 3.1 × 10^8 CFU/g) [27,32]. At 72 hours, however, yeasts showed an absolute predominance, aligning with the findings of Blandon et al. [27] and Puerta et al. [32], who identified yeasts of the *genera Candida spp., Saccharomyces cerevisiae, Rhodotorula spp., and Cryptococcus terreu*s. In contrast, Martinez et al. [34] observed that fungi of the genera *Aspergillus, Penicillium, Fusarium, and Trichoderma* are more predominant in coffee fruit. The variability in the count and predominance of fungi and yeasts is influenced by factors such as coffee variety, altitude, and growing conditions.

Regarding lactic acid bacteria, a higher concentration was observed compared to that reported by Puerta et al. [32], who found that 33% of the initial bacterial population belonged to the genus *Lactobacillus.* However, this finding contrasts with Martinez (2022), who established a relationship between the quantity of lactic acid bacteria and the altitude at which the coffee is grown. Based on the results of this study, it was concluded that altitude did not have a significant effect on the lactic acid bacteria content of the samples analyzed.

Similarly, the fresh pulp showed a high concentration of coliforms, coinciding with the findings of Torres et al. [29]. These authors associated the presence of coliforms of the genera *Enterobacter, Klebsiella, Serratia, and Citrobacter* with the quality of the water used during the fruit washing process. Deficient water supply, storage, and distribution systems often harbor these bacteria, which negatively affects the microbiological quality of the product.

The high microbial load in the fruit was influenced by the moisture content of the substrate and the soluble carbohydrate content of the pulp. To prevent spoilage caused by microbiological agents, sanitation and drying processes were implemented. These measures significantly reduced the microbial count, as detailed in Table 3, thereby extending the shelf life of the product and eliminating microbial activity that could compete with the fungus during the solid-state fermentation process.

3.3. Solid state fermentation

Physicochemical analysis revealed that coffee pulp is a suitable substrate for the growth of Rhizopus oryzae, enhancing its survival, colonization, and enzyme production [34]. Under the established conditions (temperature of 32°C, substrate humidity of 65%, and relative humidity of 77%), optimal growth of the microorganism on the substrate was observed. At pH 4, maximum growth was achieved in 38-40 hours; at pH 5, it took 32-36 hours; and at pH 6, the time was reduced to 28 hours, indicating that pH significantly

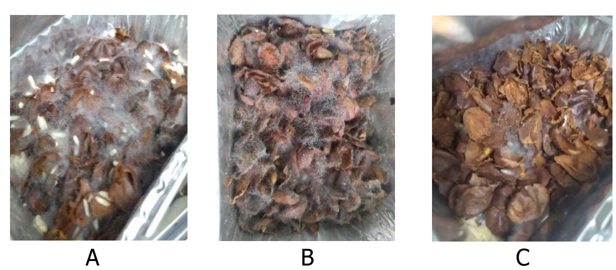

Figure 2. Comparison of the growth of Rhizopus oryzae at different concentrations of carbon source A) with 75% rice, B) with 50% rice, and C) with 25% rice.
Source: Author made

Table 4.
Results of the experimental runs for each of the parameters evaluated after the solid fermentation process.

pH	%CS	%PT	%AzT	%AzRT	Phenols	DPPH	%CT<
PST		17.32±0.36	56.95±0.96	44.26±1.51	80.00±0.03	9.84±1.30	0.300±0.006
PCT		6.40±0.70	24.93±1.05	16.56±0.80	110.24±8.50	11.74±0.51	0.305±0.015
4	25	5.28±0.58^{F}	32.60±2.08^{A}	18.54±1.69^{A}	118.74±2.04^{B}	11.21±0.66^{B}	0.174±0.021^{BC}
4	50	12.67±0.83^{CDE}	21.89±0.36^{C}	14.80±0.29^{B}	139.45±7.06^{B}	11.72± 0.12^{B}	0.191±0.035^{AB}
4	75	21.17±2.03^{A}	15.73±0.62^{D}	10.50±0.51^{D}	137.1±12.03^{B}	11.69± 0.73^{B}	0.196±0.017^{BC}
5	25	6.78±0.68^{EF}	23.08±0.80^{BC}	15.46±0.65^{B}	170.23±13.53^{B}	10.37± 0.71^{B}	0.178±0.016^{BC}
5	50	14.56±0.72^{BCD}	20.35±1.65^{C}	14.71±1.35^{B}	129.59±2.30^{B}	12.87± 0.27^{B}	0.262±0.017^{A}
5	75	8.17±0.75^{DEF}	13.41±1.09^{DE}	12.10±0.89^{C}	201.80±14.28^{B}	14.04± 0.40^{B}	0.153±0.014^{CD}
6	25	9.17± 0.13^{DEF}	24.73±0.87^{B}	19.61±2.72^{A}	284.51±16.25^{A}	17.09± 0.20^{A}	0.124±0.015^{D}
6	50	16.72± 1.14^{ABC}	11.27±1.52^{E}	11.05±1.24^{CD}	337.14±10.86^{A}	14.21± 0.80^{A}	0.175±0.015^{BC}
6	75	19.85± 1.66^{AB}	7.21±0.44^{F}	6.83±0.44^{E}	332.63±11.20^{A}	17.16± 0.06^{A}	0.165±0.008^{CD}

Note: Results expressed in percentage are equivalent to the reagent used in the calibration curve/g sample on a dry basis. Phenols (mg Gallic Acid Equivalents GAE/g d.m) DPPH (µmol Trolox Equivalents TE/g). CS: Carbon source; AzT: Total sugars; AzRT: Reducing sugars; CT: Condensed tannins; PST: Pulp without roasting; PCT: Pulp with roasting. Values with the same letter within the same evaluated parameter do not show statistically significant differences.
Source: Author made

influences the mycelial growth rate. Additionally, it was demonstrated that incorporating uncooked white rice as a carbon source (CS) had a positive impact on mycelial growth. Treatments with 75% rice exhibited the highest growth rate (Fig. 2A), followed by those with 50% (Fig. 2B) and, finally, those with only 25% (Fig. 2C).

3.4. *Quantification of compounds of interest present in coffee*

Quantification of the compounds of interest was performed on unfermented and unroasted (PST), unfermented and roasted (PCT) coffee pulp samples, as well as for each of the treatment groups. Table 4 presents the obtained results.

Proteins are the main structural and functional components of cells [35]. However, plant proteins obtained from the solid-state fermentation process must be free of any contaminants or anti-nutritional factors [35,36].

Table 4 shows that after the roasting process, the control sample exhibited a 6% decrease in protein content. This decrease is attributed to chemical reactions caused by heating, primarily between amino acids and reducing sugars, commonly known as the Maillard reaction. These reactions lead to the creation of molecules with distinct odors and flavors, thus reducing the protein content [37]. Researchers such as Londoño et al. [38], Encalada et al. [39], and Fierro et al. [40] reported soluble protein contents of 14.83%, 12.56%, and 10.63%, respectively, which are slightly lower than those found in the PST sample. These differences are attributed to variations in the growing area, soil composition, and conditions, as well as treatments applied to the crop, factors that can influence the nutritional composition of the fruit [41].

According to the ANOVA and post-ANOVA analyses ($P<0.05$), it was observed that the treatments at pH 4 and pH 6 with a CF (carbon source) of 75% presented protein amounts of 21.17% and 19.85%, respectively. Ceballos et al. [42] attribute this increase to the fact that during the first 24 hours of fermentation, the microorganism *Rhizopus oryzae* accelerates its metabolic activity and degrades compounds such as tannins through the action of enzymes like polyphenol oxidase, which breaks down the tanninprotein structure. In contrast, at pH 4 and 5 with a CF of 25%, the protein content is low, possibly due to insufficient growth of the microorganism throughout the matrix, as the mycelium did not completely invade the substrate.

According to Navarro & Roa [43], any raw material intended for animal feed is considered to have good capacity if its protein content exceeds 11%. Therefore, the fermented coffee pulp is classified as a premium raw material based on its protein content. However, it should be noted that in this research, the product is intended for human consumption, although its use in animal feed is not ruled out.

3.4.1. *Total sugars content of coffee pulp*

The sugar content of the substrate significantly influences the growth, invasion, and metabolic activity of the fungus. In the PST sample, a total sugar content of 56% was observed, which is similar to that reported by Londoño et al. [26] for coffee pulp of the same variety. However, this amount decreased considerably to 24.9% after the roasting process due to chemical and biochemical reactions involved [44].

ANOVA analysis showed statistically significant differences in the interaction between the two factors analyzed on the total sugar content, and Tukey's test revealed that the greatest decrease occurred at pH 6 with CS (carbon source) of 75% and 50%. This is because the fungus was in an optimal growth environment, which allowed it to completely invade the substrate and perform transformations on it.

A study by Ibarruri & Hernandez [45] mentions that *Rhizopus oryzae* grows better on fruit residues than on other by-products, due to the abundant presence of sugars in these substrates. Their research observed a 33% decrease in carbohydrate content after 3 days of fermentation. In contrast, a 71% decrease in carbohydrates (at pH 6 and CS of 75%) was achieved in a maximum time of 40 hours compared to the PCT sample. This was accomplished by optimizing fermentation conditions and adding a CS, which allowed higher growth of the microorganism and, therefore, a higher depletion of carbohydrates.

Thus, there was a higher consumption of carbohydrates from the substrate. It should also be noted that the decrease in this parameter is additionally due to the roasting process.

3.4.2. Reducing sugars content in coffee pulp

In terms of reducing sugars, coffee pulp, unlike coffee beans, is characterized by the presence of these compounds, especially glucose and xylose [45]. The PST samples contained 44% reducing sugars (Table 4), similar to levels reported by Gurram, Al-Shannag & Knapp [46] and Fierro et al. [40] for the same coffee variety. However, the PCT samples showed a reduction to 16.56%, representing a decrease of 62.4% in these compounds. ANOVA analysis revealed that the interaction of the two factors significantly influenced this response variable. Tukey's test indicated that a CS (carbon source) of 75% contributed to the decrease in reducing sugars in the coffee pulp samples, regardless of the pH level. This behavior can be attributed to the fact that, at a CS of 75%, there is a greater availability of reducing sugars, which enhances the growth and metabolic activity of the microorganism. This allows it to degrade compounds such as condensed tannins and increase the presence of proteins and phenolic compounds [36].

3.4.3. Content of total phenolics

Phenols are compounds known for their antioxidant, anti-inflammatory, and antimicrobial capacities [8, 47]. In the PST samples, the content of total phenolics was 80 mg GAE/g. When the pulp underwent the roasting process, a 37.5% increase in phenol content was observed (Table 3). This effect has also been reported by Diaz et al. [66] for roasted coffee, where the phenol content increased with roasting time, concluding that medium-grade roasting is favorable to obtain coffee with a high concentration of total phenols.

ANOVA analysis indicated that the interaction between factors did not significantly affect phenol content. However, post-ANOVA analysis revealed that pH did have an influence, with the highest phenol content observed at pH 6, averaging 318.1 mg GAE/g sample. The fermentation process increased the phenolic content by 189%, 52%, and 19.7% in the PCT sample at pH 6, 5, and 4, respectively. According to Londono [8], this increase is attributed to the crucial role of pH during the growth and metabolism of the microorganism. At pH between 5 and 6, the microorganism can secrete enzymes such as xylanases, α-amylases, and β-glucosidases, which perform the necessary hydrolysis to release phenols bound to other molecules and increase the content of soluble phenols.

According to Londono [8], after solid-state fermentation of coffee pulp with *Rhizopus oryzae*, approximately 46 phenolic compounds were identified, including ferulic acid, trigonelline, caffeine, and chlorogenic acid, along with 18 compounds found exclusively in coffee pulp. Meanwhile, Palomino et al. [49] reported that after fermentation of coffee pulp with *Penicillium purpurogenum,* the most abundant phenolic compound was chlorogenic acid, followed by caffeic acid and rutin.

Researchers have found significant variability in the phenolic content of coffee pulp. Authors such as Melendez [50], Cruzalegui et al. [51], and Myo & Khat-udomkiri [52] have determined that the polyphenol content can range from 46.31 to 891 mg GAE/100 grams of coffee pulp. These differences are attributed to several factors, including coffee variety, drying methods, geographical location of the crop, extraction techniques and solvents, as well as the degree of roasting. According to Diaz et al. [48], during roasting, chlorogenic and hydroxycinnamic acids and some other phenolic compounds are degraded, which increases the concentration of quinic acid. Meanwhile, Shanmagam [53] noted that trigonelline does not survive the roasting of coffee beans, being transformed into nicotinic acid, pyridine, and other volatile compounds.

When comparing the results with those of the cited authors, it is evident that fermentation and roasting significantly influenced the phenolic content of the coffee pulp. This led to an increase in its amount, showing figures similar to those recorded in the literature. However, many of these compounds were not extracted due to the methodology employed and/or were degraded during the roasting process.

3.4.4. Antioxidant capacity

The antioxidant capacity provides information on the ability of compounds present in coffee pulp to inhibit or reduce oxidative damage induced by oxidizing agents, in this case, the DPPH radical [54]. Table 4 shows a 19% increase in this capacity in the PCT samples compared to the PST samples. This increase is associated with the synthesis of secondary products such as melanoidins or brown compounds, which have antioxidant activity and are responsible for color, flavor, and reducing properties. These compounds are produced from the Maillard reaction caused by thermal processing [48]. In the ANOVA and post-ANOVA analysis, it was observed that this variable was influenced only by pH. It was found that pH 6 exhibited the highest average antioxidant capacity (64.12 μMol of TE/g), followed by pH 5 (12.42 μMol of TE/g) and then pH 4 (11.5 μMol of TE/g). The amounts obtained in this study are higher than those reported by authors such as Myo & Khat-udomkiri [52] and Thy Minh et al. [55], who found antioxidant capacities of 8.19 mg TE/g and 2.24 mg TE/g, respectively. Therefore, it can be concluded that the application of solid-state fermentation and roasting enhances the antioxidant capacity of the samples.

However, at pH 5 and 6 with a CF (carbon source) of 50%, it was found that there was no direct correlation with the phenolic content. A similar effect was reported by Lopez et al. [56], who, after fermenting coffee pulp with different strains of lactic acid bacteria, observed that an increase in phenolic content did not clearly correlate with an increase in antioxidant capacity, as measured by the DPPH and ABTS methods. They attributed this effect to the presence of reductones, which could react with free radicals to stabilize and terminate the propagation of antioxidant chain reactions.

3.4.5. Condensed tannins content

The presence of condensed tannins impacts the utilization of coffee pulp as a premium material [57]. In the PST (Pre-Solid State Fermentation) and PCT (Post-Solid State Fermentation) samples, the condensed tannin content was recorded at 0.3%, and by solid fermentation, this compound was significantly reduced (see Table 4). Analysis of variance revealed statistically significant differences in the effect of the factors on condensed tannin content. Tukey's post-ANOVA analysis results indicated that the lowest tannin content, at 0.12%, was obtained at pH 6 and a carbon source (CF) concentration of 25%, representing a decrease of 60%. This finding contrasts with that reported by Londono et al. [26], who recorded a 52% reduction in the same compound. This behavior is attributed to the optimization of the substrate, which was enriched with carbon, nitrogen, phosphorus, and sulfur sources, under conditions favorable for the metabolism of the microorganism. This allowed for sufficient production of the enzyme tannase, responsible for degrading these compounds [36].

Authors such as Noriega, Silva, & Garcia [58] and Samayoa et al. [59] report that the tannin content in the Arabica coffee variety varies between 0.14% and 8.56%, which is in agreement with the results obtained for the control samples. However, this variability is attributed to factors such as the region of origin of the samples, genetics, plant species, soil fertility, and climatic conditions, as all these variables influence the quantity and type of tannins that the plant can synthesize [60].

On the other hand, Diaz et al. [48] found that in roasted coffee, tannin content increases with roasting time. Meanwhile, Thy Minh et al. [55] observed that in coffee pulp, drying with hot air at 70°C resulted in the lowest level of condensed tannins (2.34 mg ET/g DW in dry sample) compared to vacuum drying at 90°C and 110°C. This is because condensed tannins are sensitive to light and oxygen; during vacuum drying, reduced exposure to oxygen minimizes the degradation of these compounds. Therefore, both the drying and roasting processes significantly influence the tannin content present in the samples

3.5. Fermented product selection and design

In order to add value to this by-product and considering the characteristics of the premium material, it was decided to produce an infusion-type beverage. This type of beverage has traditionally been popular in countries such as Yemen, Sumatra, Ethiopia, Jamaica, and Sudan, where this by-product has been utilized for many years. In other regions, its popularity has been increasing over time, and companies such as SUTRACAFE, Cafe La Manchuria, Indio Ramirez, and Casa Eguia are already marketing the dried pulp for the preparation of this infusion.

Table 5.
Comparison of the nutritional composition of the infusion samples control and best experimental run

Component	PST	PCT	BET
Protein (%)	17.32±0.36	6.40±0.70	19.85± 1.66
Total sugars (%)	56.95±0.96	56.95±0.96	7.21±0.44
Reducing sugars (%)	44.26±1.51	16.56±0.80	6.83±0.44
Antioxidant capacity (mg/g)	9.84±1.30	11.74±0.51	17.16± 0.06
Phenols (mg/g)	80.00±0.03	110.24±8.50	332.63±11.20
Tannins (%)	0.300±0.006	0.305±0.015	0.165±0.008

Source: Author made
Note: Results expressed in percent are equivalent to the reagent used in the calibration curve/g sample on a dry basis. PST: Pulp without roasting; PCT: Pulp with roasting, BET: Best Experimental treatment.

Table 6.
Sensory evaluation of the infusion obtained versus the control sample

Organoleptic characteristics	PCT	BET
Aroma	Wood Fresh Vegetal Toasted	Wood Toasted Fermented
Taste	Acids Mild sweetness Wood with predominance over the other notes Slight sensation of astringency	Sweet Woody notes Slight sensation of astringency
Appearance in aqueous solution	Light yellow Translucent	Light yellow Slight turbidity

Note: PCT: Pulp with roasting, BET: Best Experimental treatment
Source: Author made

In the Minitab software, the best option was evaluated based on the increase of nutritional compounds and the decrease of condensed tannins. It was found that the fermentation at pH 6 with a carbon source (CS) of 75% (see Table 5) meets these requirements with a composite desirability index of 0.73.

To determine the sensory profile and the characteristic sensory notes of the product, panelists from Agricola Himalaya S.A., specializing in the collection of tea and aromatic infusions, were consulted. The results are presented in the Table 6.

The panelists identified sensory notes in the coffee pulp that align with the findings of other researchers. Amorocho & Cortes [82] noted herbal and sweet notes, as well as fruity aromas, in infusions made from dried and unfermented coffee pulp. Similarly, Prado [62] detected aromatic notes of raisins, while flavors of tamarind, red fruits, and coffee beans were also reported. These variations can be attributed to several factors, including the variety of coffee used. Additionally, Serna et al. [63] determined that the optimal conditions for extracting antioxidant compounds from a coffee pulp infusion were at a temperature of 90°C for 4.5 minutes, using 3.3 grams of dry coffee pulp immersed in 250 mL of drinking water.

4 Conclusiones

Physicochemical analysis of coffee pulp has revealed that this by-product possesses significant potential for use in various industries, thanks to its content of bioactive compounds with functional properties. Additionally, it was determined that coffee pulp provides ideal conditions for undergoing solid-state fermentation processes, thereby maximizing its valorization as a premium material.

The optimum conditions for the fermentation process were identified as pH 6, a carbon source concentration of 75%, a temperature of 32°C, and a fermentation time of 28 hours. These conditions favor the metabolic activity of the microorganism, resulting in a significant increase in the content of proteins and total phenols. This is accompanied by a notable reduction in condensed tannins, thus enhancing the nutritional value of the final product.

The solid-state fermentation (SSF) process with Rhizopus oryzae proved effective in transforming coffee pulp, achieving up to a 60% reduction in condensed tannin content. This reduction is attributed to the fungus's ability to alter the chemistry of the substrate, highlighting its potential in the production of functional foods.

The infusion obtained from fermented coffee pulp exhibited attractive sensory profiles, characterized by sweet and woody notes. These attributes, along with its improved nutritional profile, position this product as an innovative alternative in the functional food and beverage market. This underscores the value of coffee pulp as a by-product with high potential to be transformed into a fermentation-enriched functional food, thus contributing to reducing the environmental impact associated with coffee production and generating new economic opportunities for farmers by diversifying their product offerings.

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Free shipping in e-commerce: a systematic literature review

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Abstract
Free shipping in e-commerce has become a crucial strategy to attract and retain customers in a highly competitive markets, becoming a key advantage for companies seeking to meet evolving consumer demands. This study aims to perform a systematic review of the existing scientific literature on free shipping in e-commerce, following PRISMA guidelines and using the Scopus database to ensure an up-to-date perspective. The results show the critical role of free shipping in customer retention and acquisition, and to improve customer satisfaction, influence purchase and repurchase intention, and increase sales and market competitiveness. However, it was also observed that it can lead to an increase in returns.

Keywords: e-commerce; mobile commerce; electronic commerce; e-business; online retailer; shipping fee; free shipping; shipping policy; free shipping effect; free shipping strategies.

Envío gratuito en el comercio electrónico: una revisión sistemática de la literatura

Resumen
El envío gratuito en el comercio electrónico se ha convertido en una estrategia crucial para atraer y retener clientes en mercados altamente competitivos, convirtiéndose en una ventaja clave para las empresas que buscan satisfacer las demandas cambiantes de los consumidores. Este estudio tiene como objetivo realizar una revisión sistemática de la literatura científica existente sobre el envío gratuito en el comercio electrónico, siguiendo las directrices PRISMA y utilizando la base de datos Scopus para garantizar una perspectiva actualizada.
Los resultados muestran el papel fundamental del envío gratuito en la retención y adquisición de clientes, así como en la mejora de la satisfacción del cliente, la influencia en la intención de compra y recompra, y el aumento de las ventas y la competitividad en el mercado. Sin embargo, también se observó que puede conducir a un incremento en las devoluciones.

Palabras clave: comercio electrónico; comercio móvil; comercio electrónico; negocio en línea; minorista en línea; tarifa de envío; envío gratuito; política de envío; efecto del envío gratuito; estrategias de envío gratuito.

1 Introduction

The COVID-19 pandemic has accelerated the shift towards a heavier use of e-commerce and communication platforms. Today, more people are going online to work, study, shop, entertain themselves, and even visit the doctor [1].

E-commerce is vital to consumers, entrepreneurs and governments as it allows them access to a global marketplace and greater sales opportunities as users can buy products and services anytime, anywhere. As e-commerce becomes a bigger part of the economy, it contributes more to the total economic GDP of countries, which can drive their overall economic growth [2].

Free shipping is a strategy that has been extensively studied and researched to understand its impact both on consumer behavior [3] and on the profitability of companies [4]. It appears to be a fundamental strategy, given that it stands out as the most influential factor in purchase intention and repeat purchases [5],

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shaping the competitive landscape of e-commerce, as retailers that do not offer free shipping options risk being left behind in an increasingly competitive marketplace [6], directly impacting their performance and growth.

E-commerce companies must consider several key points when implementing a free shipping offer. One is to establish a minimum purchase threshold to qualify for free shipping, as well as offer a partial shipping rate for customers who do not reach that minimum amount [7]. Another factor to consider is the distance and location of customers, as the cost of offering free shipping may vary by region [8].

On the other hand, the disadvantages of free shipping in e-commerce for fashion retailers include the risk of increasing the number of returns by setting a minimum order value [9].

A strategy e-commerce can use to counteract the increase of returns in the free shipping environment, is to establish an integrated return shipping policy and a free return shipping policy, which are very effective in improving the relationship between buyers and sellers [10].

The present article details a systematic literature review on free shipping in e-commerce. The main objective is to analyze the trends and current state of knowledge on this topic. It also seeks to answer the following research questions:

- RQ1: What is the trend in publishing articles that address free shipping?
- RQ2: How does free shipping affect consumer behavior in e-commerce?
- RQ3: What is the impact of free shipping on e-commerce performance and growth?
- RQ4: What are the key strategic considerations for implementing a free shipping policy in e-commerce?
- RQ5 What are the disadvantages of a free shipping strategy in e-commerce and how can they be countered?

After this introduction, this article is organized as follows: Section 2 presents the materials and methods, showing the search equation, the Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA) methodology. Section 3 presents the results and discussions, where the research questions are answered. Finally, section 4 presents the conclusions and future research suggestions.

2 Materials and methods

To conduct a systematic literature review in the context of free shipping in e-commerce, we adopted the standard systematic review method according to the original guidelines proposed by [11]. This process includes several key steps: formulating specific research questions, conducting a thorough search process, applying inclusion and exclusion criteria, assessing the quality of selected studies, collecting and analyzing data, and documenting any deviations from the initial protocol.

This section describes the search equation and inclusion and exclusion criteria, and the methodology used to conduct the systematic review of the literature on free shipping in e-commerce.

The study was carried out using journals indexed in the Scopus database, since it provides an updated perspective to carry out a bibliographic review in different areas of study. The following is Table 1, which contains the keywords used to retrieve the largest number of articles related to the study topic.

Table 1.
Search equation keywords.

Keyword group 1	("e-commerce" OR "mobile commerce" OR "electronic commerce" OR "e-business" OR "Online Retailer")
Keyword group 2	("shipping fee" OR "free shipping" OR "shipping policy" OR "free shipping effect" OR "free shipping strategies")

Source: Authors' own work, 2024

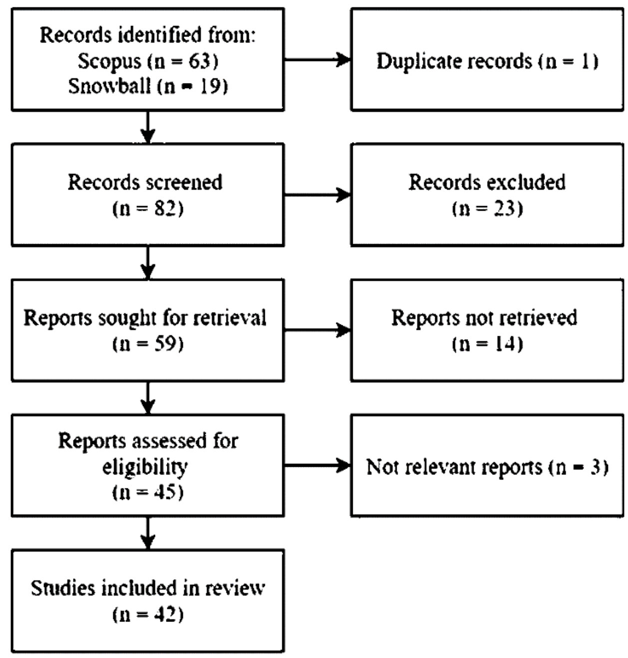

Figure 1. Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA), applied to a systematic review of the literature on free shipping in e-commerce
Source: Authors' own work, 2024.

Keyword group 1 seeks to bring together all the articles that deal with e-commerce, so five variants referring to this group were used. The purpose of Keyword group 2 is to gather the articles that study the strategy of free shipping in e-commerce.

The Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA) flowchart [12], illustrated in Fig. 1, was used to document the study selection process, ensuring transparency and rigor.

The selection and classification of articles were conducted by a single researcher, strictly following the predefined inclusion and exclusion criteria. To mitigate the risk of bias, the entire process was closely supervised by two additional researchers, ensuring adherence to methodological standards and maintaining oversight throughout the review. Furthermore, all authors actively participated in the discussion and interpretation of the results, contributing to the robustness and validity of the findings.

The following inclusion criteria were considered: (1) articles with final publication status, (2) articles in English, and (3) articles that provide information relevant to at least one of the five research questions of the topic.

Exclusion criteria include the following: (1) conference papers or papers under review, (2) articles that address companies without an online sales platform, and (3) articles that do not directly address the dynamics or impact of free shipping on e-commerce.

Sixty-three articles (63) were identified using the search equation in the Scopus database and considering the inclusion and exclusion criteria. The last search was performed in May 2024. After the title, abstract and key words were read, only 40 articles were found that met the inclusion criteria. However, it was not possible to access the complete version of 8 of these articles. After the complete reading of the remaining 32 articles, 1 duplicate article was identified and excluded, leaving 31 articles for analysis.

A similar process was carried out with the articles identified by the snowball method. Initially, 19 relevant studies were identified. Of these, 6 were excluded due to lack of access to the article. Another 2 were excluded because they were not relevant to the subject of the study. In the end, a total of 11 more articles were added to the final sample.

In total, 42 papers were included for a bibliometric and critical analysis of the topic. During the process of reading the 42 selected articles, the information was classified according to how relevant it was in answering the research questions.

3 Results and discussions

In this section, we address the research questions posed. To answer RQ1, the entire corpus of selected articles was analyzed. For RQ2 to RQ5 a more targeted approach was employed. Table 2 presents a comprehensive overview of the relevant articles, categorized according to each research question and the specific product type under investigation.

3.1 What is the trend in the publication of articles addressing free shipping?

Fig. 2 shows the number of documents published per year in relation to free delivery in e-commerce.

It is clear the number has increased compared to 2005. There was an atypical increase in 2012 and 2020. It should also be noted that the bar corresponding to 2024 corresponds to articles published between January and May 2024, the date on which the search was performed.

Table 2.
Type of product according to the five research questions.

Product	RQ2	RQ3	RQ4	RQ5
Dry, fresh and gourmet foods.	[13] [14]	[15]	[14,16]	
Personal and pharmaceutical products	[14]	[15]	[14]	[17,18]
Clothing	[19]	[20,21]	[16]	[9,17,18,19,22]
Electronics	[3]	[21] [23]	[24,25]	[10,17]
Generic	[5] [26] [27] [28] [29] [6]	[30,31] [32,33] [27,34] [4,6,35]	[7] [36] [37] [38] [33] [39] [8,28] [40] [41]	[27,42] [43] [44]

Source: Authors' own work, 2024

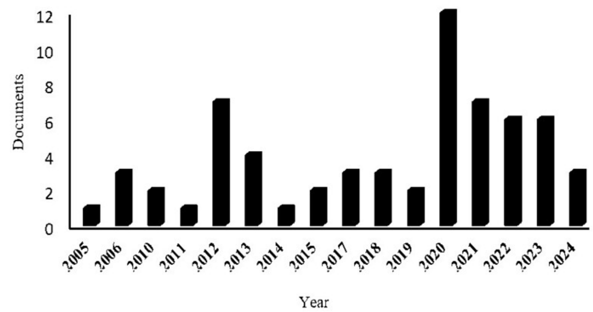

Figure 2. Number of documents published per year.
Source: Authors' own work, 2024.

The increase in publications in 2012 can be justified by the accelerated growth of e-commerce worldwide. Similarly, 2020 sees the highest growth due to the circumstances of the COVID-19 pandemic. With widespread shutdowns and social distancing measures in effect, consumers were forced to rely heavily on online shopping and businesses had to adapt quickly to meet changing demands [1].

Excluding 2012 and 2020, since they are outlier years, it can be clearly seen that there was sustained growth between 2005 and 2020. From 2021 onwards, the number of research articles on this topic has remained constant.

In conclusion, the publication trend reflects the growing importance of e-commerce and the impact of the COVID-19 pandemic on the industry. The increase in free shipping publications in e-commerce is a response to the changing needs of consumers and businesses.

3.2 How does free shipping affect consumer behavior in e-commerce?

Analysis of consumer behavior towards the offer of free shipping in e-commerce reveals a few significant trends and perceptions.

A study based on a sample of 21,905 Internet users who browsed several online store websites evidenced that 46% of customers are inclined to make repeat purchases because of the free shipping offer [5].

Therefore, it is important to consider that the absence of a free shipping offer may lead customers to abandon the purchase process [26]. Additionally, if shipping charges are high, they may discourage purchases or encourage larger orders to avoid such charges [6,29].

3.2.1 Consumer purchase decision

Free shipping can be implemented for different types of products. For example, [13] analyzed the interaction between product category (fresh and indulgent) and purchase factors (shipping costs and delivery time) through an experiment based on 240 surveys and its subsequent analysis of variance. The study concluded that free shipping and fast delivery increase consumer satisfaction and positively influence purchase intention.

Thus, satisfaction, purchase intention, and repurchase are based on consumers' preference for free shipping, as it is the strategy with the greatest impact [5,13,19], especially for lower-priced products [3]. Even for risky products, free shipping promotions can motivate consumers to make purchases [19].

This means customers tend to make repeat purchases when the seller offers free shipping. Consequently, implementing free shipping not only improves competitiveness, but also positively influences consumer behavior [26].

3.2.2 Perceived risk and customer experience

Another important aspect is the long delivery time, which generates a sense of risk in customers. This results in reduced satisfaction and negatively impacts purchase intentions. Online retailers could use free shipping strategies as an alternative to counteract extended delivery times [28], as this would lead buyers to experience a higher level of satisfaction [27].

Therefore, the positive perception towards free shipping impacts online behavior considerably, as consumers are attentive to the availability of the offer [5, 26]. Even showing free shipping by including the shipping cost in the product price potentially influences the purchase decision [25], as consumers are very sensitive to shipping charges [14].

3.3 What is the impact of free shipping on e-commerce performance and growth?

E-commerce can benefit greatly from the implementation of free shipping. The literature supports this benefit and growth in the number of sales from their platforms. For example, [4] indicates that there is only a 5.27% probability that implementing free shipping promotions will result in less than 5.07% of the expected profit, suggesting a high likelihood of success. This means the implementation of the free shipping strategy should be done effectively and adapted to the market dynamics to maximize profitability [31,32].

Another study confirms that prominently displaying the shipping offer drives purchases and increases the shopping cart value [21]. This strategy is especially effective, as free shipping generates a higher incidence of orders and is the most effective in terms of customer acquisition [15], increasing the proportion of those who visit and end up purchasing on the platform [27]. Therefore, those retailers that do not offer free shipping options will lose out in a competitive marketplace [6].

3.3.1 Coordination among market players

Considering the study discussed in [30], it is usually assumed that a retailer A which has accumulated extensive experience on the platform and has abundant sales information will be able to forecast demand more accurately. In contrast, retailer B is a newcomer with limited information about market demand. In the scenario where retailer B obtains information and both retailers offer free shipping, the author, through numerical analysis, concludes that the platform reaches its maximum profitability when both information exchange and free shipping are carried out simultaneously.

Retailers' free shipping policies impact not only their own profits, but also those of the supplier [31]. When there is coordination in the determination of the free shipping threshold with the delivery operator, it will generate higher profits [34].

In a domain analysis (retailer, supplier) in the platform-dominated model, it is observed that as the selling price decreases, the platform service level tends to decrease. The free shipping strategy can be a key component in maintaining a competitive service level [33].

Therefore, retailers must not only focus on their own costs and profit margins, but they must also strive to effectively manage lead times [45] to generate a positive impact on the profitability of the supplier, the retailer, and end customers [35]. Additionally, carefully determining base prices and shipping rates is crucial, as sometimes base prices of products tend to increase when free shipping is offered [15,23].

3.4 What are the key strategic considerations for implementing a free shipping policy in e-commerce?

The previous points have shown consumer behavior and the impact of free shipping in e-commerce, but this is not enough. One must also be aware of the strategic considerations and the different free shipping policies that online retailers can consider [41].

The distance from the company to the customer's point of location can be an important factor in considering whether to offer free shipping. A retailer with a relatively small local market size may benefit from moving online under a free shipping policy. Those retailers who offer goods or services to different regions, on the other hand, will see their prospective shipping cost affected according to the distance from one region to another [8].

Likewise, it is important to consider the timing when framing shipping promotions. For offers in the immediate future, emphasizing 'no shipping costs' is relatively more effective. Conversely, for promotions set in the more distant future, framing the offer as 'free shipping' tends to be more effective [38].

3.4.1 Pricing considerations for free shipping

Retailers with low prices should opt for a free shipping policy to outperform the competition and increase their profits, while those with high prices benefit more by adopting the calculated shipping policy, thus mitigating the impact of higher shipping rates [31]. Meanwhile, another study [16] mentions that the price of shipping service for a retailer should be carefully considered. In the case of selling fashion items, it is recommended to offer free shipping, while for commodities this practice is not advised. The literature also presents a mathematical model for pricing.

In addition, including the cost of shipping in the price of the product avoids variations in shipping costs. This is what many retailers are looking for to keep the price constant and not be affected by unpredictable changes in shipping costs. [24].

If two hypotheses are posed in which retailers using split pricing (product price and shipping price) and retailers using net pricing (shipping cost included in the product price) are compared, it is evident that net pricing captures the attention of certain consumer groups, even when it is more costly [25].

Furthermore, if an online retailer cannot offer fast shipping, then it may choose to offer free shipping. This involves including shipping charges in the price of the product to reduce perceived ambiguity, which can increase satisfaction and purchase intentions [28].

3.4.2 Collaboration in the supply chain

It is clear collaboration between all links in the supply chain is important and free shipping can be used by all of its components. That is to say, if carriers could offer discounted shipping rates to retailers that handle large quantities, this would motivate retailers to implement free shipping [36]. It would be the same for suppliers offering a free shipping policy to the e-retailer when the order quantity reaches a predefined quantity, motivating retailers to offer free shipping themselves [33,37].

Similarly, all rational retailers should place joint orders when their inventories are insufficient to meet demand or do not qualify for free shipping. These discounts could stimulate the final retailer to offer free shipping themselves [40].

3.4.3 Free shipping thresholds

Some companies offer free shipping, but in order for a customer to benefit from this offer, they must short a minimum threshold, meaning their purchase must meet a minimum amount. However, not all customers reach this threshold and may thus become discouraged during the purchase process. Therefore, establishing a partial shipping fee would be a viable alternative to avoid this situation. If the customer falls short of the minimum order threshold, a proportional discount would be applied based on the amount purchased, which could contribute to an approximate 9% increase in sales on the e-commerce platform [7].

Complementary item recommendations also play a crucial role in e-commerce strategies. When customers fall short of the minimum order threshold for free shipping, an effective recommendation system can encourage additional purchases to meet this requirement. This approach not only increases the order value but also reduces the likelihood of cart abandonment. By strategically suggesting relevant items, e-commerce platforms can simultaneously enhance customer satisfaction and boost sales, turning potential lost sales into successful transactions [46].

In a segment model where the company can categorize its customers into various segments and then set shipping rates, a free shipping promotion is predicted to increase order incidence by at least 10% for all customers, but by more than 35% for the most responsive segment [14].

3.5 What are the disadvantages of a free shipping strategy in e-commerce and how can they be countered?

So far, the reviewed and analyzed literature related to free shipping in e-commerce shows its implementation can be highly beneficial. However, every strategy has disadvantages or areas that need improvement.

3.5.1 Relationship between free shipping and returns in E-commerce

In the free shipping strategy, returns predominate in fashion categories. In addition, newsletters, paid search, catalogs, and free shipping substantially increase returns by as much as 18% [22].

It is noticeable that there is a relationship between consumer confidence and free shipping [18] and this effectively fuels the explosive growth of e-commerce, but it also hinders the improvement of logistics service quality, pushing the e-commerce market into a free shipping trap [43].

Free shipping promotions encourage consumers to purchase risky products, those whose quality is difficult for consumers to evaluate, leading to high return rates. This phenomenon, known as the free shipping effect, has a higher impact on online retailers that market risky products, such as clothing [19]. For example, for an online retailer specializing in urban and sports fashion, setting a minimum order value increases the number of returns [9].

3.5.2 Countering returns

The relationship between buyers and sellers gets damaged by returns, which is why an integrated return shipping policy, and a free return shipping policy can be established, both of which are very effective in improving the relationship between buyers and sellers. Online sellers should consider employing these approaches to improve their relationship marketing [10].

Offering free returns has a positive impact on customer purchase behavior, generating a significant increase in post-return purchases [17].

It should be noted that the implementation of free returns policies in e-commerce has a significant influence on conversion rates. Those retailers that bear the costs associated with returns manage to reduce both uncertainty and expense for consumers [27].

Thus, free return shipping is often the dominant strategy in comparison to no-cost returns [42], however, depending on various factors, retailers may choose to offer free returns or define a specific cost for returns [39].

4 Discussion and Conclusions

This systematic literature review provides a comprehensive and up-to-date analysis of free shipping in e-commerce, being the first published study to address this topic exclusively. It compiles existing literature from the Scopus database and follows PRISMA guidelines to ensure rigor and transparency in the selection and analysis of the reviewed studies.

RQ1: Significant growth in research on this topic has been observed since 2005, with a notable increase in 2020. This increase is mainly attributed to the COVID-19 pandemic, which boosted e-commerce due to the isolation policies implemented by the governments of several countries.

RQ2: Consumer behavior improves with free shipping, increasing satisfaction and purchase intent, showing that there is a strong preference for free shipping. This strategy encourages repeat purchases and decreases shopping cart abandonment, increasing the competitiveness of companies and mitigating the negative impact of long delivery times.

RQ3: Existing literature supports that free shipping in e-commerce has a positive impact on platform performance and growth by increasing sales, conversion rate and profitability, but requires careful cost and logistics management to maximize its effectiveness.

RQ4: To implement a free shipping policy in e-commerce, it is crucial to consider aspects such as customer distance, pricing strategy, collaboration with suppliers and the inclusion of partial shipping rates. These strategic actions can be decisive in maximizing sales and the competitiveness of platforms in the online market.

RQ5: While free shipping in e-commerce can attract more customers and drive sales, it can also lead to an increase in returns, especially in fashion categories. Implementing effective free returns policies can mitigate these challenges, improving customer satisfaction.

By addressing these aspects, this study serves as a reference for refining shipping strategies in e-commerce. The implementation of tailored free shipping policies aligned with business models and market conditions is recommended.

The practical implications of free shipping relate to its effects on business operations, logistics, and consumer behavior. While it increases sales and customer satisfaction, it also raises shipping and return costs, requiring businesses to optimize logistics, set purchase thresholds, and refine return policies. Consumers are more likely to complete purchases and prefer retailers offering free shipping, influencing market competition. However, in industries with high return rates, such as fashion, businesses must balance free shipping incentives with strategies to minimize financial losses.

Despite extensive research on free shipping in e-commerce, several gaps remain. There is limited exploration of how artificial intelligence and machine learning can optimize free shipping strategies to reduce operational costs without compromising customer satisfaction. Additionally, the environmental consequences of increased shipping frequency due to free shipping policies are not well understood, leaving uncertainty about their sustainability impact. Moreover, most existing studies focus on developed markets, with little insight into the challenges and effectiveness of free shipping strategies in regions with underdeveloped logistics and emerging e-commerce sectors.

In this context, future research should investigate AI-driven models for optimizing free shipping policies, emphasizing cost efficiency and consumer experience. Further studies on the environmental impact of free shipping and potential sustainable alternatives, such as carbon-neutral delivery solutions, are needed. Additionally, examining how free shipping strategies can be adapted to developing markets, considering logistical and economic constraints, would provide valuable insights into their global applicability and long-term feasibility.

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Optimization of enzymatic hydrolysis of corn starch to obtain glucose syrups by genetic algorithm

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Abstract
This work corresponds to the optimization of the operating variables of the enzymatic hydrolysis of corn starch to obtain glucose syrups using the genetic algorithm of Matlab (2020a). For this reason, the hydrolytic process is mathematically modeled by response surface methodology. Pareto chart indicated that saccharification variables exert the highest influence on starch conversion. This mathematical model is beneficial for a better understanding and operational control of hydrolysis at the industrial level. The optimization problem solution shows that a maximum dextrose equivalent of 98.13% can be reached if the hydrolysis is performed under optimal operating conditions, which were also confirmed experimentally. The results show that to achieve the highest yield, liquefaction should be carried out at a temperature of 92ºC, pH of 6.3, α-amylase dose of 1.5 mg enzyme/g starch and hydrolysis time of 1 hour; while saccharification should be conducted at a temperature of 57ºC, pH of 4.9, glucoamylase dose of 1.15 mg enzyme/g starch and hydrolysis time of 34 hours. The reversion phenomenon is detected when the hydrolysis time exceeds 35 hours, with a negative incidence on the dextrose equivalent.

Keywords: enzymatic hydrolysis; glucose syrups; amylases; genetic algorithm, dextrose equivalent.

Optimización de la hidrólisis enzimática del almidón de maíz para obtener siropes de glucosa mediante algoritmos genéticos

Resumen
Este trabajo corresponde a la optimización de las variables de operación de la hidrólisis enzimática de almidón de maíz para la obtención de jarabes de glucosa utilizando el algoritmo genético de Matlab (2020a). Para ello, el proceso de hidrólisis se modeló matemáticamente mediante la metodología de superficie de respuesta. El diagrama de Pareto indicó que las variables de sacarificación ejercen la mayor influencia en la conversión del almidón. Este modelo matemático es de gran utilidad para una mejor comprensión y control operacional de la hidrólisis a nivel industrial. La solución del problema de optimización muestra que puede alcanzarse un equivalente máximo de dextrosa del 98,13% si la hidrólisis se realiza en las condiciones operacionales óptimas, las cuales se comprobaron experimentalmente. Los resultados muestran que, para alcanzar el mayor rendimiento, la licuefacción debe llevarse a cabo a una temperatura de 92ºC, pH de 6,3, dosis de α-amilasa de 1,5 mg de enzima/g de almidón y tiempo de hidrólisis de 1 hora; mientras que la sacarificación debe realizarse a una temperatura de 57ºC, pH de 4,9, dosis de glucoamilasa de 1,15 mg de enzima/g de almidón y tiempo de hidrólisis de 34 horas. El fenómeno de reversión se detectó cuando el tiempo de hidrólisis superó las 35 horas, con una incidencia negativa sobre el equivalente en dextrosa.

Palabras clave: hidrólisis enzimática; jarabes de glucosa; amilasas; algoritmo genético, equivalente de dextrosa.

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1 Introduction

The global production of glucose syrups has increased considerably in recent years. Industrial production of glucose syrups is based on starch hydrolysis, which can be performed by either acid or enzymatic catalysis or by a combination of both methods [1-3]. The use of enzymes allows selective hydrolysis under mild conditions, which minimizes sugar degradation and leads to dextrose equivalents above 95% [4]. Furthermore, the production cost is reduced by 30%, ashes by 50%, and secondary products by 90% through the first stage of conversion of enzymatic hydrolysis [5].

The enzymatic hydrolysis consists of three main stages: gelatinization, liquefaction, and saccharification [6]. This stage is of great importance because, starch is insoluble in water, and solubilized starch is more susceptible to attack by amylases [7-8].

During liquefaction, which begins once the substrate is solubilized, the starch chains are partially cleaved by the action of the enzyme α-amylase resulting in the formation of dextrins [9], and a decrease in viscosity due to this partial hydrolysis [7]. After that, the mixture is cooled and submitted to the saccharification process [9], where the dextrins are converted to glucose by the action of glucoamylase [7] until reaching the desired dextrose equivalent.

The control of the enzymatic hydrolysis process is extremely complex, and its efficiency depends directly on the degree of conversion of starch to glucose. Enzymes are catalysts that require particular working conditions to develop their maximum catalytic activity. They are highly sensitive, and minimal changes in the work environment can lead to their inactivation, which is often irreversible (denaturation) depending on the specific pH and temperature values.

In turn, the process of enzymatic hydrolysis of starch to obtain glucose may be affected by the reversion phenomenon. Reversion is an adverse phenomenon consisting of the regrouping of glucose molecules, which has serious consequences for the process yield. This occurs at high concentrations of glucose that occur at a determined hydrolysis time [10]. Inhibitory effects can also appear during hydrolytic processes due to the presence of high concentrations of starch or glucose, which consequently decreases the catalytic activity [6].

Hence the importance of determining the values of the operational parameters that allow the maximum hydrolysis yield and a more efficient use of enzymes, which are expensive industrial materials.

This work is aimed at determining the optimal parameters of the hydrolytic process. For this purpose, mathematical modeling of the hydrolysis is necessary, which is performed by using a statistical design of experiments by response surface. Surface response methodology has proven to be a powerful tool in research related to the enhancement of properties and processes related to enzymatic hydrolysis, as evidenced by multiple studies [11]. The optimization problem is solved using genetic algorithms. This attractive mathematical method is very useful for the determination of global optimum in complex mathematical models, showing very good results compared to traditional methods [12]. This research provides new experimental evidence that allows a better understanding of this hydrolysis. The results obtained support the control and making of operational decisions in the industrial process.

2 Materials and methods

2.1 Materials

Labiofam (Cienfuegos, Cuba). Enzyme preparations Bialfa-T (α-amylase from Bacillus licheniformis) and Glucozyme (glucoamylase from Aspergillus niger), both produced by Biocon (Barcelona, Spain) were used. All other chemical were analytical grade.

2.2 Enzyme characterization

2.2.1 Enzyme activity assay

Enzyme activity was determined according to Miller method [13], which is based on the quantification of reducing sugars. Potato soluble starch was used as substrate (1% w/v) in 20 mM sodium acetate buffer (pH 6.5 for α-amylase, and pH 4.5 for glucoamylase). The reaction mixture containing 0.5 mL of substrate solution and 0.5 mL of enzyme (diluted) was incubated for 10 min at 40oC for α-amylase, and at 60oC for glucoamylase. The reaction was terminated by adding 1 ml of 3,5-dinitrosalycyclic acid solution (DNS) and then was heated at 100oC for 10 min. Finally, the mixture was cooled to ambient temperature, 1.2 mL water was added, and the absorbance was measured at 546 nm using spectrophotometer (UV1800, Shanghai, China). One unit (UI) of enzyme activity is defined as the amount of enzyme that catalyzes the production of 1 μmol of reducing sugar (glucose) per minute under the specified assay conditions.

2.2.2 Determination of protein content

Protein content in the enzyme preparation was determined by Folin-Lowry method [14] using bovine serum albumin as standard in the range of 0.1–1 mg/mL, such as Akhtar, A. et al. [15] and Nakov, G. et al. [16].

2.2.3 Effects of temperature and pH on enzyme activity

The effect of temperature on enzyme activity was determined in the range of 40-95^{o}C at pH 6.5 for α-amylase, and between 40^{o}C and 85^{o}C at pH 4.5 for glucoamylase. The effect of pH was investigated in the range of pH 2.5 – pH 11 at 40°C for α-amylase and between pH 2.5 and pH 8.5 at 60°C for glucoamylase. The buffers used were 0.1 M acetic acid-sodium acetate (pH 2.5-6.5), 0.1 M $NaHPO_4$ -NaH_2PO_4 (pH 7-8.5) and 0.1 M NaH_2PO_4 - NaOH (pH 9-11). The activity was expressed as relative activity (%) based on maximal activity.

2.3 Experimental modeling of corn starch hydrolysis by response surface

The mathematical model that describes the corn starch hydrolysis was obtained by response surface methodology (RSM) through statistical design of experiments. The operational variables considered in the modeling as experimental factors were pH, temperature, time, and enzyme dosage for each hydrolysis stage. Those variables were selected based on the significant influence that they exerted on starch conversion to glucose. In addition, they were analyzed in a range that covers the normal values that used in the industrial process.

For the liquefaction stage, the pH from 5.5 to 7.5, temperature from 70 to 95ºC, enzyme dosage from 0.5 to 1.5 mg enzyme/g starch, and hydrolysis time from 1 to 2 hours were analyzed. In turn, for the saccharification stage, the pH from 4 to 6, temperature from 50 to 70ºC, enzyme dosage from 0.5 to 1.5 mg enzyme/g starch and hydrolysis time from 24 to 48 hours were studied.

The dextrose equivalent (DE) was used as a response variable because it is directly dependent on glucose production, and it is the main quality parameter of syrup. DE is a measure of the reducing sugars contained in a product, and it is expressed as percentage on a dry substance.

The parameters of the gelatinization stage (time and temperature) were held constant, and, therefore, were not considered as experimental factors in the mathematical model. They were set to values ensuring the complete solubility of the substrate in order to ensure an appropriate enzymatic degradation. The gelatinization was performed at 100ºC for 7 minutes, according to the values used in the industry. Higher values than those would not completely solubilize the very concentrated (35% (w/v)) starch suspension, and they would cause irreversible enzyme denaturation.

A central composite design with star points (2 ^ 8-2 + star) was performed using the software Statgraphics Centurion XVI (version 16.2.04). The design was of fractional type due to the high number of experimental factors. Design of experiments was face centered with an axial distance of 1. Five replicas were incorporated in the center to the design of experiments, according to what was established by Montgomery, D. C. [17] for a better quality of model. Center runs provided a means for estimating the experimental errors and a measure of lack of fit. Statistical design composed to 85 experimental runs and 40 error degrees of freedom was obtained. This design is sufficient to fit a quadratic model as shown in Eq. (1), containing square terms and linear terms. The model does not include the interactions among the factors experimental that this design is fractioned.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 \quad (1)$$

Where:

Y: response variable

βo, βi, βii: Regression coefficients for intercept, linear and quadratic terms, respectively

Xi: Independent variables

k: Number of experimental factors

2.4 *Enzymatic hydrolysis*

A 500 mL corn starch suspension (35 % w/v) was used as a substrate in reactor of 1 L of capacity. A 5% (w/v) calcium chloride solution was added until achieving a concentration of 50 ppm in substrate. The pH was adjusted to the work values by adding 0.1 M Na_2CO_3 or 0.1 M HCl, which are typically used for pH adjustment in industrial-scale operations. After conditioning the substrate suspension, α-amylase was added, and the gelatinization was developed by placing the flask with the reaction mixture in a heating bath at 100°C for 7 minutes with constant manual stirring. Starch solubilization was monitored by the iodine qualitative procedure established by Corn Refiners Association [18].

The liquefaction was carried out in a heating bath to operational conditions established in the design of experiments. Subsequently, the hydrolyzate was cooled to room temperature, and the pH was adjusted to the required value for the saccharification. Glucoamylase was added and the reaction mixture was incubated with shaking at 43 rpm (DW-90, Shanghai, China) and the required temperature and time.

The dextrose equivalent was calculated as:

$$\mathrm{DE} = \frac{\text{Amount of reducing sugar expressed as glucose (mg)}}{\text{Amount of starch (mg)}} \cdot 100\ \% \quad (2)$$

The amount of reducing sugars was determined by the DNS method, such as Miafo, A.-P. T. et al. [19].

2.5 *Statistical analysis*

Analysis of the statistical design of experiments by response surface was performed in Statgraphics Centurion XVI software (version 16.2.04). The analysis of significance of the experimental factors and their interactions was determined through Pareto charts of standardized effects [20]. Goodness of fit to the mathematical model was determined by Fisher's test and the relationship between the observed and predicted value of the response variable.

According to Montgomery, D. et al. [21], for a linear regression model to be valid, the mathematical assumptions made when applying this modeling technique must be checked. The assumption of normal distribution of residuals was verified by the Shapiro-Wilk test, the homoscedasticity assumption of the residuals by the Breusch-Pagan test and the independence assumption of the residuals by the Durbin-Watson test [22]. These tests were performed in RStudio (versión 1.3.959) software.

2.6 *Optimization*

The maximum dextrose equivalent value is determined using the genetic algorithm method in Matlab (2020a). For the solution of the optimization problem, the following setting parameters are used in the genetic algorithm: 100 generations, a reproduction factor of 0.8, an initial population of 20, and an error of 1e-6 as stopping criterion [23].

The optimization results were validated with two replicates by experiments and compared in terms of relative error (eq. 3). The maximum admissible variation was 5%.

$$\text{Relative error} = \frac{|\text{DE}_1 - \text{DE}_2|}{\text{DE}_1} \cdot 100\ \% \qquad (3)$$

Where:
DE_1: Experimental dextrose equivalent (%)
DE_2: Dextrose equivalent determined with mathematical model (%)

3 Results and discussion

3.1 Enzyme characterization

The enzyme activity of the α-amylase preparation was 32 270 U/mL and its protein concentration was 38.6 mg/mL. The specific enzymatic activity of 836 U/mg protein. The activity of the glucoamylase preparation was 21 678 U/mL, the protein concentration was 100 mg/mL, and the specific activity was 216 U/mg.

The α-amylase activity was above 90% in range between 70 and 95ºC, and the highest value was observed at 90ºC (100 %) (Fig. 1-A). This indicates that the enzyme preparation can be used for hydrolysis at high temperature values. On the other hand, the enzyme activity was above 80% at pH values between 5 and 8, with a maximum of catalytic activity observed at 7 (Fig. 1-B).

Numerous studies report different types of α-amylase of industrial interest with similar characteristics. In this regard, Hobbs, L. [1], Olsen, H. [24], and Balakrishnan, D. et al. [25] refer α-amylases from Bacillus licheniformis with high activity at temperatures between 80 and 110ºC, and more specifically between 90 and 105ºC. Similarly, Olsen, H. [24], Balakrishnan, D. et al. [25] and Wong, D. [26] mention examples of enzymes of this type with maximum activity to pH between 5-7 from Bacillus licheniformis.

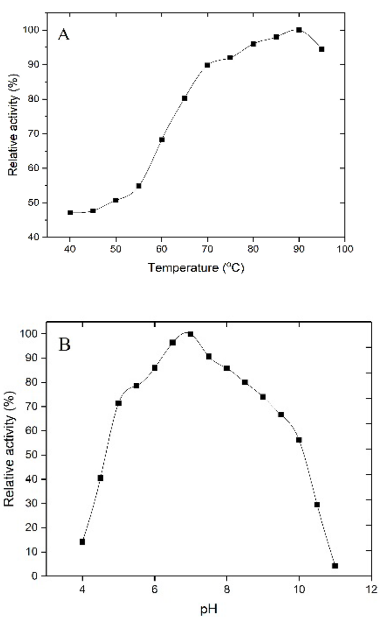

Figure 1. Enzyme activity of α-amylase at different values of temperature (A) and pH (B)
Source: The authors.

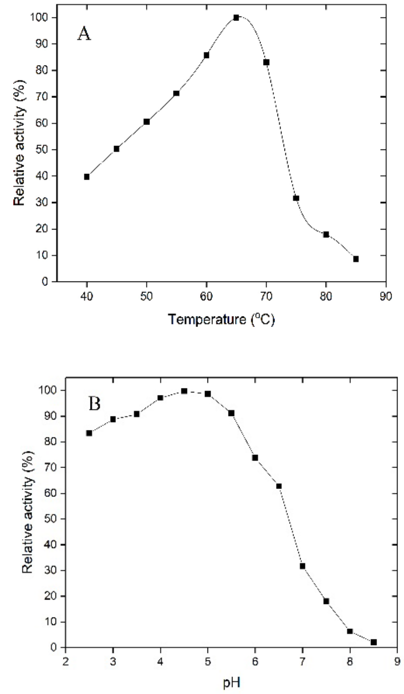

Figure 2. Effect of temperature (A) and pH (B) on glucoamylase activity
Source: The authors.

Glucoamylase has more than 90% of its activity at pH between 3.5 and 5.5 at 60ºC, with a maximum value at 4.5 (100%) (Fig. 2-B). In the case of temperature, this enzyme has more than 90% catalytic activity at values between 60 and 70°C at a pH of 4.5 (Fig. 2-A). The maximum enzymatic activity is verified at 65ºC (100%).

This trend is in correspondence with that stated by Friedl, A. [9], Helstad, S. [3] and Hobbs, L. [1]. They refer as typical to glucoamylase of industrial interest that presents the highest activity at pH values that are between 3.5 and 6.5 and temperature between 55 and 70ºC.

The above-discussed results show that both enzyme preparations are appropriate for investigating starch hydrolysis under conditions typical for industrial processes. In addition, these results allow to identify the specific work values of pH and temperature to be used as independent factors in the experimental design.

3.2 Enzymatic hydrolysis

The statistical significance of the experimental factors and their quadratic effects on the response variable (dextrose equivalent) was analyzed by means Pareto chart of standardized effects (Fig. 3). Pareto chart illustrates an analysis of variance, where the most influential variables have a probability value less than 0.05 for a 95% confidence interval. The interactions between the experimental factors are not considered because of the fractional nature of the experiment design.

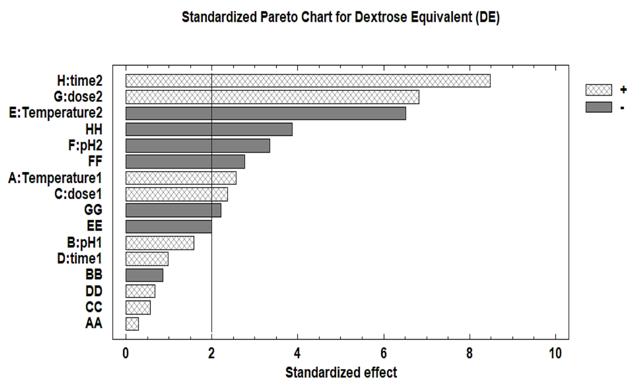

Figure 3. Pareto chart of standardized effects for dextrose equivalent (1-liquefaction 2-saccharification)
Source: The authors.

The saccharification time and the glucoamylase dosage exert the strongest influence on dextrose equivalent, and they have a directly proportional effect, which means that an increase in its value causes an increase in response.

It is known that glucoamylase only removes glucose molecules from the non-reducing end of dextrin chains obtained of liquefaction [7]. Since the liquefaction also leads to some limit dextrins, which are not fully hydrolyzable by α-amylase due to the presence of α-1,6-glycosidic branching bonds [27], and that slows down saccharification. Therefore, reaction times longer than 12 hours are required to obtain a high dextrose equivalent, and sometimes saccharification can last up to 72 hours [4,28].

The pH of saccharification has a negative influence because at the upper limit of the study a lower enzymatic activity is verified with respect to the central value. This result is corroborated with by behavior of Fig. 2-B. Liquefaction temperature and α-amylase dose have a statistically significant impact on the dextrose equivalent, although not in the same magnitude as the variables of the saccharification stage. Conversion in the liquefaction progresses to a critical point, which reduces the influence on the response of this variable in relation to those of the second stage. In addition, α-amylase requires at least three glucose units in the substrate [29].

The experimental results were used for developing a mathematical model describing the influence of the operational conditions on the response variable (Eq. 4). The experimental factors that did not exert significant influence on the response were excluded from the model. This consideration allowed obtaining a less complex mathematical expression, with a similar description level and better goodness of fit of the statistical model.

$$\begin{aligned}\mathbf{DE}\,(\%) = {} & -\mathbf{321.604} + \mathbf{0.0107}\cdot\mathbf{T_1} + \mathbf{2.47}\cdot\mathbf{D_1} \\ & + \mathbf{5.845}\cdot\mathbf{T_2} + \mathbf{71.252}\cdot\mathbf{pH_2} \\ & + \mathbf{53.113}\cdot\mathbf{D_2} + \mathbf{2.17}\cdot\mathbf{t_2} \\ & - \mathbf{0.0515}\cdot\mathbf{T_2}^2 - \mathbf{7.3}\cdot\mathbf{pH_2}^2 - \mathbf{23} \\ & \cdot\mathbf{D_2}^2 - \mathbf{0.032}\cdot\mathbf{t_2}^2\end{aligned} \tag{4}$$

Were:
T_1: Temperature of liquefaction (°C)
D_1: Dose of α-amylase (mg enzyme/ g starch)
T_2: Temperature of saccharification (°C)
pH_2:pH of saccharification
D_1: Dose of glucoamylase (mg enzyme/ g starch)

3.3 Analysis of the goodness-of-fit of the mathematical model and the residuals of the mathematical model

When analyzing the variation between the observed and predicted values of the response variable, only 27.06% of the experiments are not in the estimation range established by the software for 95% confidence. The model correctly explains the experimental values of dextrose equivalent because only 5.88% of predicted values have a relative error higher than 10%.

Fisher's test (F test) shows that there is a statistically significant relationship between the variables at a 99% confidence level since the P-value of the multiple regression analysis is less than 0.01. This confirms that the mathematical model has an adequate goodness of fit.

Table 1 shows the results of the validation tests of the linear regression assumptions. The P-value of the Shapiro-Wilk test is higher than the significance level (P-value>0.05), which shows that the residuals have a normal distribution [30]. The residual homoscedasticity is corroborated since the P-value of the Breush-Pagan test is higher than the significance level (p-value>0.05) [31]. As the P-value of the Durbin-Watson test (0.156) is above the significance level (p-value>0.05), there is no evidence of autocorrelation in the residuals [32]. The residual independence is a very important aspect to evaluate the quality of the experimental hydrolysis since it indicates that all variables affecting the response were controlled in the experiments [22].

3.4 Sensitivity of mathematical model and optimization

This analysis is carried out to evaluate the sensitivity of the response according to the variation of the experimental factors within the limits of the study. The analysis of sensibility is only carried out with the experimental variables of the saccharification, because they exert the strongest influence on the response. In addition, the terms of surface of the mathematical model correspond to the quadratic effects of variables of the saccharification stage (they represent a surface different to plane). Fig. 4 shows the relationship between either the saccharification time or the glucoamylase dosage and dextrose equivalent.

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Table 1.
Results of the validation tests of the linear regression assumptions (95% confidence)

P-value Shapiro-Wilk test	P-value Breush-Pagan test	P-value Durbin-Watson test
0.084	0.147	0.156

Source: The authors.

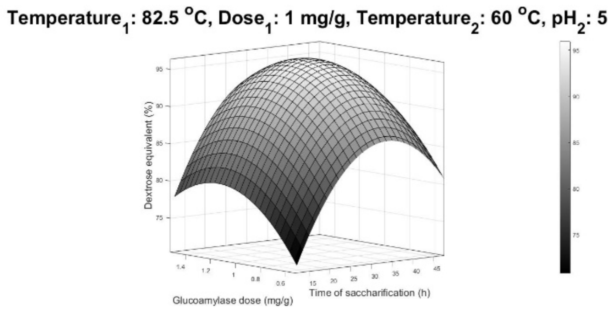

Figure 4. Effect of saccharification time and dose of glucoamylase on dextrose equivalent.
Source: The authors.

the mathematical model correspond to the quadratic effects of variables of the saccharification stage (they represent a surface different to plane). Fig. 4 shows the relationship between either the saccharification time or the glucoamylase dosage and dextrose equivalent.

There is a region of maximum equivalent dextrose for a saccharification time between 28 and 39 hours, at a glucoamylase dose of 0.95 to 1.35 mg of enzyme/g of hydrolyzed starch. While the hydrolysis time elapses at dose constant, the hydrolytic conversion increases with the increase of the reaction time, then it reaches a maximum value, and after that a gradual decrease is observed (Fig. 5). That decrease can be attributed to reversion phenomena leading to glucoamylase-catalyzed recombination of the hydrolysis products with formation of maltose and isomaltose [24,29,33]. Reversion is a totally undesirable phenomenon in the industry, because it causes a considerable decrease in the dextrose equivalent. Therefore, in order to avoid reversion, glucoamylase should be inactivated immediately after reaching the desired dextrose equivalent [24].

As revealed from the experimental results, after 35 hours of saccharification the reversion begins to be significant. Consequently, in an industrial process, constant and rigorous monitoring of dextrose equivalent should be implemented in order to identify the time point giving the maximum glucose release, and thus minimize further losses due to re-association.

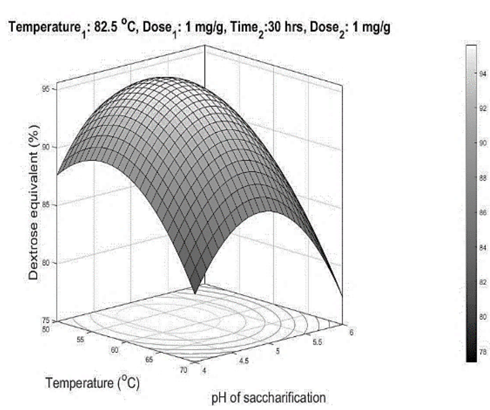

Figure 5. Dependence of dextrose equivalent on pH and saccharification temperature.

Source: The authors.

Table 2.
Results of optimization

Experimental factor Factor	Value
Temperature of liquefaction [ºC]	92.4
pH of liquefaction	6.3
Dose of α-amylase [mg enzyme/g starch]	1.5
Time of liquefaction [h]	1.0
Temperature of saccharification [ºC]	56.8
pH of saccharification	4.88
Dose of glucoamylase [mg enzyme/g starch]	1.15
Time of saccharification [h]	34.4

Source: The authors.

The graph shows a region of maximum dextrose equivalent at pH values between 4.4 and 5.5. This behavior coincides with that described in obtained in the characterization of the glucoamylase enzyme (Fig. 2-B).

With the increase in saccharification temperature, hydrolysis is favored until reaching a maximum glucose production between 51 and 62ºC. From that point on, the conversion begins to decrease, which can be attributed to reduction of catalytic activity of the enzyme due to denaturation [34].

The values of the operating variables that maximize the dextrose equivalent were determined by optimizing the response surface model by genetic algorithm in Matlab (2020a). The results show that a maximum dextrose equivalent value of 98.13% can be achieved under the conditions indicated in Table 2.

The liquefaction temperature predicted by the model is in agreement with the values typically used in industrial hydrolysis of starch. According to different authors, the liquefaction temperature should be around 90ºC [7], between 80 and 90ºC [9], at 95ºC [24] or between 90 and 100ºC [33]. The time value of the first stage of hydrolysis is between 1 and 2 hours, interval in which it is normally verified in industrial process too [35-36]. The liquefaction pH predicted by the model is also consistent with the usual values of the industrial process [1,24,37].

The saccharification temperature also coincides with the values cited by BeMiller, J. N. [2], Fernandes, P. y Carvalho, F. [4], Olsen, H. [24] and Friedl, A. [9], which are between 55 and 60 ºC. The pH of second stage corresponds to values at which saccharification is developed in industrial hydrolysis, according to: Hobbs, L. [1], Van der Maarel, M. [35], Fernandes, P. y Carvalho, F. [4], Olsen, H. [24] and Zhu, D. et al. [28]. Similarly, saccharification time is consistent with that mentioned by Hobbs, L. [1] and Zhu, D. et al. [28].

The results shown in Table 2 are very important to be in correspondence with the values normally referred to for this process, because this also constitutes (although indirectly) a criterion to validate the response surface model obtained. The optimal dextrose equivalent for the conditions shown in Table 2 is verified by means of an experiment with two replicates. Correct prediction model for these conditions is verified since the values of the dextrose equivalent observed and predicted differ by less than 5%.

The results presented in Table 2 indicate a significant economic advantage, by reducing production costs related to the consumption of enzymes, energy, water, and other substances needed for pH adjustment. The optimal enzyme dosage for each hydrolytic stage is crucial, considering the high costs of these industrial inputs.

In fact, one of the major challenges in the industrial process of enzymatic hydrolysis of corn starch is the expense associated with the enzymes used. The largest market for industrial enzymes is in the food and beverage manufacturing sector, which accounts for 26% of the global market [39]. This is mainly led by two strong producers *Novozymes* y *Dupont Enzymes* [7]. The report presented by Freedonia Group, states that the global demand for enzymes in 2021 would be at 5 trillion dollars with an annual growth of 4%. According to the Global Market Insights, by 2024, the enzyme trade of interest in the food industry would amount to 3.6 trillion dollars [39]. Therefore, making a more rational use of the enzymes used in starch hydrolysis is essential, considering that they represent about 30% of the world's production of industrial enzymes [40].

Higher amounts of enzyme do not necessarily lead to higher starch conversion. When low amounts of enzyme are used, its concentration is directly proportional to the reaction rate because the substrate is in abundance [35]. In contrast, as the dosage increases, the relationship with the reaction rate stops behaving linearly and starts to exhibit an asymptotic trend because the amount of substrate is a limiting factor. This behavior has a great economic impact on the industrial hydrolytic process, since an increase in enzyme dose does not necessarily lead to higher starch conversion.

The optimum temperature of the hydrolysis stages has a significant impact on the economics of the process, either because of its influence on enzyme activity and starch conversion (expensive raw materials) or because of the costs associated with the generation of steam used as a heating agent in the reactors. An increase in a few degrees of hydrolysis temperature implies high energy consumption and consequently, an increase in the operational cost according to: i) the large production volumes and ii) the concentration of dissolved solids (brix) of the hydrolysates. The brix of the hydrolysates influences the heat capacity and therefore the energy demand needed to increase the temperature. The temperature difference between liquefaction and saccharification influences the cooling water consumption in the intermediate heat transfer equipment involved in temperature regulation.

Synergistically, longer hydrolysis times lead to higher expenses incurred in maintaining temperature conditions in isothermal reactors, as well as higher power consumption in auxiliary agitation and circulation systems. This effect is of greater importance in saccharification, whose operation times can be up to 72 h [29,37]. Hence the significance of controlling this variable toward optimal values, in addition to its influence on phenomena previously addressed such as reversion.

Adjusting the pH to the optimum level affects the consumption of sodium carbonate and hydrochloric acid. This, in turn, impacts the costs associated with purchasing pH adjustment agents, as well as the expenses related to preparation, application, waste treatment operations, and ultimately the quality of the glucose syrup produced. Improved consumption of these inputs leads to decreased corrosion issues, a reduction in the formation of secondary compounds (some of which are colored) [36], and less salt production due to neutralization [41]. Some of the secondary compounds that can be generated during hydrolysis by acidifying agents include 5-hydroxymethylfurfural, levulinic acid, and derivatives of formic acid.

4 Conclusions

The mathematical model of hydrolysis obtained through response surface methodology presented an excellent goodness to fit according to Fisher test. The mathematical model showed that glucose production is more affected by the saccharification stage than by the liquefaction stage, and that saccharification time, temperature, and glucoamylase dose are the variables that exert the greatest effects on starch hydrolysis. The use of the mathematical model obtained can also be very useful for better operational control of the industrial process. The values of the operational variables that allow reaching a maximum dextrose equivalent (98.13%) were established by genetic algorithm in Matlab (2020a). Reversion affects remarkably the glucose yield, and that is evident above 35 hours of saccharification.

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Participatory monitoring for water management: a bibliometric analysis

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Abstract
Communities play a central role in participatory water monitoring by contributing their local knowledge, engaging in data collection, and participating in decision-making related to the management and implementation of solutions. A systematic review was carried out in four phases under the PRISMA methodology. In phase 1, the study topic was defined. Phase 2 involved defining guiding questions and searching databases such as Scopus, Scielo, and Google Scholar. In phase 3, eligibility criteria and the search equation were established. Finally, in phase 4, review articles were selected, and the information was processed using VOSviewer software, followed by qualitative and quantitative analyses. Finally, it was determined that the studies conducted by various authors do not present participatory monitoring methodologies that are easy and affordable to apply in all community contexts. Each context must be analyzed individually. Additionally, most studies indicate that parameter measurements are not conducted in situ, highlighting a research gap in the application of participatory monitoring.

Keywords: participatory-community monitoring; water; water quality; community

Monitoreo participativo para la gestión del agua: un análisis bibliométrico

Resumen
Las comunidades desempeñan un papel central en el monitoreo participativo del agua aportando su conocimiento local, comprometiéndose en la recopilación de datos e involucrándose en la toma de decisiones relacionadas con la gestión e implementación de soluciones. Se realizó una revisión sistemática a través de 4 fases bajo la metodología PRISMA, en la fase 1 se definió el tema de estudio, en la fase 2 la definición de preguntas orientadoras y la búsqueda en bases de datos como Scopus, Scielo y Google Scholar, la fase 3 definición de los criterios de elegibilidad y la ecuación de búsqueda, por último, en la fase 4, se realizó la selección de los artículos de revisión y el procesamiento de la información a través del software VOSviewer y los respectivos análisis cualitativos y cuantitativos. Finalmente, se definieron aquellos estudios realizados por los diferentes autores que no presentan metodologías de monitoreo participativo fáciles y asequibles de aplicar en todos los contextos comunitarios, cada contexto debe ser analizado de manera diferente, adicional, la mayoría de los estudios muestran que la medición de parámetros no se realizan in situ, lo que se puede considerar como vacío investigativo al aplicar monitoreo participativo.

Palabras clave: monitoreo participativo-comunitario; agua; calidad del agua; comunidad.

1 Introduction

Ecosystem services (ESS) are those benefits provided by ecosystems to the population [1]. Among these, there are provision services, where water supply is outlined according to the Millennium Ecosystem Assessment. This assessment emphasizes water's fundamental role in the well-being of all living beings and its importance in the sustainable

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development and management of territories.

Water is a renewable resource; however, it is also finite, with both natural and anthropogenic uses [2]. Efficient management of water in the context of sustainability involves balancing economic interests derived from water uses with the sustainable administration of the resource [3], protecting quality and promoting responsible use practices. Implementing adequate strategies in terms of water governance promotes the conservation, reuse, and protection of watersheds. This ensures fair distribution in terms of water uses, benefiting all community members [4].

Currently, the use of Participatory Monitoring (PM), an approach that involves community collaboration in data collection and problem identification, is being promoted. This method varies in the level of engagement, ranging from supporting scientific research to a full commitment to problem-solving and adjusting monitoring strategies based on available needs and resources [1]. In this way, it can be defined that participatory monitoring contributes to the formation of links between society and academia for the understanding of various socio-ecological problems [5].

Around the world, various experiences have been evidenced as a result of scientific and social collaboration applied to the MP of water resources in countries such as Canada [6], Colombia [7], Mexico [1,8] Kenya [9] and, Switzerland [10], the importance of the role played by entities, such as Global Water Watch, in providing conceptual and methodological support to establish and certify community monitoring networks in nations such as Argentina, Brazil, Ecuador, Mexico and Peru is emphasized. It has also influenced this process in the Philippines, Thailand and Kenya [11].

It is crucial to define the problem before starting monitoring, as this allows us to understand conflicts in the basin and water use, such as territorial disputes or access difficulties. Identifying these problems is essential to establish the parameters and monitoring points necessary to develop an effective program. This can be achieved with the help of actors and experts from the area of influence, including them as leaders of the process [12]. Likewise, according to this same source, citing Walker et- al [13], water management actors must understand its complexity from the initial interest in its conservation to the implementation of collaborative projects. This involves the contribution of experts in the field, utilizing technology for the dissemination of updated information, and engaging the community through mobile applications, social networks, and community radio stations. These efforts are crucial to ensuring the success of water resource monitoring and management projects.

This article reviews studies published from 2014 to 2023 related to community-participatory water monitoring. It explores research trends and identifies knowledge gaps through networking using VOSviewer software, which helps analyze the behavior and correlations within the literature on this topic. This analysis will enable the academic and scientific community to identify primary publications and topics associated with the study focus. It will also pinpoint research gaps to be explored, highlight authors and research institutions addressing these issues, identify countries showing significant interest, and assess cooperation among researchers.

2 Methodology

The systematic review was conducted following the PRISMA methodology guidelines. Initially, a keyword search was performed to formulate the search equation. The processing of information followed the sequence outlined in Fig. 1, illustrating the procedure for analyzing the research processes that have been consolidated for the study of community-participatory water monitoring processes. The procedure is based on four main phases. First, the research topic was defined, and the search began with keywords. This was followed by a clear definition of the problem, which was consolidated into research guiding questions. Next, the search equation was defined, and finally, the process and analysis of the information were carried out.

The review had the following research questions:

Are there studies that implement clear and easy-to-execute monitoring methodologies in communities?

Are communities really involved in the implementation of community monitoring?

Are the parameters taken in situ during the monitoring?

In this article, a systematic review of the published scientific literature in relation to community-participatory water monitoring has been carried out. For its preparation, the guidelines of the PRISMA statement have been taken into account [14] for the correct conduct of the systematic review. Fig. 2 details the process of developing the methodology in its different phases.

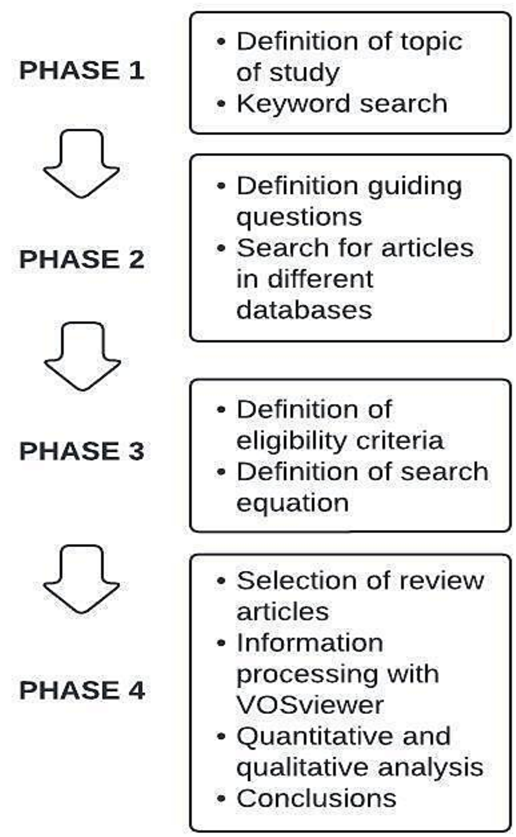

Figure 1. Phases of the Methodology.
Source: the authors.

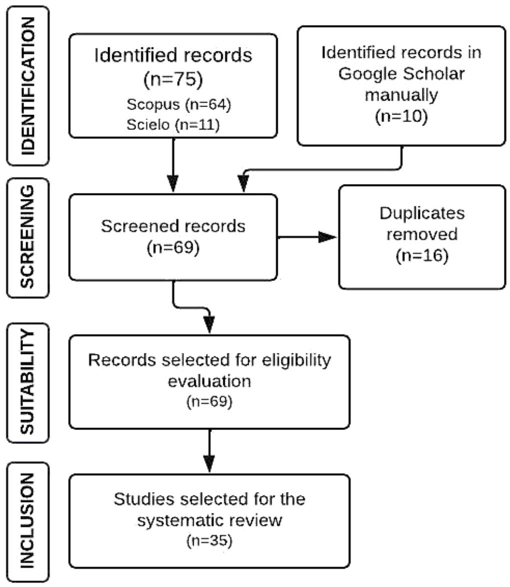

Figure 2 PRISMA flowchart in four levels.
Source: the authors.

2.1 *Initial searching*

The first searches were carried out in July 2023 by combining the terms "participatory" "water" "monitoring" in the Scopus, Scielo databases, and manually in Google Scholar. Following this, it was found necessary to expand the search using a combination with the operator "OR" to include the term "community". This search yielded a considerable number of results, some of which were not very relevant to the review as they were not related to the study subject. However, they provided a global perspective on the breadth of the topic under investigation. Participatory monitoring extends beyond water to include monitoring at the forest level and biodiversity, among other areas.

2.2 *Systematic Search*

The systematic search was carried out in Scopus, Scielo and Google Scholar, taking into account the established time range from 2014 to the present 2023.

The combination of terms that yielded the best results in search engines was as follows:

("community") AND ("water") AND ("monitoring") OR ("participatory")

In this way, the inclusion and exclusion criteria were defined:

2.3 *Inclusion criteria*

1. These are research articles and doctoral work
2. That they use participatory monitoring as a method.
3. That bias is studied in an environmental context.
4. Published between 2014 and 2023, including both.
5. That they have monitoring field data.
6. That it shows the gaps in the investigation.
7. That they are articles where monitoring techniques are shown that are easy to execute with the communities.
8. That they really involve the communities when executing the CCM.

2.4 *Exclusion criteria*

1. Studies that refer to wetland monitoring and not to community-participatory wetland monitoring are excluded.
2. Studies that have performed the monitoring, but the analysis of the results has been carried out in the laboratory, are excluded.
3. Those studies that do not contain results of the parameters measured in the field are excluded.
4. Those studies that do not perform the measurement of parameters in situ are excluded.

Specifically, 85 articles were obtained: 64 from Scopus, 11 from Scielo, and 10 from Google Scholar. Following the criteria mentioned earlier, articles were selected and screened based on their titles and abstracts. Sixteen duplicate articles were identified and removed, resulting in 69 articles for the systematic review—35 included and 34 excluded.

The qualitative analysis involved reading the abstracts of each included article to extract relevant information that aligned with the eligibility criteria. For the quantitative analysis, articles were manually categorized by year and country due to their dispersion across different databases. Graphs were then created to visualize and interpret the findings of the analysis.

Additionally, the VOSviewer software was executed for the articles found in Scopus (64) to establish the co-occurrence analysis of the publications made between different countries, taking into account that at least five documents have been published on the subject.

Additionally, bibliometric networks were generated by combining keywords through co-occurrence to analyze the relationships declared by the authors, aiming for enhanced visualization of these connections. Subsequently, citations per document were analyzed, considering a minimum of 10 citations per document. Additionally, citations registered in journals were taken into account, considering a minimum of five documents per journal.

3 Results and discussion

3.1 *Quantitative analysis*

The year of publication was the first selection criterion. As shown in Fig. 3, the research found that the largest number of articles corresponded to the years 2021 (13) and 2020 (10), and to a lesser extent to the years 2013 (1) and 2019 (3). It is important to note that the article corresponding to the year 2013 does not meet the time range defined in the selection criteria, however, Burgos et. Al [15], mentions 2 of the 3 most relevant keywords in this study (see Fig. 6.): Water quality and community or community-based monitoring, keeping a high correlation with the study topic, which is why it was included in the study.

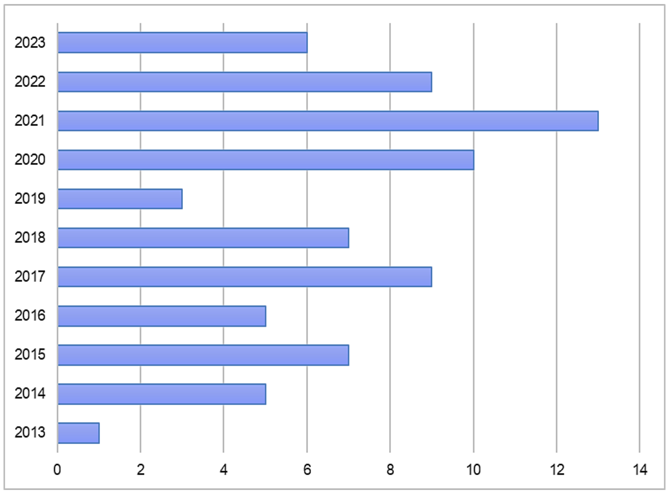

Figure 3. Distribution of articles by year of publication.
Source: the authors.

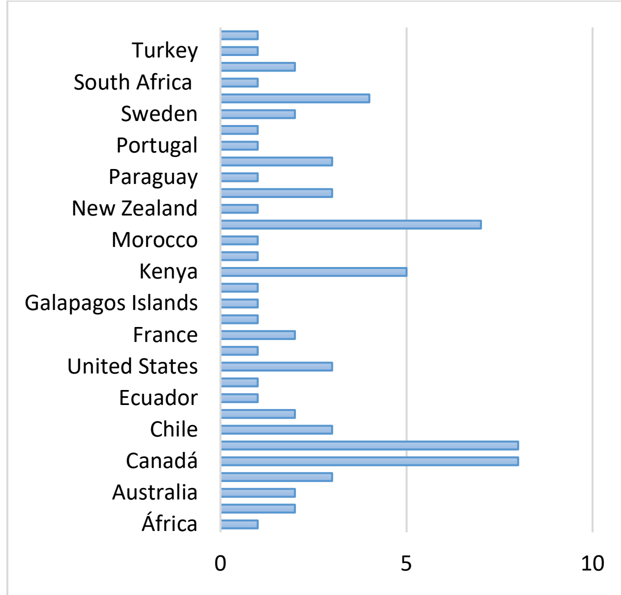

Figure 4. Distribution of articles by year of publication.
Source: the authors.

In relation to the country where the investigations were carried out, a predominance of investigations was observed (Fig. 4) in Colombia (8), followed by Canada (8) and Mexico (7). In addition to this, international collaborations were found between different countries such as Argentina, Peru and Colombia (3) and studies carried out in Kenya (5), Switzerland (4), and the Netherlands (3). The predominance of research in Colombia is attributed to the issues highlighted by Casso-Hartmann et al. [16] in La Toma, regarding the challenges in accessing safe, treated water. These challenges stem from the lack of water, sanitation, and hygiene infrastructure in rural communities, which correlates with findings discussed by Ulloa et al. [17] in 2021, within the context of Latin American countries like Argentina, Peru, and Colombia, communities have organized themselves to establish networks between academia, Non-Governmental Organizations (NGOs), and social organizations. These efforts aim to foster knowledge appropriation processes for decision-making and seek funding sources that support local monitoring and advocacy regarding community water resources management. This underscores the necessity to investigate the phenomenon of community monitoring of water quality.

In that which converges the countries with the greatest number of studies, which meet the conditions of inclusion of this study, the thematic or problematic axis arises from mining activities, in Colombia and Latin America, respectively, Casso-Hartman et. Al, [16] and Ulloa et. Al [17], and in Canada, Gérine-Lajoie et. Al [18], this means that the impacts of economic activities are monitored in a participatory manner to assess the water quality governed by Himley [19]. The pre-existence of economic activities tends to generate greater research interest.

3.2 Qualitative analysis

There is a lack of focus on participatory community monitoring techniques in research involving productive activities. Espinoza and Blanco [7], emphasize the importance of selecting independent laboratories to conduct analyses, as exemplified by the Universidad Nacional de Cuyo in the province of Mendoza, which is perceived to maintain autonomy from mining interests. This, together with what was emphasized by Ulloa et. Al [17], emphasizes the importance of selecting monitoring methods based on the autonomy of the laboratory or individual conducting the assessments. This ensures objectivity and independence in research outcomes, particularly in contexts involving productive activities such as mining.

In the analyzed articles, a methodological approach was identified that outlines the execution of community monitoring in micro-watersheds, with the Río Frío in the Valle del Cauca department serving as a reference. Five phases stand out: analysis of the need, review of national standards, comparison with international models, identification of priority elements, and analysis of local experiences. It is proposed to apply monitoring at three levels: Basic (education and awareness), Advanced (pollution monitoring) and Strategic (ensuring long-term quality). The choice of level will depend on the specific characteristics and needs of each community [12], this can be related to what was found in the methodology established by Mateus et al. [20] in the context of the Galapagos Islands, a simple methodology was established for *in situ application in* monitoring areas prioritized by the community. Physicochemical parameters of water supplied by the water treatment plant for human consumption were analyzed, revealing concerns among participants about the presence of copper and water hardness. Additionally, microbiological and physicochemical analyses of household-level water were conducted to verify its quality.

This approach can help to adequately define what would be the most convenient level to apply the monitoring according to the characteristics of the community where it will be implemented, since each one has different complexities, and according to Burgos et al. Al [15], attention to the sanitary protection of the water consumed by communities must take into account strategic planning for water security. On the other hand, in monitoring water quality, it is essential to instruct participants from the beginning, with the collaboration of the academic community and experts. Likewise, it is necessary to schedule at least two field trips in different seasons of the year to ensure the continuous participation of the community and evaluate how water quality varies with different climates.

In Mexico, various studies have been conducted regarding the subject analyzed in this review. One of these studies mentions a portion of the methodology where monitoring was conducted through collaboration between the community and academia, with voluntary participation supported by research projects. Before each field excursion, the place, date, and time were coordinated, involving 3 to 6 participants who alternated in applying supervision techniques and recording data on field sheets [1]. As a result of this work, they obtained data on water quality parameters from three springs in the study area using MCP.

3.3 Analysis with VOS viewer Software

The analysis in this software was carried out with the information obtained in the Scopus database, which was composed of 48 articles, where it was possible to obtain that, in total, 29 countries have contributed with publications on community-participatory water monitoring Fig. 5. It should be noted that the United States and Canada lead the scientific production with 12 and 8 publications, followed by the Netherlands with 6 and Mexico with 4 publications. These countries in addition to having the largest output of publications, also exhibit substantial collaboration in terms of joint publications.

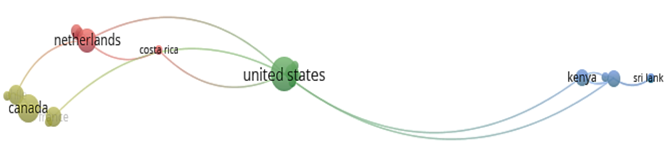

Figure 5. Collaboration of Scientific Production Between Countries.
Source: the authors.

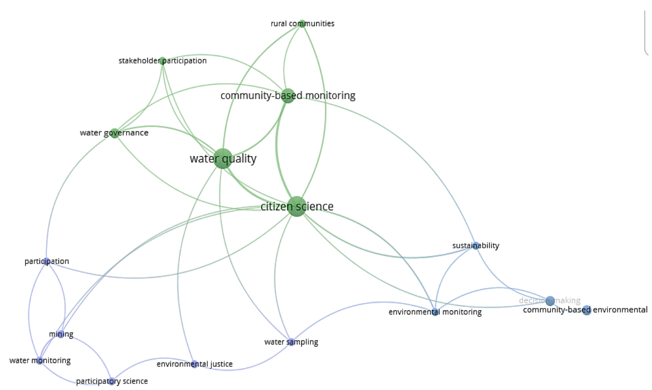

Figure 6. Keywords related to the topic of study.
Source: the authors.

The results from the co-occurrence analysis of keywords reveal that trends in community-participatory water monitoring are closely linked to citations concerning water quality, community monitoring, citizen science, water governance, and rural communities. Fig. 6 illustrates that citizen science, water quality, and community monitoring are the most relevant topics in this context.

4 Conclusions

Most research into community-participatory water monitoring has concentrated on devising strategies to engage communities and gain their approval for executing various projects in their territories. However, these efforts often fall short of truly involving communities, as genuine community involvement necessitates collaborative efforts to empower them in both the processes to be undertaken and the technical knowledge required regarding water resources.

Community-participatory monitoring can become established as an indispensable tool for social empowerment and community decision-making. With this in mind, community engagement can enhance the quality of collected data because local residents possess intricate knowledge about their environment. This knowledge can help prevent errors or misunderstandings during data collection processes. Engaging communities in monitoring projects not only addresses project-specific issues, but also strengthens local capacity and improves territories. Local training and skills development can have long-term benefits for the community.

Variations in climate can affect water quality in a variety of ways, as changes in climate conditions have a direct impact on water bodies and hydrological processes. These effects go hand in hand with precipitation and runoff, temperature changes, extreme weather events, among others. All these alterations can directly and indirectly impact water quality, disrupting natural processes and augmenting pollutant loads in water bodies. These changes can have repercussions for human health, aquatic biodiversity, and overall water resources.

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Energy balance and GHG emissions from oil and natural gas production in Venezuela

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Abstract
This paper determines the energy balance based on Venezuela oil and natural gas production and its impact on GHG emissions during the 2023-2050 period. The historical behavior of energy consumption was established, and six (6) scenarios were proposed with the LEAP software considering the grade of economic opening in Venezuela and the grade of adoption of mitigation measures in the world. Results showed potential GHG emissions between 211.50 and 302.35 $MMtCO_2e$ by 2030, reaching 148.54 and 413.50 $MMtCO_2e$ by 2050. Five (5) scenarios indicated the compliance of Venezuela's NDC objective. The sixth scenario would require mitigation measures starting 2026: increase electricity generation by renewable sources, incorporation of electric vehicles and decrease of natural gas flaring and venting, which would reduce 17.06% of GHG emissions.

Keywords: oil; natural gas; energy balance; GHG emissions; mitigation.

Balance energético y emisiones de GEI de la producción de petróleo y gas natural en Venezuela

Resumen
Este trabajo determina el balance energético con base en las producciones de petróleo y gas natural en Venezuela y su impacto sobre las emisiones de GEI en el período 2023-2050. Se estableció el comportamiento histórico del consumo energético y se plantearon seis (6) escenarios con el programa de computación LEAP, considerando el grado de apertura económica en Venezuela y el grado de adopción de medidas de mitigación del cambio climático en el mundo. Los resultados mostraron potenciales emisiones de GEI entre 211,50 y 302,35 $MMtCO_2e$ para el 2030, alcanzando 148,54 y 413,50 $MMtCO_2e$ en 2050. Cinco (5) escenarios indicaron el cumplimiento del objetivo de la CND de Venezuela. El sexto escenario requeriría medidas de mitigación a partir de 2026: incremento de generación eléctrica por renovables, incorporación de vehículos eléctricos y disminución de la quema y venteo de gas natural, con lo cual se reducirían las emisiones de GEI en 17,06%.

Palabras clave: petróleo; gas natural; balance energético; emisiones GEI; mitigación.

1 Introduction

Venezuela has the largest proven oil reserves in the world and ranks seventh in proven natural gas reserves, according to British Petroleum (BP) [1], therefore it is convenient to have knowledge of the demand, supply, and transformation of these energy sources, as well as their alternatives, to ensure the supply of Venezuela's domestic demand, as indicated by the Latin American Energy Organization (OLADE) [2].

Even though Venezuela occupies one of the first places on proved oil and natural gas reserves in the world, the

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impact on the environment of the exploitation of these reserves has not been studied in depth, especially on the GHG emissions. In addition, most of the current information related to the demand and transformation of energy in the country is unavailable, which leaves a window of opportunity to the present study. This data collection is of global interest and allows to study the GHG emissions from an energy balance point of view.

According to the Organization of Petroleum Exporting Countries (OPEC), in 2019 Venezuelan production was 1.81 EJ, equivalent to 796 thousand barrels per day (mb/d) [3]. Of those, 0.31 EJ (135 mb/d) were headed to national refineries for processing [1], and the remaining for export. The International Energy Agency (IEA) exposed that the processed crude oil domestic consumption for the same year included categories such as electricity generation (0.05 EJ), transport (0.43 EJ), industry (0.04 EJ), among others [4,5]. Additionally, oil production in 2021 was 1.26 EJ (556 mb/d) and 1.55 EJ (684 mb/d) in 2022 [6].

Regarding natural gas, 2.07 EJ were produced by 2019, equivalent to 59,657 million cubic meters (Mm^3). From those, 3.70% were used in power plants, 0.92% as domestic consumption, 6.07% in industry and 0.03% in transport [4,7]. The remainder was injected, flared and vented [8].

Electricity in Venezuela is generated primarily from hydraulic energy, representing 81.70% of the national electricity generation matrix in 2020, followed up by fossil sources (oil and natural gas) with 18.30% [9].

Fossil energy sources are important not only for the industrial and transportation sectors in Venezuela, but also for the electricity and domestic markets. Nevertheless, fossil resources implicate the emission of a significant amount of carbon dioxide (CO_2) into the atmosphere. CO_2 is one of the GHG and contributes to climate change [10]. Gases such as carbon monoxide (CO), methane (CH_4) and hydrocarbons are also produced from the combustion of fossil fuels, and eventually they oxidize and turn into CO_2 [11]. To express the emissions of these gases in a way that they can be compared with CO_2 emissions, the unit of carbon dioxide equivalent (CO_2e) is used [12]. In the case of Venezuela, a breakdown of the GHG emissions produced by energy consumption and transformation has not been previously studied, which results of interest for this work.

The impact caused by the emissions of GHG has been a worldwide problematic, and several measures have been applied to reduce them. The Paris Agreement (2016) was held at COP21 with the objective to prevent the rise of global temperature above 2°C and documents entitled Nationally Determined Contributions (NDC) are delivered by each Party of the United Nations (UN) to the Secretary of the Convention, manifesting measures aimed at complying the Paris Agreement [13]. In this sense, Venezuela ratified its commitment to the 20% reduction of GHG emissions by 2030 in 2018.

The scope of this work is to determine Venezuela's energy balance until 2050 according to oil and natural gas production, and analyse its impact on GHG emissions, considering the country's context and the necessary mitigation measures. In this sense, the LEAP program [14] was used, and energy scenarios were established, determining the main variables that affect the scenarios by 2030 and 2050.

1.1 Background

1.1.1 Energy scenarios in a global context – IEA

In a global context, different scenarios for the coming years regarding the energy sector are projected.

One of the scenarios proposed by the IEA is the "Stated Policies Scenario" (STEPS), which considers that the energy circumstances will continue to develop in the same way as in previous years, without significant changes in government policies. This scenario, commonly known "Business As Usual" (BAU), projects an oil demand of 104,000 mb/d for the mid-2030s, declining slightly by 2050 [15]. IEA also presented a scenario totally focused on the compliance of NDC objectives, called "Net Zero Emissions" (NZE). In this case, the emissions produced by anthropogenic activities are counteracted with its removal or reduction, projecting an oil demand of 74,000 mb/d by 2030 and 24,000 mb/d by 2050 [15,16].

1.1.2 Historical oil production in Venezuela

In the last decade, Venezuela has presented a relevant decrease in its oil production. Fig. 1 shows the decrease in oil production from 5.26 EJ (2,318 mb/d) for 2015 to 1.13 EJ (498 mb/d) in 2020, increasing slightly to 1.26 EJ (556 mb/d) for 2021 and 1.55 EJ (684 mb/d) in 2022 [3,6,17-23].

OPEC and Ministry of Petroleum (MPPP) with the Oil and Other Statistical Data (PODE) 2014 values of oil production were compared, resulting in an average of 21.23% for the 2011-2014 period [3,17-24]. Official data from Venezuelan Government has not been released since this last reference. However, OPEC's primary sources will be represented in this article as the official Venezuelan data.

1.1.3 Historical natural gas production in Venezuela

Fig. 2 shows Venezuelan natural gas production from 2010 to 2022. PODE 2014 reported data from 2010 to 2014, while Gas Energy Latin America included production until 2022, concurring both references in the 2010-2014 period. The year 2016 presented a peak of 2.85 EJ (82,117 Mm^3), descending then to 1.58 EJ (45,529 Mm^3) in 2022 [8,24,25].

1.1.4 Historical GHG emissions in Venezuela

The GHG emission values were consulted from the Statistical Review of World Energy, which until the year 2021 was reported by BP and currently is published by the Energy Institute. Fig. 3 presents the data from 2010 to 2022, values that considered energy uses, process emissions, methane and flaring of natural gas [1,26].

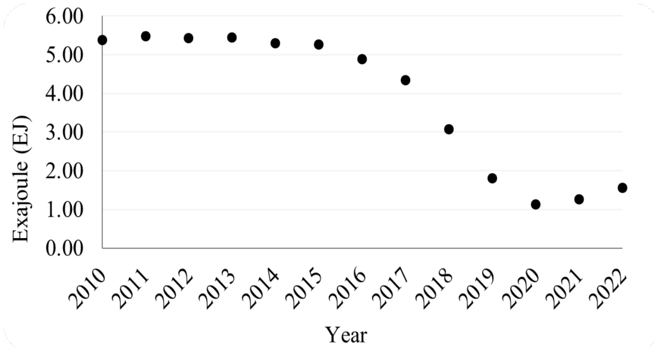

Figure 1. Historical oil production in Venezuela.
Source: Adapted from OPEC, 2015-2022 and 2024.

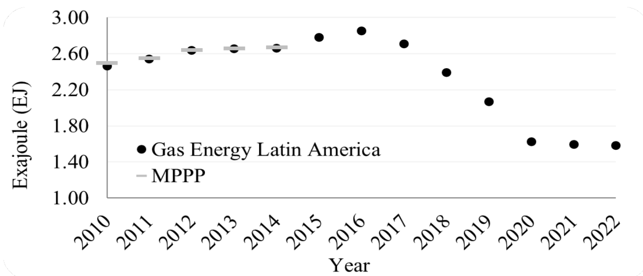

Figure 2. Historical natural gas production in Venezuela.
Source: Adapted from Gas Energy Latin America, 2020, MPPP, 2016 and Alvarado and Valera, 2023.

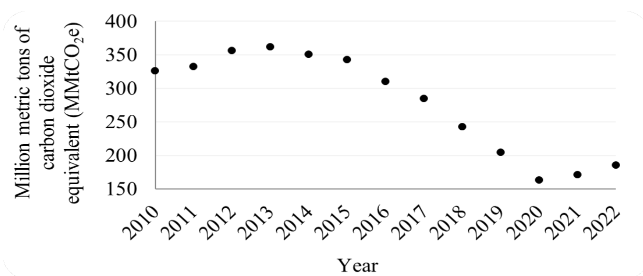

Figure 3. Historical GHG emissions of CO_2e in Venezuela.
Source: Adapted from BP, 2022 and Energy Institute, 2023.

1.1.5 Venezuelan Government commitments regarding GHG emissions

In the last decade, the intention to increase the use of renewable alternatives over fossil fuels has risen, with the purpose of contributing to the NDC commitments.

Venezuela formalized its NDC in February 2018, ratifying the commitment to the reduction of GHG emissions [27]. Thereby, it proposed the 20% reduction of GHG emissions by 2030 in comparison to the inertial scenario, which considered the reported emissions until 2011 [28].

Based on the historical data from 1990 to 2011 [1] an adjustment for GHG emissions was done to obtain the inertial scenario and Venezuela's objective for 2030, resulting in 369.60 $MMtCO_2e$ and 295.68 $MMtCO_2e$, respectively. Also, for 2035 and 2050 the NDC objective aim to 300.99 and 314.37 $MMtCO_2e$ in total emissions.

1.1.6 LEAP program (Low Emissions Analysis Platform)

LEAP, acronym for Low Emissions Analysis Platform, is a simulation program developed by the Stockholm Environment Institute (SEI) that offers the possibility to analyze energy scenarios, considering aspects, such as the consumption, production, mitigation measures, and its evaluation. LEAP has been used by countries as part of its NDCs, as well as institutes and, researchers, specially studying the impact on the environment of diverse scenarios with their respective energy requirements, analyzing GHG emissions. These scenarios can be evaluated in an unlimited years horizon. Nevertheless, most of the research carried out considers a study period of 20 to 50 years [29].

LEAP hierarchically organizes the information in a "tree" structured into branches [14]:

- *Key Assumptions:* Includes independent variables that can be used in other branches.
- *Demand:* Includes final energy consumption by each technology, referring to electricity, natural gas, gasoline, diesel, among others.
- *Transformation:* Simulates the conversion, transmission, and distribution of energy from the extract point of the resource to where it is consumed.
- *Resources:* Disaggregates primary and secondary sources, considers consumed and produced fuels.

1.1.7 LEAP in the analysis of energy scenarios

Serrano and Méndez modeled in 2020 three sustainable energy planning scenarios. First, BAU, maintaining energy use rates with no modifications. Secondly, "Uso Eficiente de Energía", with changes in the energy use indicators for the residential and commercial sector, and replacement of GLP for natural gas, considering the increase in the activities of the BAU scenario. Finally, in "Ciudad Compacta y Movilidad" transport consumption was reduced, and electric public transport was incorporated [10].

On the other hand, in 2021 Hernández and Fajardo used LEAP to estimate a projection of Bogota's emissions, Colombia, evaluating three scenarios: BAU; "Reducción de carbono", implementing new environmental policies that will limit carbon use in energy production and, lastly, "Mitigación", which removed all fossil fuels except natural gas and electricity generation from renewable sources [30].

In this sense, several studies have considered alternative energy planning scenarios using LEAP program as a tool to estimate the energy demand and GHG emissions, demonstrating its versatility through a wide range of possibilities.

2 Methodology

LEAP version 2020.1.0.76 under the "Student Research" license from SEI was used, and 2011 was chosen as base year. The year 2012 was the first year of the scenario and 2050 the last. Data and estimations from period 2012-2022 were used as the basis for demand and transformation projections. The following data from national and international entities were collected:

- Key Assumptions: Population and Gross Domestic Product (GDP) data [31-34] were included.

- Demand: Households, industry, transport, and commercial and public services sectors were established [5,7,24,31,35-40].
- Transformation: Transmission and distribution, electricity generation, oil production, crude oil refining, and production, injection, flaring and venting of natural gas data were considered [1,4,8,39,40,41-54].
- Resources: Bituminous coal, hydro, solar, wind, crude oil, natural gas, and firewood, were considered as primary sources, while the secondary sources diesel, residual fuel oil, naphtha, bitumen, lubricants, petroleum coke, gasoline, electricity, kerosene, jet kerosene, and LPG [54-56].

Natural gas flaring and venting were computed as the difference among natural gas total production and its use for electricity generation, domestic market, and injection.

2.1 Variables

Variables considered and its impact are listed in Table 1.

Table 1.
Main variables in scenarios

Variable	Impact
Population	Household consumption
GDP	Industry, transport, and commercial and public services consumption
World's oil demand projection in the international market and Venezuela's fraction on world demand	Venezuelan oil production
Oil production	Gas Oil Ratio (GOR) and natural gas production
Venezuela's objective according to NDC	Reduction of GHG emissions by 20% for 2030 and mitigation scenarios
Solar and wind energy potential	Change in electricity generation matrix as mitigation measure

Source: Own elaboration

2.2 GHG emissions calculation

The consumed energy was computed as the product of the total activity and the energy intensity (eq. 1), while GHG emissions as the product of GHG environmental load factor and the energy consumed, as seen in eq. (2) [14]. The GHG considered for the determination of the emissions were CO_2, CH_4 and N_2O. According to LEAP those are the main GHG.

$$Consumed\ energy = (Total\ Activity).(Intensity) \tag{1}$$

$$(Emission)_{GHG} = (Environmental\ load)_{GHG}(Consumed\ energy)_{GHG} \tag{2}$$

Eq. (1) refers to each technology, scenario, and year.

By default, LEAP includes the Global Warming Potential (GWP) for the calculation of the CO_2e emissions, as stated by the IPCC's Fifth Assessment Report (AR5). These GWP, expressed in tons of CO_2e per ton of pollutant, allowed to express all GHG emissions in terms of tons of CO_2e [14].

2.3 Scenarios

As previously mentioned, six energy scenarios for the 2023-2050 period were established. The scenario names were arbitrarily designated by the authors. The two main considerations were the grade of economic opening in Venezuela and the level of adoption of climate change mitigation measures in the world. The proposed scenarios are presented in Table 2.

Table 2.
Proposed scenarios

Grade of adoption of climate change mitigation measures in the world	Grade of economic opening		
	Without change	Pragmatic	Total
100%	Titanic (TIC)	Halfway (AMC)	Problematic Panorama (PP)
	O&G production would decrease to 320 mb/d in 2050, while crude oil refining increases slightly, using 18% of the installed capacity. There would be no development in the industry. Slight population and GDP increase caused by emigration.	GDP increase to 2.1 times the value of TIC in 2030. It would have production limitations, but show an increase in oil production to 1,500 mb/d by 2030 and a crude oil refining up to 40% of the installed capacity by 2050.	Most optimistic scenario among those with 100% adoption of mitigation measures. Would reach NZE top oil production in 2030 of 1,972 mb/d and a resulting GDP of 2.8 times the value of TIC. Increasing to 60% usage of the installed capacity for crude oil refining by 2050.
Without relevance	Lucky Country (PCS)	Production Increase (ADP)	Venezuelan Happiness (FV)
	As a result of the irrelevancy of international mitigation measures, oil production would increase to 1,420 mb/d by 2035. GDP would reach 2.45 times the value of TIC in 2030 and 50% of the installed capacity for crude oil refining will be used by 2050.	Economic boom that would allow industrial development, with a resulting GDP of 3.15 times the value of TIC in 2030 and a usage of 65% of the installed capacity for crude oil refining by 2050. Without environmental limitations, oil production would soar up to 2,140 mb/d in 2035.	Significant growth in population due to the increase of immigration. Oil production reaching 2,850 mb/d by 2035, the top value in STEPS. Meanwhile increasing the usage of installed capacity for crude oil refining up to 95% by 2050 and a GDP value of 4.9 times the value of TIC in 2030.

Source: Own elaboration

The oil production premises presented in scenarios were based on data from international organizations, such as the energy planification scenarios STEPS and NZE from IEA. Oil refining estimations were based on the use of the installed capacity (219.52 mb/d) for 2023 and the development in the industry, representing a different percentage of that capacity for each one of the six scenarios. Additionally, natural gas production was estimated according to the GOR historical values and oil production, while natural gas injection on its historic reported values. Population growth was determined on the values reported by the Latin American and Caribbean Demographic Centre and the UN [32], and accordingly to the develop of the economy varied from 40 to 180% of the estimated value. On the other hand, GDP values depended on population growth and the economic change.

1 Results and Discussion

1.1 Historical period 2011-2022

Based on the information collected from national and international entities, the demand historical behavior, the electricity generation, oil production and refining, natural gas production, injection, flaring and venting, and exports and imports for the period 2011-2022 were assumed. As a result of this compilation, GHG emissions for the period were determined, as shown in Fig. 4.

A minimum of 159.15 $MMtCO_2e$ in 2020 was observed, which increased to 203.05 $MMtCO_2e$ in 2022. This behavior is consistent due to the interruption of the national electricity service in 2019 and the COVID-19 pandemic in 2020. Next to this period, the reactivation of the activities and operations was expected, as well as the growth in the emissions exhibited in 2020, as shown in 2021 and 2022.

The data reported by BP and Energy Institute was considered for the GHG emissions and its historical validation [1, 26]. In the period 2011-2022, historical data and LEAP results showed an average difference of 5.65%, which is considered in an acceptable range.

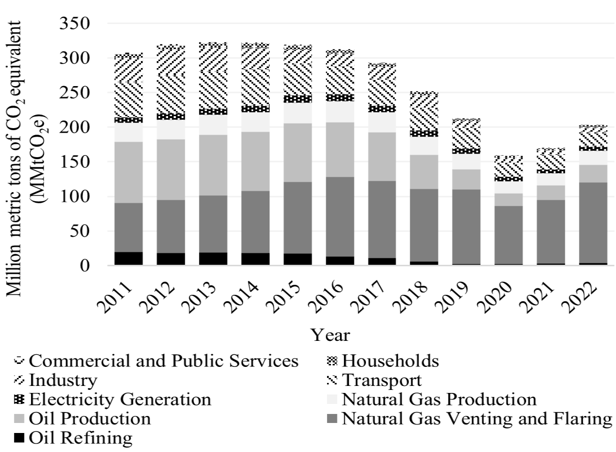

Figure 4. GHG emissions for period 2011-2022
Source: Own elaboration

It is relevant to mention that at the time this simulation was carried out, the data of natural gas production was unknown, and it was calculated based on oil production and the reported GHG emissions. The authors estimated a higher natural gas production in 2022 than the one reported recently by Gas Energy Latin America, which explains why the value of total emissions presented for that year in Fig. 4 is higher than the one reported from the Energy Institute. The difference in emissions is specifically related to natural gas production, flaring and venting.

1.2 Scenarios 2023-2050

The Demand branch depends directly on population and GDP, as established in the premises of the scenarios, which explains Fig. 5. TIC would present the lowest demand by 2050, 0.89 EJ, and FV the highest, with 2.48 EJ. As the demand of energy increases, the electricity demand is higher, as well as the electricity generation.

Fig. 6 shows oil production of each scenario, starting from the estimated value of 800 mb/d in 2023. TIC would not have any improvement in the oil industry, which explains the drastic decline of production through the years, lacking a peak after 2023, ending 2023-2050 with 657 mb/d. Nevertheless, all the other scenarios considered a top oil production between 2030 and 2035, according to the expectations of the IEA in the NZE and STEPS scenarios, estimating for the latter a global oil demand of 98,000 mb/d by 2050 and a 2.74% for Venezuela's fraction on global oil demand [17]. AMC and PP would present a top oil production in 2030 and a significant decrease by 2050, according to the 100% adoption of mitigation measures in the world, which translates into a considerable reduction of fossil fuels use, reaching 861 and 1,340 mb/d, AMC, and PP, respectively. However, in the scenarios where the mitigation measures are irrelevant, oil production would increase notably until 2035, and then decrease slightly up to 2050. In this case, FV would present the higher production, due to the total economic change, reaching a peak of 2,850 mb/d, in contrast to ADP with 2,140 mb/d and PCS with 1,420 mb/d.

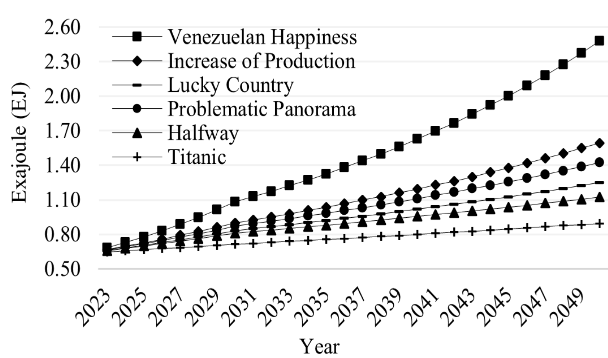

Figure 5. Demand branch of each scenario for 2023-2050
Source: Own elaboration

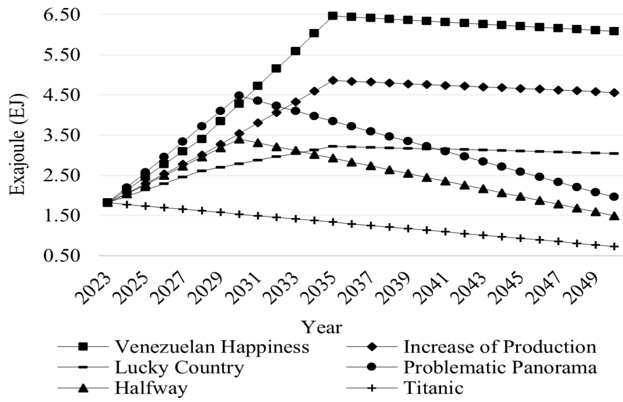

Figure 6. Oil production of each scenario for 2023-2050
Source: Own elaboration

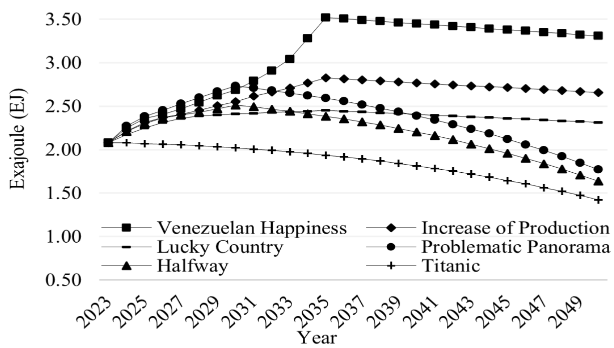

Figure 7. Natural gas production of each scenario for 2023-2050
Source: Own elaboration

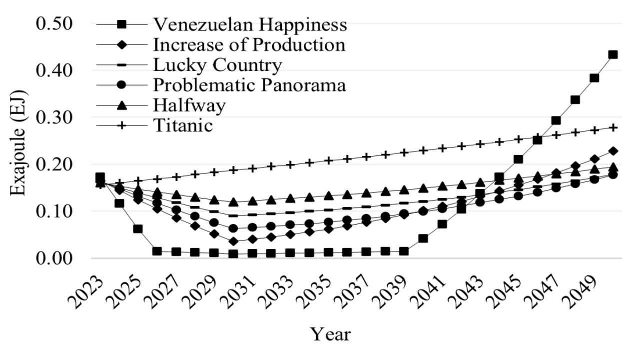

Figure 8. Total imports of each scenario for 2023-2050 period
Source: Own elaboration

Fig. 7 shows that natural gas production would have the same behavior, starting 2023 with 59,942 Mm^3. Due to the lack of official data, GOR values from 2011-2022 period were used, as well as the oil production estimates, which made it possible to project the production, starting off the premise that most Venezuelan natural gas is associated to oil.

Even though FV would present the lowest total imports for 2023-2050, the scenario would have a noticeably increase in 2039 due to the rise of oil refined products demand, as a consequence of the drastic population growth. The imports would include mainly gasoline and LPG, followed up by kerosene. Total imports of each scenario are shown in Fig. 8.

The exports (see Fig. 9) would have an opposite behavior, with the most optimistic scenario (FV) as the one with highest exports (116.86 EJ) and the most pessimistic (TIC) with the lowest (26.91 EJ). This would be the result of oil production, being crude oil the main fuel to export, representing between 64.89 and 73.80 % of total exports.

Once all the categories were known, it was possible to determine the GHG emissions for the 2023-2050 period (see Fig. 10). It can be concluded that an increase in population and an economic change, pragmatic or total, will lead to a growth in GHG emissions. TIC would show the least emissions due to poor oil and natural gas production. On the contrary, FV economic change would allow to a greater investment in process improvement and equipment maintenance, developing the industry and producing higher GHG emissions. Even though TIC would flare and vent more produced natural gas compared to FV, the latter would present greater volumes of natural gas flared and vented (see Table 3).

If TIC, AMC, and PP are grouped, as well as PCS, ADP and FV, a tendency to decrease or increase the GHG emissions can be observed, as the economic situation emerges and as the oil and natural gas production develops, according to the international context.

The two main GHG would be CO_2 and CH_4, followed up by NO_2. For all scenarios, the average proportion of CO_2 in the interested years, 2030, 2035 and 2050, would be 64.07% and 35.77% for CH_4. NO_2 would cover the rest, 0.16%.

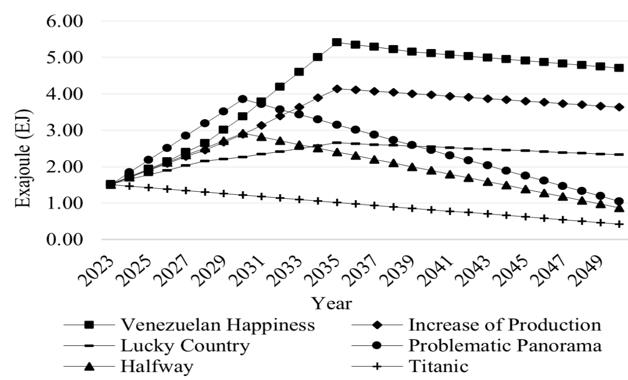

Figure 9. Total exports of each scenario for 2023-2050 period
Source: Own elaboration

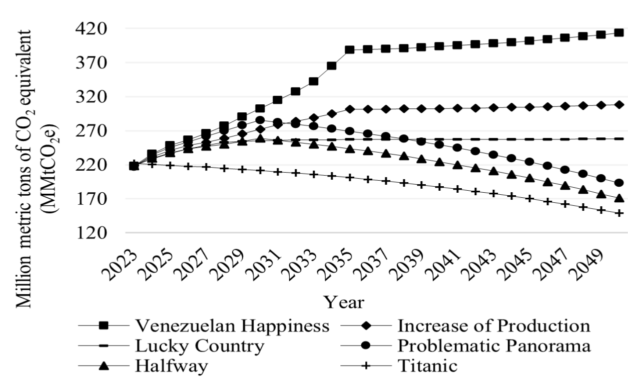

Figure 10. GHG total emissions of each scenario for 2023-2050
Source: Own elaboration

Table 3.
Emissions and percentage that flaring and venting represent on natural gas production in 2050

Scenario	GHG emissions ($MmtCO_2e$)			Flaring and venting in 2050 (%)
	2030	2035	2050	
TIC	211.50	200.93	148.54	66.14
AMC	258.56	243.54	170.67	47.09
PP	285.25	269.25	193.32	35.68
PCS	255.41	257.41	258.10	61.21
ADP	272.20	301.55	307.99	51.74
FV	302.35	388.35	413.50	47.06

Source: Own elaboration

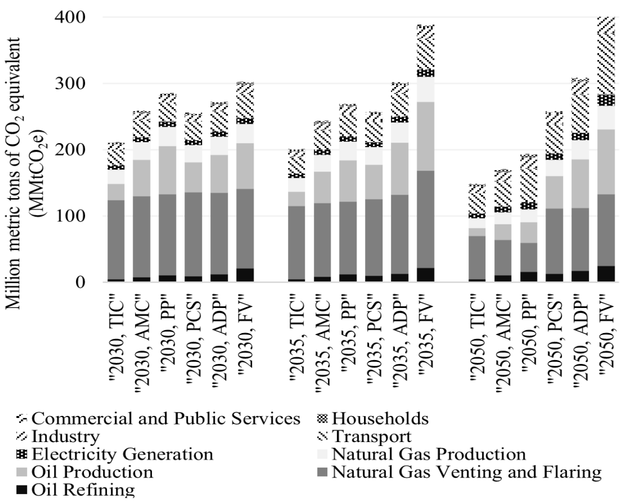

Figure 11. GHG emissions by categories for 2030, 2035 and 2050
Source: Own elaboration

Fig. 11 shows GHG emitted in 2030, 2035 and 2050 by category. Natural gas flaring and venting and the transport sector would be the categories that would emit more GHG by 2050 in the scenarios with 100% adoption of mitigation measures in the world. On the other hand, PCS, ADP and FV would have natural gas flaring and venting and oil production.

Table 4 shows the energy balance in 2050 for the studied scenarios. Among the scenarios with 100% adoption of mitigation measures in the world an increase in natural gas total demand is evident, with 0.16, 0.20 and 0.25 EJ in TIC, AMC and PP, respectively, as a result of the population growth. PCS, ADP and FV maintained the same behavior, but with 0.22, 0.28 and 0.44 EJ, respectively.

Additionally, the rise in population would lead to an increment of natural gas total transformation, which contemplates the categories of natural gas injection, flaring and venting, and electricity generation, resultant in 1.26, 1.44 and 1.52 EJ for TIC, AMC, and PP scenarios, respectively. This behavior is a consequence of the electricity generation increase from natural gas (0.11 EJ in TIC, 0.14 EJ in AMC, and 0.17 EJ in PP), along with the injection increment to benefit the production (0.21 EJ in TIC, 0.53 EJ in AMC, and 0.72 EJ in PP), leading to a lower amount of natural gas flared and vented (0.94 EJ in TIC, 0.77 EJ in AMC, and 0.63 EJ in PP).

The rise of natural gas production, as well as total transformation, electricity generation and injection would remain in the scenarios PCS, ADP, and FV. Although flaring and venting decreases from PCS to ADP, it would increase in FV. Unlike the other two scenarios without relevance in the adoption of mitigation measures, the peak of flaring and venting in FV would be obtained in 2035, with 2.11 EJ (60,807 Mm^3), because in the same year the maximum natural gas production would be reached, and due to its magnitude, it would exceed the increase in injection, natural gas demand and consumption for electricity generation.

In the TIC, AMC and PP scenarios, the rise of crude oil production would not be high enough to maintain the growth in the oil exports, supplying the national demand. Thus, crude oil exports in TIC would be 0.15 EJ, which would increase to 0.19 EJ in AMC and, finally would be approximately zero in PP, with all national production destined to refining.

The opposite would happen to the other three scenarios, where a significant augmentation in oil production would maintain the augmentation in crude oil exports, with 1.41 EJ in PCS, 2.44 EJ in ADP, and 2.99 EJ in FV by 2050.

1.3 Required mitigation measures

Among the studied scenarios, FV is the only one that would exceed the 20% reduction of the GHG emissions established by Venezuela's NDC. This scenario would require mitigation measures applied to transport, sector demand, electricity generation, and natural gas flaring and venting, which led to a new scenario called FV2. In FV, the transport sector represented 22.20% of total emissions by 2050, with 91.81 $MMtCO_2e$. STEPS scenario indicates that the European Union will promote the use of electrical vehicles, countries such as South Korea and Japan will provide subsidies for the purchase of these vehicles and Canada presented the inclusion of mass public transport buses [15]. For Venezuela, the NDC proposed the guarantee of the public transport service with the "Sistema Trolebús" units with dual motor, preferring the electrical ones [27]. It is observed how different countries seek to implement measures that allows to modify the fuel matrix of the transport sector, migrating to the use of electric vehicles, promoting the use of public transport, reducing the use of gasoline and diesel vehicles, and improving vehicle energy efficiency. As a result, it allows to reduce emissions.

The first mitigation measure considered a change in the transport matrix starting 2026, reaching electric transport 28% of the matrix by 2050. Additionally, gasoline and diesel fuels would represent 65 and 2% of the fuel consumption matrix for this sector by 2050, reducing by 29.94 and 70.64%, respectively. Finally, natural gas would cover the remaining, representing 5% by 2050.

The second measure would consider the introduction of electricity generation with non-conventional renewable sources. Fig. 12 shows the change in the electricity generation matrix starting 2026, until achieving 60% in hydroelectric, 5% in natural gas and 35% in non-conventional renewables, which contemplated 75% of wind and 25% of solar energy by 2050. Although the objective is to reduce GHG emissions, first was necessary to guarantee energy security, maintaining the diversification of the generation matrix, which explains why natural gas was not completely removed.

Finally, the third measure would focus on exporting a fraction of the produced natural gas, reducing consequently natural gas flaring and venting. This mitigation measure was included at Venezuela's NDC, which proposed the increase of compression, treatment, and distribution capacities for natural gas internal consumption [27].

Table 4.
Energy balance for the scenarios by 2050

Exajoule (EJ)	Solid Fuels	Natural gas	Crude oil	Hydropower	Renewables	Biomass	Electricity	Oil Products	Natural Gas Output	Total
TIC										
Production	0	1.42	0.73	0.19	0	0.01	-	-	-	2.35
Imports	-	0	-	-	-	-	-	0.28	-	0.28
Exports	-	-	-0.15	-	-	-	-	-0.26	-	-0.41
Natural gas injection	-	-0.21	-	-	-	-	-	-	0.21	-
Natural gas flaring and venting	-	-0.94	-	-	-	-	-	-	0.94	-
Oil refining	-	-	-0.58	-	-	-	-	0.52	-	-0.05
Electricity generation	-	-0.11	-	-0.19	0	-	0.31	-0.01	-	0
Transmission and Distribution	-	-	-	-	-	-	-0.10	-	-	-0.10
Total Demand	0	0.16	-	-	-	0.01	0.21	0.51	-	0.90
Unmet Requirements	-	-	-	-	-	-	0	-0.02	-1.15	-1.17
AMC										
Production	0	1.64	1.49	0.23	0	0.02	-	-	-	3.38
Imports	-	-	-	-	-	-	-	0.19	-	0.19
Exports	-	-	-0.19	-	-	-	-	-0.68	-	-0.87
Natural gas injection	-	-0.53	-	-	-	-	-	-	0.53	-
Natural gas flaring and venting	-	-0.77	-	-	-	-	-	-	0.77	-
Oil refining	-	-	-1.3	-	-	-	-	1.18	-	-0.12
Electricity generation	-	-0.14	-	-0.23	0	-	0.38	-0.02	-	0
Transmission and Distribution	-	-	-	-	-	-	-0.12	-	-	-0.12
Total Demand	0	0.20	-	-	-	0.02	0.26	0.64	-	1.12
Unmet Requirements	-	0	-	-	-	-	0	-0.04	-1.3	-1.33
PP										
Production	0	1.77	1.95	0.28	0	0.02	-	-	-	4.02
Imports	-	-	-	-	-	-	-	0.18	-	0.18
Exports	-	-	0	-	-	-	-	-1.05	-	-1.05
Natural gas injection	-	-0.72	-	-	-	-	-	-	0.72	-
Natural gas flaring and venting	-	-0.63	-	-	-	-	-	-	0.63	-
Oil refining	-	-	-1.95	-	-	-	-	1.77	-	-0.18
Electricity generation	-	-0.17	-	-0.28	0	-	0.46	-0.02	-	
Transmission and Distribution	-	-	-	-	-	-	-0.14	-	-	-0.14
Total Demand	0	0.25	-	-	-	0.02	0.32	0.83	-	1.42
Unmet Requirements	-	0	-	-	-	-	0	-0.06	-1.35	-1.41
PCS										
Production	0	2.31	3.04	0.24	0	0.02	-	-	-	5.62
Imports	-	0	-	-	-	-	-	0.18	-	0.18
Exports	-	-	-1.41	-	-	-	-	-0.91	-	-2.33
Natural gas injection	-	-0.53	-	-	-	-	-	-	0.53	-
Natural gas flaring and venting	-	-1.42	-	-	-	-	-	-	1.42	-
Oil refining	-	-	-1.63	-	-	-	-	1.48	-	-0.15
Electricity generation	-	-0.15	-	-0.24	0	-	0.41	-0.02	-	0
Transmission and Distribution	-	-	-	-	-	-	-0.13	-	-	-0.13
Total Demand	0	0.22	-	-	-	0.02	0.28	0.73	-	1.25
Unmet Requirements	-	-	-	-	-	-	0	0	-1.94	-1.94
ADP										
Production	0	2.65	4.56	0.30	0	0.02	-	-	-	7.54
Imports	-	-	-	-	-	-	-	0.23	-	0.23
Exports	-	-	-2.44	-	-	-	-	-1.19	-	-3.63
Natural gas injection	-	-0.81	-	-	-	-	-	-	0.81	-
Natural gas flaring and venting	-	-1.37	-	-	-	-	-	-	1.37	-
Oil refining	-	-	-2.12	-	-	-	-	1.92	-	-0.19
Electricity generation	-	-0.18	-	-0.30	0	-	0.5	-0.02	-	0
Transmission and Distribution	-	-	-	-	-	-	-0.16	-	-	-0.16
Total Demand	0	0.28	-	-	-	0.02	0.35	0.94	-	1.59
Unmet Requirements	-	0	0	-	-	-	0	0	-2.19	-2.19
FV										
Production	0.01	3.31	6.08	0.45	0	0.02	-	-	-	9.86
Imports	-	-	-	-	-	-	0	0.43	-	0.43
Exports	-	-	-2.99	-	-	-	-	-1.72	-	-4.71
Natural gas injection	-	-1.03	-	-	-	-	-	-	1.03	-
Natural gas flaring and venting	-	-1.56	-	-	-	-	-	-	1.56	-
Oil refining	-	-	-3.09	-	-	-	-	2.81	-	-0.28
Electricity generation	-	-0.27	-	-0.45	0	-	0.75	-0.03	-	0
Transmission and Distribution	-	-	-	-	-	-	-0.23	-	-	-0.23
Total Demand	0.01	0.44	-	-	-	0.02	0.51	1.49	-	2.48
Unmet Requirements	-	0	-	-	-	-	-	0	-2.59	-2.59

Source: Own elaboration.

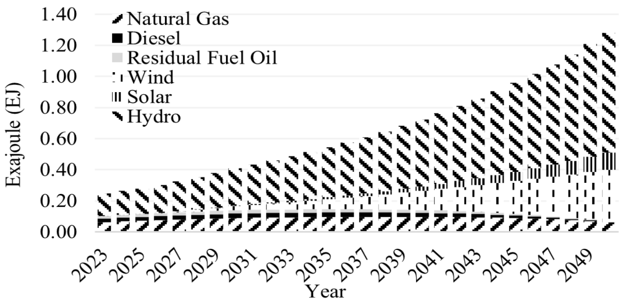

Figure 12. Electricity generation by source for FV2 scenario
Source: Own elaboration

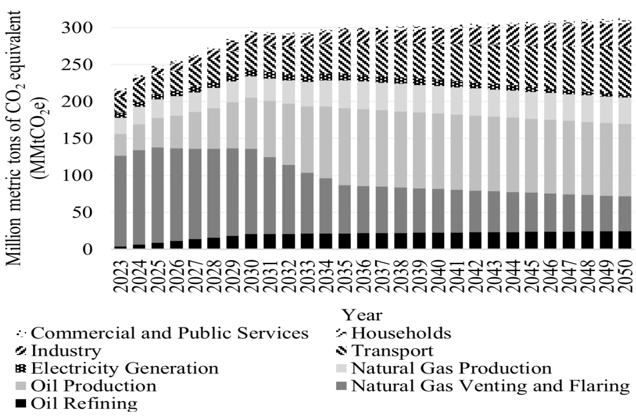

Figure 13. GHG emissions for scenario FV2
Source: Own elaboration

As the international context considers a market for fossil fuels, the export of natural gas can take an important role for Venezuela. Therefore, the GHG emissions from the flaring and venting category could be reduced by more than 50% by 2050, reaching 0.68 EJ (19,597 Mm^3).

These measures combined would reduce 17.06% of GHG emissions, reaching 295.37, 300.01 and 312.61 $MMtCO_2e$ by 2030, 2035 and 2050, respectively, as seen in Fig. 13. However, this would require an additional capacity of 14,500 megawatts (MW) of non-conventional renewables by 2048 and 25,000 MW of hydroelectric capacity by 2040.

1 Conclusions

An energy balance based on the production of oil and natural gas in Venezuela during the period 2023-2050 and the associated GHG emissions was carried out. Six energy scenarios were established considering two main variables: the grade of economic opening in Venezuela and the grade of adoption of mitigation measures in the world, besides demographic and macroeconomic parameters, oil productions adjusted to global energy demand scenarios, as well as compliance with the reduction of GHG emissions established in Venezuela's NDC.

The scenario with the highest imports in the 2023-2050 period would be TIC, with 6.02 EJ, while the lowest would be FV with 2.95 EJ, being gasoline and LPG the main imported fuels. The scenario with the highest exports would be FV, reaching 116.86 EJ, and TIC the lowest, with 26.91 EJ. Crude oil would be the main exported fuel, representing between 64.89 to 73.80% of total exports.

Potential emissions were determined for scenarios between 211.50 and 302.35 $MMtCO_2e$ by 2030 and 200.93 and 388.35 $MMtCO_2e$ by 2035, reaching 148.54 and 413.50 $MMtCO_2e$ in 2050. Natural gas flaring and venting would be the category that would generate the highest potential GHG emissions by 2050 in all the scenarios, followed up by the transport sector in the scenarios with 100% adoption of mitigation measures in the world, and oil production for those in without a relevance. CO_2 and CH_4 would be the main GHG emitted, with proportions of 64.07 and 35.77%, respectively, with N_2O remaining.

FV would be the only scenario that would exceed the 20% reduction of GHG emissions from the inertial scenario. Mitigation measures in a scenario FV2 were applied in the transport sector, electricity generation and natural gas flaring and venting, without modifying oil and natural gas production, reducing emissions by 17.06%. This scenario would require an additional capacity, needing 25,000 MW of hydroelectric capacity by 2040 and 14,500 MW of non-conventional renewables by 2048.

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Playful strategy for the analysis of a production system from a lean manufacturing approach

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Abstract
This article presents the development of a playful learning strategy where it is expected that students and future professionals in process management within a company understand what a production chain is and the importance of having tools for diagnosing and improving the value chain in a company. Additionally, it aims to complement the learning of lean manufacturing tools such as 5S and value stream mapping (VSM) for process productivity improvement. The playful approach was applied to different groups in the Industrial Engineering program at Corporación Universitaria Minuto de Dios, Buga Regional Center, and was led by members of the GLIOSP research group within the same program. Among the main results obtained, the strengthening of knowledge and the use of lean manufacturing tools as support for improving production processes stands out.

Keywords: educational game; production; decision making; cognition; education.

Estrategia lúdica para el análisis de un sistema productivo desde un enfoque de manufactura esbelta

Resumen
En este artículo se plantea el desarrollo de una estrategia lúdica de aprendizaje donde se espera que los estudiantes y futuros profesionales de la administración de procesos dentro de una empresa, conozcan lo que es una cadena productiva y la importancia de contar con herramientas para el diagnóstico y mejora de la cadena de valor en una compañía. Asimismo, se espera complementar el aprendizaje sobre herramientas de manufactura esbelta como 5s y mapa de cadena de valor (VSM) para la mejora de la productividad de procesos. La lúdica fue aplicada a distintos grupos del programa de ingeniería industrial de la Corporación Universitaria Minuto de Dios, centro regional Buga y fue liderada por los integrantes del semillero de investigación GLIOSP del mismo programa. Dentro de los principales resultados obtenidos se destaca el fortalecimiento del conocimiento y uso de herramientas de manufactura esbelta como soporte para la mejora de procesos productivos.

Palabras clave: juego educativo; producción; toma de decisiones; cognición; educación.

1 Introduction

Within companies, production chains are a set of standardized operations that transform specific inputs into goods and services through the application of techniques according to the company's operational activities [1]. This work aims to identify the actors involved in a production line and their main issues through tools that promote improvement, such as value stream mapping (VSM) and 5S, lean manufacturing techniques applicable to improving time, organization, and resource reduction in a production operation [2]. The following are some studies where Lean tools have been used for process improvement in business contexts.

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[3] diagnoses a corrugated logistics process in a glass packaging company using the value stream mapping tool. It identifies time, space, and cost waste inherent in the analyzed activities, and defines a series of improvement strategies to be implemented by the organization. These strategies are then represented in a future value stream map. Similarly, [4] applies the value stream mapping strategy in an automotive company, identifying waste in the process and implementing improvements that reduce delivery time, increase manufacturing speed, and decrease work-in-progress inventory. [5] identifies problems associated with the production process of a tannery using the value stream mapping tool, and vali-dates the proposed improvements through simulation, resulting in a reduction in cycle time and lead time for the company.

Another successful case of using the value stream mapping tool is described by [6], which provides a detailed diagnosis of harvesting and post-harvest operations in a pineapple production company. The aim is to identify the most relevant improvements for the process, which are then simulated using Flexsim software. Following this research line, [7] analyzes the production and commercialization process of Hass avocados using the value stream mapping tool. They not only identify activities that do not add value but also define the most relevant risks for the process. Subsequently, strategies for mitigating these events are established, directly related to Lean techniques.

On the other hand, there are alternative methodologies to value stream mapping that have shown positive results in organizations. For example, [8] propose a framework for implementing manufacturing cells in productive environments as a strategy for improving productivity. In contrast, [9] establish a strategic plan for total productive maintenance (TPM) to reduce production downtime and increase manufacturing speed.

Although lean manufacturing tools emerge as a solution to the waste of time, space, and money within organizations [10], professionals working in companies lack a practical framework that allows them to clearly understand how to execute different Lean tools and the potential impact they can have on process performance indicators. To generate effective learning about the methodology for implementing Lean tools, a playful approach is proposed to actively engage students [11]. The following are some references that have successfully implemented learning processes based on playful strategies. [12] establish a playful learning strategy to improve the competencies of Industrial Engineering students in topics related to time standardization and work study. Similarly, [13] create a role-playing game as a strategy to generate meaningful learning in university students in Chile. Conversely, [14] uses a playful strategy with educational robots to teach the importance of technology to elementary education students, aiming to develop competencies necessary for their future as professionals. [15] develops a playful activity to explain concepts of production line balancing, using the Bucket Brigades methodology. In contrast, this paper presents a playful learning strategy that simulates a paper boat production line. It describes a system with various difficulties encountered in production processes and then presents an improved line with the application of value stream mapping (VSM) and 5S. The two scenarios are compared to demonstrate the effectiveness achieved by using lean manufacturing tools, and the learning results obtained in the participating group are presented.

2 Methodology

The methodology proposed for the development of the playful learning strategy considers basic concepts in the field of industrial engineering related to the application of lean manufacturing techniques. It aims to strengthen the competencies of future professionals in this field through the simulation of a paper boat construction process, promoting decision-making and teamwork among participants. Therefore, a learning path is presented, consisting of specific criteria de-fined in three phases:

Phase 1: In this stage, the playful activity is developed, taking into account the participants' prior knowledge. The initial understanding of the concepts is measured through a survey. Then, two groups of 4 to 5 people are formed. Three participants will take on the role of operators in the production line, one will be responsible for time measurement, and another will be designated as the quality manager, ensuring that the requested order is fully met. Each team is provided with the necessary materials for the construction of the paper boat and given a 10-minute time frame to fulfill the customer's orders. At the end of the simulation, a discussion session is opened where the participants can share their experiences, and the problems identified in the initial construction process.

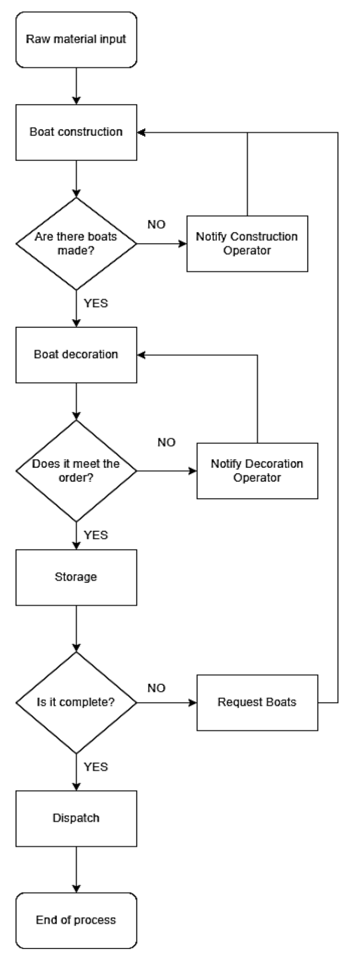

Figure 1. General Flowchart of the Paper Boat Construction Process.
Source: The authors.

Table 1.
Conceptual Framework.

Concept	Definition
Value Stream Map (VSM)	A tool used to diagnose the production systems of goods and services through the proper identification of activities that do not add value [16].
5S	A lean strategy that aims to increase productivity in workstations through proper organization, cleanliness, and standardization [17].
WP	It refers to the inventory that is within the manufacturing process and does not belong to the raw materials inventory or the finished goods inventory [18].

Source: The authors.

Figure 1 shows the overall process of the proposed playful activity's production chain, from the construction of the paper boat to the complete order dispatch to the customer. It is important to consider that validation activities are included in the process to ensure that the customer's requested product is fully met.

Phase 2: The entire group of participants is provided with contextualization on the concepts presented in Table 1. Additionally, materials are given to the teams to proceed with the construction of the value stream map (VSM) and the subsequent identification of issues associated with the process. It is important to note that in this case, the creation of the VSM will require calculating indicators such as cycle time, productivity, and lead time.

Phase 3: After the diagnostic stage, each team must adjust the production process to eliminate the identified flaws and implement the techniques explained by the leading team of the activity. In essence, it is necessary to organize the work areas, ensure material availability, and clearly define the role of each operator within the process. Once this simulation is completed, materials are provided to the team to proceed with the construction of the future value stream map, where the proposed indicators for the production chain should be included again. Finally, a comparison of the results before and after the implementation of lean manufacturing techniques is conducted, followed by a final survey to measure the participants' learning.

3 Results

The ludic activity was carried out in different settings, such as the Ninth National Meeting of the Iddeal Network and the Third Meeting of Ludic Activities in Engineering held at the Minuto de Dios University Corporation, Buga Regional Center. It was also applied to students in the industrial engineering program of the same university within the framework of the GLIOSP research group. The most relevant results are presented below:

Figure 2 shows the value stream map constructed in one of the initial simulated scenarios based on the data collected in Phase 1. In this scenario, the production system is unbalanced, and issues related to order errors, delivery delays, and high levels of work-in-process inventory are identified.

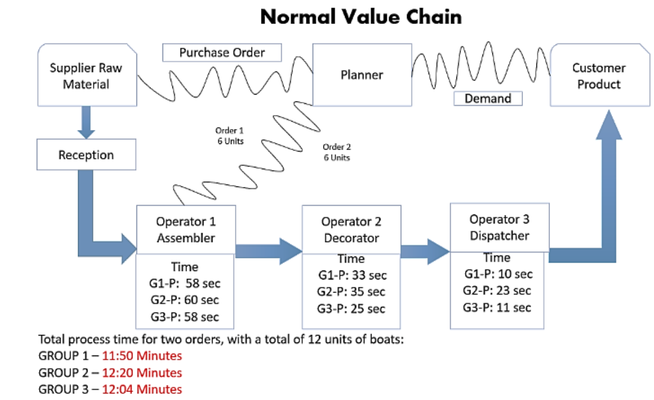

Figure 2. Current Value Stream Map of the paper boat construction process.
Source: The authors.

Subsequently, a discussion is held with the participants to identify problems within the process and address them using Lean philosophy tools such as 5S. Based on this sharing session, the paper boat construction process is modified by each team to eliminate non-value-added activities. Figure 3 presents the future Value Stream Map constructed from the simulation of the process with the improvements implemented by the teams.

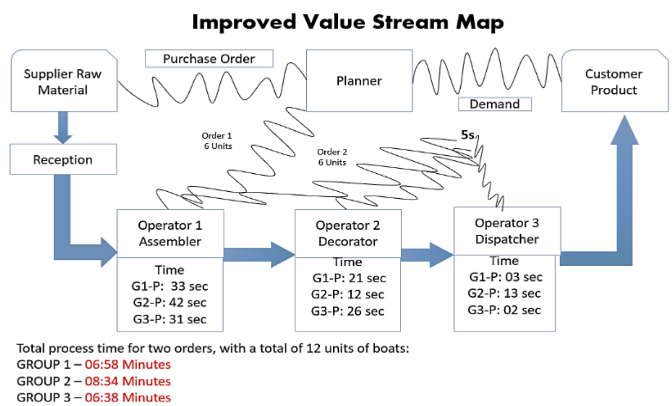

Figure 3. Future Value Stream Map
Source: The authors.

In this future value stream map, the process of building paper boats has been further improved based on the implementation of Lean principles and feedback from the participants. The focus is on eliminating waste, reducing lead time, and improving overall efficiency. The activities have been reorganized, and standardization has been implemented to ensure consistent and high-quality output.

Table 2 shows how the cycle time for the three simulated groups is reduced by an average of approximately 44% after the implementation of 5S and the standardization of the production process, thus confirming the effectiveness of using Lean techniques to improve indicators in production processes.

Table 2.
Measurement of Cycle Time Before and After Implementation of Lean Techniques in Paper Boat Construction Process.

Group	Cycle Time (s) - Phase 1 (without improvements)	Cycle Time (s) - Phase 2 (with improvements)	% Reduction
1	710	418	41,1%
2	740	394	46,8%
3	724	398	45%

Source: The authors.

One of the main objectives of the ludic learning strategy was to generate knowledge among the participants. To achieve this, a measurement of knowledge was conducted at the beginning and end of the activity, aiming to validate the acquisition of new knowledge. The following is a detailed description of the main results obtained.

Initially, the participants were surveyed about their general knowledge of lean production philosophy. As shown in Figure 4, it can be observed that 60% of the students had a general understanding before the ludic activity began. However, after the knowledge sharing session, it was ensured that 100% of the participants were familiar with the central axis of the philosophy, which focuses on reducing non-value-added activities within processes.

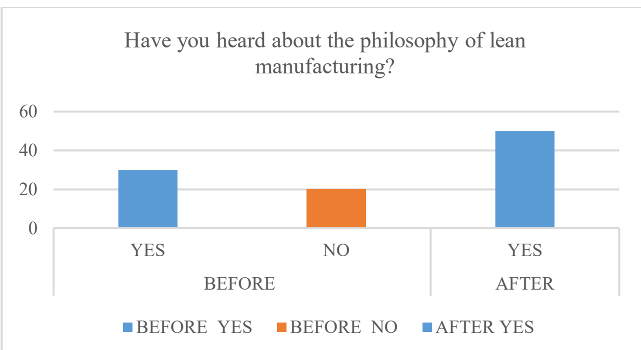

Figure 4. Effect of learning on lean manufacturing philosophy.
Source: The authors.

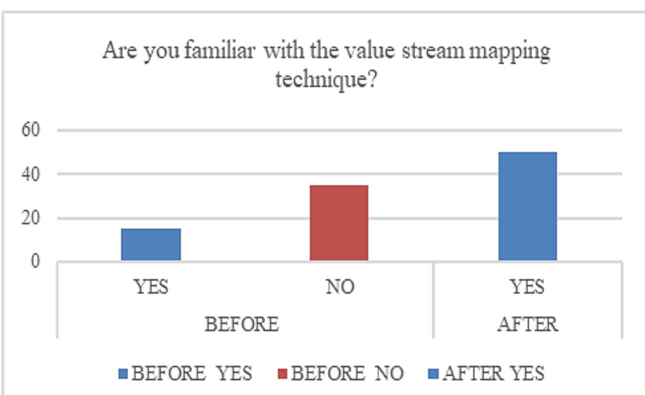

Figure 5. Learning effect on the concept of value stream mapping.
Source: The authors.

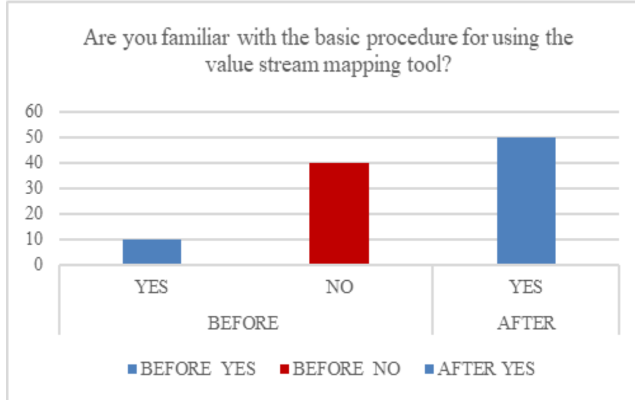

Figure 6. Prioritization of humanitarian aid distribution
Source: The authors.

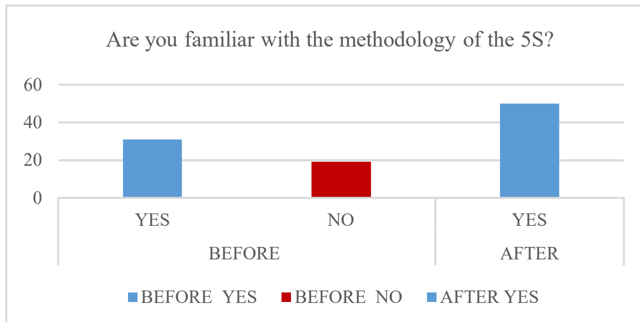

Figure 7. Effect of learning on the concept of the 5S technique.
Source: The authors.

The game was applied to a group of industrial engineering students from different semesters, and it can be observed that there is not a broad knowledge about some basic techniques of Lean Manufacturing philosophy such as VSM and 5S. In Figure 5, it can be noticed that only 30% of the participants were previously familiar with the value stream mapping technique, and even more specifically, only 20% had a clear understanding of the methodology for diagnosing and improving a process (see Figure 6). After the game activity, it is ensured that 100% of the students not only know the concept associated with the value stream mapping technique but also have a clear roadmap for its implementation in various business contexts.

Figure 7 shows that 64% of the participants had prior knowledge of the 5S, while for the remaining 36%, it was an unfamiliar term. After completing the proposed playful activity, it can be observed that this knowledge gap is closed, and 100% of the participants learn about the concept and its implications in a production process.

In summary, analyzing the learning outcomes, it can be observed that the developed ludic strategy allows closing the knowledge gap regarding various concepts associated with Lean Manufacturing philosophy and the use of some of its key tools, such as the value stream mapping (VSM) and the 5S.

This article presents a methodological framework for the implementation of a ludic learning activity in industrial engineering programs and related fields, aiming to improve the understanding of various concepts associated with the use of

Lean Manufacturing philosophy, such as the value stream mapping (VSM) and 5S techniques. It is worth noting that although some previous references have addressed ludic strategies to enhance the competencies of industrial engineering students [19], there has not been a ludic strategy specifically developed to address the use of the value stream mapping technique in conjunction with the 5S methodology in productive environments within an industrial engineering laboratory.

In contrast to where a ludic activity is developed to explain the concept of production line balancing using the bucket brigade's methodology, this article provides a conceptualization of Lean Manufacturing philosophy, with emphasis on two of its main tools, namely the value stream mapping (VSM) and 5S, through a ludic activity that promotes the simulation of a paper boat construction process in an academic environment. From this simulation, strategies for improving critical indicators of a production process, such as cycle time, delivery time, and work-in-process inventory level, are developed.

4 Conclusions

The ludic learning strategy proposed in this document allows for the acquisition of basic knowledge related to the use of Lean techniques such as value stream mapping (VSM) and 5S. When implemented in a simulation context within an industrial engineering laboratory, these techniques increase the productivity of a paper boat production line by reducing rework and controlling excess inventory.

The implementation of the 5S Lean Manufacturing tool successfully represented the improvement in the paper boat production line. Additionally, thanks to the value stream mapping tool, a detailed analysis of the process was conducted to identify process improvements. Although significant improvements were achieved in the production times of this production chain, it is important to note that any production process can always be further improved by identifying process flaws and utilizing available methods for enhancing organizational productivity.

It should be noted that the methodological framework proposed in this research can be implemented in various professional or educational settings. Therefore, in future research, the aim is to enhance the scope of the ludic approach so that it can be utilized as support for training in Lean topics within the industry.

Future research endeavors could focus on enhancing the scope of the analysis to include not only production activities but also logistical operations, ensuring a systemic view of business processes. This way, the ludic approach can be used not only in classrooms but also as a training tool within the industry to strengthen the knowledge of workers, as suggested by [20]. Expanding the application of the ludic approach to real-world industrial settings would provide valuable insights into the practical implementation of Lean principles and techniques, fostering continuous improvement and enhancing overall organizational performance.

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Financial sustainability in Colombia's Lodging SMEs: the role of technological transformation in Colombia's Lodging SMEs

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Abstract
Given the role of sustainability and technological transformations in the global economy and in the growth of companies, the objective was to analyze their effect on the financial sustainability of SMEs in the lodging sector. To achieve this, (1) a bibliometric analysis was conducted using VOSviewer and Biblioshiny, (2) a mean difference test (T-student) was performed to compare technological transformation and financial sustainability variables, and (3) a correlation analysis was carried out between indebtedness and liquidity risk, based on financial data from 2022 for SMEs in the top five regions according to the Colombian Regional Tourism Competitiveness Index. The findings highlight a scarcity of research on financial sustainability and digital transformation processes in Colombian SMEs, in contrast to other regions worldwide. Regarding the T-test, no statistically significant differences were found between the variables analyzed. Therefore, we strongly recommend further research incorporating multivariate analyses to include additional variables relevant.

Keywords: lodging sector; financial sustainability; SMEs; technological transformation; liquidity risk; profitability

Sostenibilidad financiera de las PYME hoteleras en Colombia: el papel de la transformación tecnológica en las Pymes de alojamiento en Colombia

Resumen
Dado el papel de la sostenibilidad y las transformaciones tecnológicas en la economía mundial y en el crecimiento de las empresas, se analizó su efecto en la sostenibilidad financiera de las Pyme del sector del alojamiento. Para ello, (1) se realizó un análisis bibliométrico utilizando VOSviewer y Biblioshiny, (2) una prueba de diferencia de medias (T-student) para comparar las variables de transformación tecnológica y sostenibilidad financiera, y (3) un análisis de correlación entre endeudamiento y riesgo de liquidez, a partir de datos financieros de 2022 de Pymes de las cinco primeras regiones según el Índice de Competitividad Turística Regional de Colombia. Los hallazgos resaltan escasez de investigaciones sobre sostenibilidad financiera y procesos de transformación digital en Pyme colombianas, en contraste con otras regiones del mundo. Respecto a la prueba T, no se encontraron diferencias estadísticamente significativas entre las variables analizadas. Recomendamos investigaciones que incorporen análisis multivariados con variables adicionales relevantes.

Palabras clave: sector de alojamiento; sostenibilidad financiera; Pyme; transformación tecnológica; riesgo de liquidez; rentabilidad.

1. Introduction

1.1 An approach to Colombian microenterprises

According to Decree No 957 of June 05, 2019, in its Article 2.2.2.1.13.2.2, the size of the enterprise in Colombia is determined considering the range of their income from annual ordinary activities, according to the economic sector in which they are located, as illustrated in Fig. 1.

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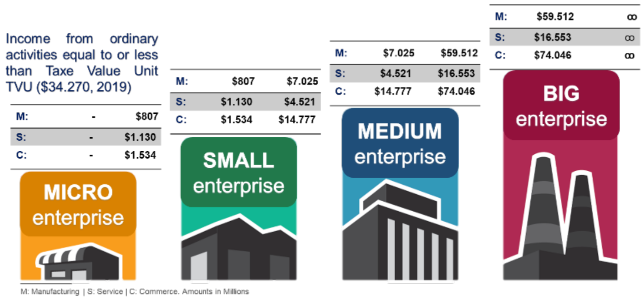


Figure 1. New classification of Colombian companies
Source: based on [1]

The manufacturing sector is made up of those whose income from ordinary annual activities is less than or equal to 23,563 Tax Value Units (UVT), for the services sector, with income from ordinary annual activities less than or equal to 32,988 UVT, and the commerce sector with income from ordinary annual activities less than or equal to 44,769 UVT.

1.2 Financial sustainability in SMEs in the lodging sector

The objective of any company, regardless of its size and scope of activity, is based on maintaining a stable financial situation and results, which is associated with financial sustainability [2,3]. This financial equilibrium is one of the most important aspects in relation to the financial stability of an economic entity and its long-term financial sustainability, which significantly reduces the risk of bankruptcy, ensures healthy financing, efficient use of the company's assets and guarantees an exclusive advantage over companies that have an unfavorable situation [4]. Consequently, one of the economic activities with the greatest volatility in its financial flows is undoubtedly the lodging sector, which is closely related to the tourism industry, whose growth could have a strong influence on the organizational performance of the hotel industry. Therefore, the expansion of tourism activities directly enhances the development of the hotel industry, increasing the occupancy rate and, consequently, sales revenue [5]. However, for companies to be more competitive and achieve their financial objectives, they must invest in processes to transform their business models, strategies and operations, which is related to the concept of financial sustainability [6]. Moreover, a company's financial performance depends on its ability to generate revenues and maintain stable business continuity [5]. Thus, to ensure sustainable existence and growth, companies must analyze the correlations between the assets they own and use, together with their sources of financing, to assess the extent to which these are related to their fixed and working capital requirements [7]. Therefore, the use of an optimal mix of investments and sources of financing ensures the highest level of financial sustainability, which translates into a greater capacity to generate value for the owners and provide continuity of operations over the long term [2].

1.3 Technological transformations: key tools for SMEs strengthening.

Technological transformation has constantly evolved, generating countless possibilities to access the world. Thus, the Internet has radically changed the way in which people communicate, seek information, make decisions and, above all, purchase goods and services, generating a considerable growth in electronic distribution channels [8]. In order to remain competitive in today's globalized market, SMEs have increasingly turned to the adoption of Information and Communication Technologies (ICTs) as a strategic means to rival large corporations [9,10]. As a primary driver of development and innovation in the modern world, ICTs have become a crucial factor in fostering growth and innovation [11]. Although the literature on the significant positive influence of ICT on business performance is extensive, especially in SMEs [12-14], in the hotel sector this relationship is not so evident [11]. In line with the above, some researchers argue that ICT adoption is a competitive advantage factor, as it improves customer experience, which can increase hotel performance [15,16].

In line with the above, several authors [17-19] have extensively explored the consequences of adopting new technologies and practices on the overall improvement of organizational performance. In this order of ideas, it can be stated that digital orientation focuses on collaboration and the amalgamation of technological and business strategies [20], providing guidance and principles through which organizations adopt and use technologies to achieve superior advantage and sustainable growth [21]. It should be noted that, "travel products in particular have proven to be some of the most suitable ones to sale online" [8]. In fact, it has been stated that SMEs with digitalization processes survive in international markets [22], facilitates organization, to improve communication and information processing [23], [24], [25], increase operational efficiency [26], and expand their businesses [27]. Therefore, companies' orientation towards digitization contributes to organizational learning and information sharing, which is essential for business continuity [28]. However, resource scarcity, financial constraints, lack of technical know-how and government policies are the main challenges and barriers faced by SMEs to organizational digital orientation [29-31]. Although SMEs often lack the necessary skills, they must adopt emerging technologies and methodologies, such as the Internet of Things (IoT) and artificial intelligence (AI), to maintain their competitiveness [32].

1.4 Lodging sector: business models and transformations.

Hospitality and tourism industry became vital to the economic development in several regions worldwide [33]. In Colombia, this sector has experienced remarkable growth and has become a fundamental pillar in the national economy [34]. However, this sector, like others, has resorted to transforming its business models as a result of the opening of markets and the technology revolution, whose rapid advances in innovation, especially smartphones and Internet services, have led to changes in consumer behaviors [35], leading many companies to move from developing tangible products to providing services [36-38]. According to [39], SMEs in the tourism sector must be at the forefront of technologies and propose devices, techniques and technological achievements using the most current and high-level IT developments. Thus, in the digital economy, most of the hoteliers need to face the new challenges on emerging strategic issues and concerns which were the impact from the information and telecommunication technology revolution [40]. However, other authors consider that the adoption of ICTs cannot increase hotel performance, since it is not directly aimed at improving productivity, but rather these innovative systems aim to improve customer service and increase the number of services offered, which leads to not identifying ICTs adoption as a critical success factor for achieving exceptional company performance [41-43]. In addition to the above, investments in technology lead the company to improve product quality, increasing production costs and, consequently, decreasing the company's performance [43]. “In SMEs, digital technologies will mark the beginnings of a new business change” [44]. However, much remains to be done in the SME sector [45].

Table 1.
Design of the search strategy

Step	Applied search terms Words used	Number of publications	
		Scopus®	WOS™
1	("financial sustainability") AND ("SME*" OR "SMEs" OR "smallor medium-sized enterprises" OR "small and medium-sized enterprises" OR "small to midsize enterprise" OR "small and medium sized business" OR "Small and Medium-Sized Entities" OR "lodging sector" OR "hotel*")	45	22
2	("sustainable business model*") AND ("SME*" OR "SMEs" OR "smallor medium-sized enterprises" OR "small and medium-sized enterprises" OR "small to midsize enterprise" OR "small and medium sized business" OR "Small and Medium-Sized Entities" OR "lodging sector" OR "hotel*")	87	56
3	("financial sustainability" OR "sustainable business model*") AND ("SME*" OR "SMEs" OR "smallor medium-sized enterprises" OR "small and medium-sized enterprises" OR "small to midsize enterprise" OR "small and medium sized business" OR "Small and Medium-Sized Entities" OR "lodging sector" OR "hotel*")	132	78
4	When filtering by item, the result is:	96	76
5	("technological change" OR "technology*" OR "digital tools") AND ("sustainable business model*" OR "financial sustainability") AND ("SME*" OR "SMEs" OR "smallor medium-sized enterprises" OR "small and medium-sized enterprises" OR "small to midsize enterprise" OR "small and medium sized business" OR "Small and Medium-Sized Entities" OR "lodging sector" OR "hotel*")	23	16
6	Adding the results of the steps, the following results are obtained:	119	92

Source: own elaboration

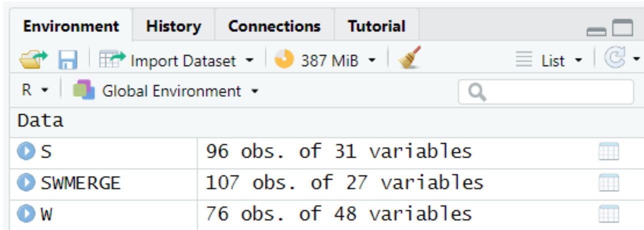


Figure 2. Unification and cleaning of information
Source: Own elaboration by using R Studio 4.4.1

2. Methodology

2.1 Planning

In this first stage, the bibliometric analysis is prepared, for which the scientific databases Scopus and Web of Science (WoS) were selected as inputs in the search for information (Table 1).

After searching for articles through the equations, the information was migrated in BibTeX format to the RStudio software, where the debugging and filtering process was carried out using the mergeDbSources command. The result yielded a total of 107 observations with 27 variables (Fig. 2).

2.2 Data Description

The second stage of this research is focused on analyzing the effect of sustainability and technological transformations on the financial sustainability of SMEs in the Colombian lodging sector. To obtain the sample, the financial statements were extracted from the SIIS portal of Superintendencia de Sociedades (Supersociedades), for the period 12/31/2022 for SMEs-Individuals. This query yielded a population of 24,536 companies that reported for the period analyzed. Subsequently, a filter was performed according to the activities: I5511 - Hotel accommodation, I5512 - Aparthotel accommodation, I5513 - Resort accommodation, I5514 Rural accommodation, I5519 - Other types of accommodation for visitors, I5520 - Activities of camping areas and parks for recreational vehicles, I5530 - Accommodation services by the hour and I5590 - Other types of accommodation n.e.c., which yielded 290 companies from different departments. Subsequently, companies from the District of Bogota and the departments of Valle, Risaralda, Antioquia and Bolivar were filtered, obtaining a final result of 74, 23, 7, 44 and 29 companies, respectively. The selection was based on data from the Ministry of Trade, Industry and Tourism, which indicates that these territories accounted for 47% of tourism service operators and 44% of lodging and accommodation services [46].

With the Statement of Financial Position and Income Statement of the selected companies, the different financial indicators were calculated: Acid Test - AT, Working Capital Ratio - WK, Cash Ratio – CT, Current Ratio - CR, Accounts Receivable Turnover - AR, Gross Margin - GM, Operating Margin - OM, Net Margin - NM, Return on Assets - RA, Return on Equity - RE, Total Indebtedness - TI, Financial Indebtedness - FI, Total Leverage - TL and Financial Leverage - FL, necessary for the correlational analysis and the T-test. On the other hand, dichotomous variables were defined as Technology - TCN, Website - WP, Sustainable Development Goals - SDG and Sustainability Reports - SR, obtained through the websites and reports of each of the companies in the sample.

2.3 Hypothesis

To achieve the objective authors worked with a correlational approach [47,48], and sought to corroborate the following hypothesis: *Ha: there are no statistically significant differences in financial sustainability between companies in the lodging sector that do or do not apply technological transformation processes, Hb: There is a positive relationship between capital structure and liquidity risk.* For the first hypothesis, the independent variable was "technological transformation" (categorical), and the dependent variable was "financial sustainability" (continuous), the latter measured through liquidity and indebtedness indicators. For the second, capital structure was taken as an independent variable and liquidity risk as a dependent variable to prove that the higher the indebtedness, the higher the level of liquidity risk and vice versa.

2.4 Data analysis strategies

The data analysis was divided into two stages: (1) bibliometric analysis, (2) correlation and mean difference analysis. For the first one, bibliometric technological tools such as VOSviewer and R Biblioshiny - bibliometrix were also used. For the second, the R software Version 4.4.1 was used, where it was used for the bivariate correlation analysis, the leveneTest and ShapiroTest were applied for variance and normality validation. Also, the Stata software was used for multivariate analysis. Given that database, parametric tests of mean differences (T-Test) were performed for Bogotá and Antioquia, and nonparametric tests (Mann-Whitney U) for independent samples of less than 30 observations in the case of Valle, Risaralda and Bolívar.

3. Results

3.1 Overview and Historical distribution of papers

Before starting with the bibliometric analysis, describing how the data is structured is essential. Fig. 3 contains 107 articles taken from 71 sources, with the participation of 312 authors, among which a percentage of 1.869% international co-authorship, with an average of 3.12 documents per author and 5.03 documents per year. The average annual citation presented an increase equivalent to 2.81%.

Figure 3. Main information & Annual Scientific Production
Source: Own elaboration by using Biblioshiny in R

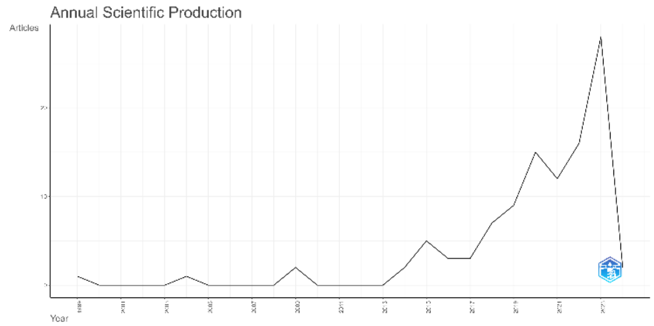


Figure 4. Annual Scientific Production
Source: Own elaboration by using Biblioshiny in R

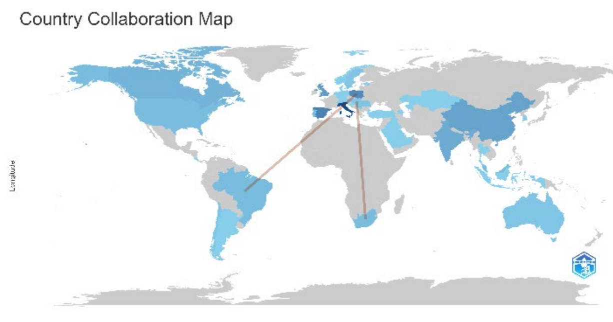


Figure 5. Country Collaboration Map
Source: Own elaboration by using Biblioshiny in R

Fig. 4 illustrates a relatively low production on the topic studied between 1999 and 2024. Nevertheless, from 2014 onwards, an increase in the number of publications is evident, reaching its peak in 2023 with 28 documents. Despite the initially low production, a 54% average growth trend is recorded. The observed decrease in 2024 is attributed to ongoing production at the time of the consultation.

An examination of the international collaboration map (Fig. 5), reveals sparse co-authorship among nations, with collaborations between Poland and Brazil, and Hungary and South Africa, being particularly noteworthy. Within Latin America, only Brazil, Argentina, Chile, and Costa Rica are represented these scientific production efforts. This underscores the potential for initiatives aimed at promoting international research collaboration, which could significantly increase the global reach and dissemination of scientific knowledge.

3.2 Collaboration and research trends

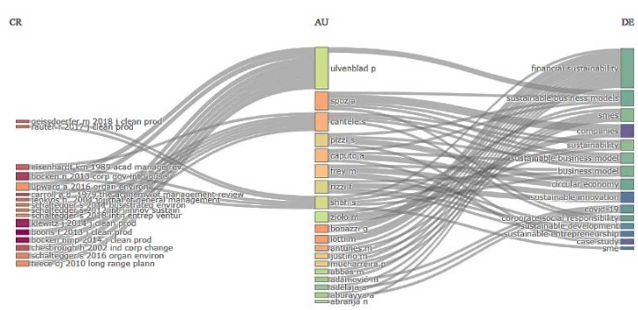


Figure 6. Three-Field Plot
Source: Own elaboration by using Biblioshiny in R

In accordance with the previous figures, among the authors with the greatest production, Ulvenblad, P. out and has published on the topics of sustainable business models. On the other hand, there is Spoz, A. contributed to the lines of sustainable business models, sustainability & corporate social responsability. Other authors on the list include Cantele, S., Pizzi, S., Caputo A., and Frey M., as shown in Fig. 6.

This figure also shows the topics that set a trend in research, for which the analysis is divided into four quadrants, where the driving themes such as sustainability, innovation, financial sustainability, which have been studied in SMEs, stand out. On the other hand, basic topics such as business models, sustainable development, sustainable business and business development are shown. As shown in Fig. 4, these are topics that despite being located in the quadrant of basic topics, there is a tendency towards motor topics, given their connection with other areas of research.

The analysis of co-occurrence networks (Fig. 7), yielded four clusters, which prominently feature terms such as *small and medium-sized entreprise, sustainability, sustainable develpment, innovation, model, profitability, tourism, bankruptcy, financial sustainability, hotels, developing countries, business model innovation*. These terms reflect the importance of co-occurrence among the topics under investigation, highlighting the complex relationships between these key concepts.

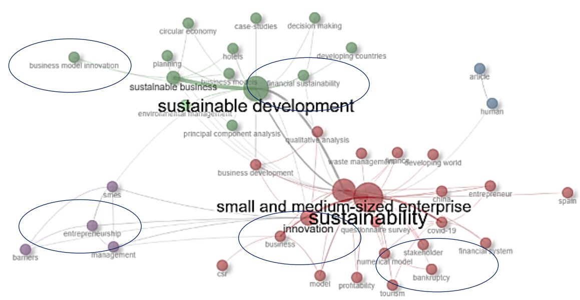


Figure 7. Co-occurrence Network
Source: Own elaboration by using Biblioshiny in R

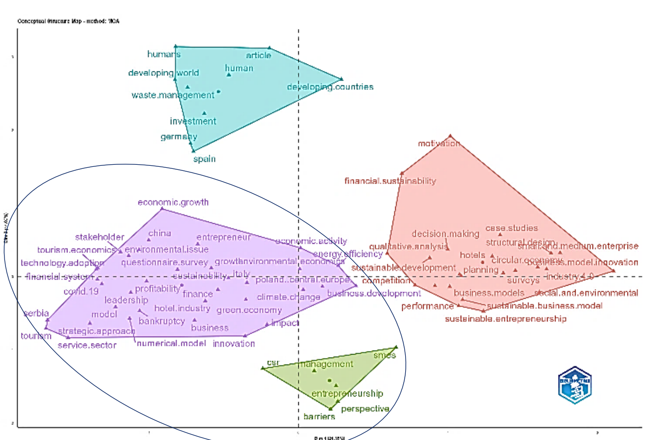
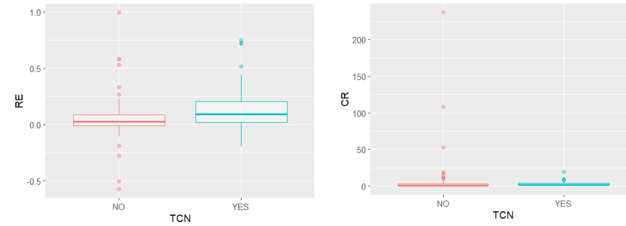


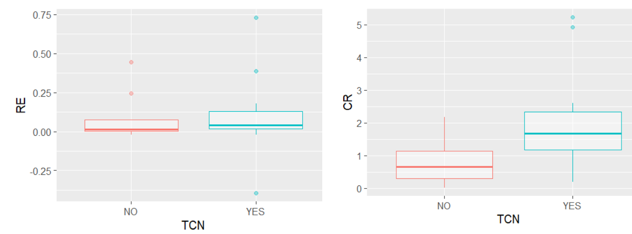
Figure 8. Factorial Analysis
Source: Own elaboration by using Biblioshiny in R



> t.test(RE ~ TCN, data = DATOS_B, var.equal = T)
data: RE by TCN
t = -1.8204, df = 72, p-value = 0.07285

> t.test(CR ~ TCN, data = DATOS_B , var.equal = T)
data: CR by TCN
t = 1.1371, df = 72, p-value = 0.2593

Figure 9. Bogota T-test analysis
Source: Own elaboration by using R Studio 4.4.1



> wilcox.test(x = YES$RE, y = NO$RE, alternative = "two.sided", paired = F)
data: YES$RE and NO$RE
W = 76, p-value = 0.4389

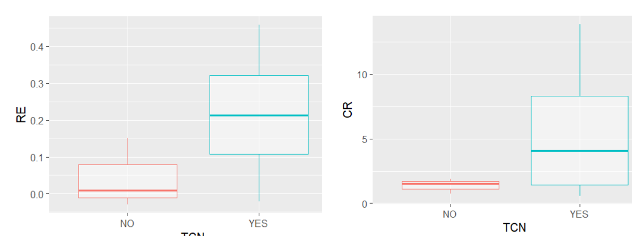
> wilcox.test(x = YES$CR, y = NO$CR, alternative = "two.sided", paired = F)
data: YES$CR and NO$CR
W = 97, p-value = 0.03275

Figure 10. Valle Mann–Whitney U test analysis
Source: Own elaboration by using R Studio 4.4.1

The Factor Analysis (Fig. 8) provides a clearer visualization of the cluster configuration, revealing that the lilac and olive-green clusters constitute the network with the most diverse array of terms. These clusters include prominent concepts such as tourism, sustainability, innovation, entrepreneurship, and SMEs, which underscore the complex relationships between the aspects investigated in this study.

3.3 Technological transformation processes in companies of the lodging sector in Bogota, Valle, Risaralda, Antioquia and Bolivar

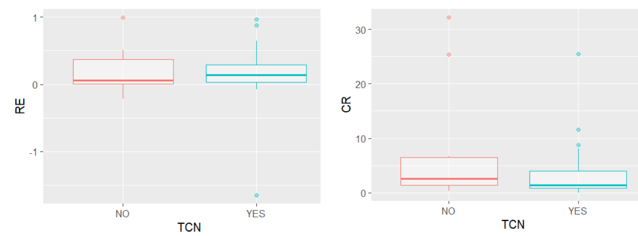
In the case of Figures 9 to 13, it can be observed that all variables are at the same level, which at first glance reflects the non-existence of a difference in means, although there are some outliers, which may in turn generate the difference between the averages.



> wilcox.test(x = YES$RE, y = NO$RE, alternative = "two.sided", paired = F)
data: YES$RE and NO$RE
W = 9, p-value = 0.4

> wilcox.test(x = YES$CR, y = NO$CR, alternative = "two.sided", paired = F)
data: YES$CR and NO$CR
W = 8, p-value = 0.6286

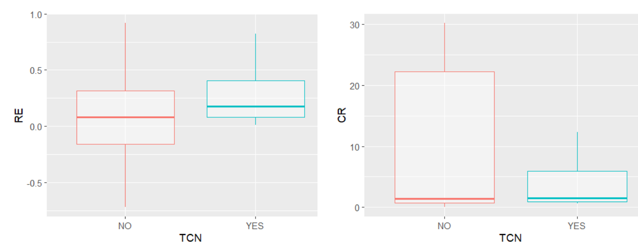
Figure 11. Risaralda Mann–Whitney U test analysis
Source: Own elaboration by using R Studio 4.4.1



> t.test(RE ~ TCN, data = DATOS_A, var.equal = T)
data: RE by TCN
t = 0.23826, df = 42, p-value = 0.8128

> t.test(CR ~ TCN, data = DATOS_A , var.equal = T)
data: CR by TCN
t = 1.6098, df = 42, p-value = 0.1149

Figure 12. Antioquia T-test analysis
Source: Own elaboration by using R Studio 4.4.1



> wilcox.test(x = YES$RE, y = NO$RE, alternative = "two.sided", paired = F)
data: YES$RE and NO$RE
W = 115, p-value = 0.2534

> wilcox.test(x = YES$CR, y = NO$CR, alternative = "two.sided", paired = F)
data: YES$CR and NO$CR
W = 86, p-value = 0.8714

Figure 13. Bolivar Mann–Whitney U test analysis
Source: Own elaboration by using R Studio 4.4.1

However, the results of the test show that there are no statistically significant differences between the means of variables (RE and CR) at a 5% significance level, for Bogota, Valle, Risaralda, Antioquia and Bolivar. At the financial level, this means that the fact of applying technology in the selected companies has no effect on their profitability or liquidity. In other words, if the company makes the decision to invest in new technology, it will not increase or decrease profitability. However, in the case of Risaralda there is a statistically significant difference in the CR indicator, reflecting a higher indicator for those companies that choose to invest in technologies.

3.4 Indebtedness and liquidity risk in companies of the lodging sector.

Since the goal of businesses is to achieve a stable financial position, called financial equilibrium, this can be analyzed with the help of specific indicators which are aimed at the relationship between the permanent and temporary needs compared to the permanent and temporary sources [36]. For this purpose, two types of indicators are used, i.e., indicators in absolute sizes such as working capital [37], working capital needs, net treasury, as well as indicators in relative sizes, such as liquidity and solvency ratios [38].

Accordingly, Figure 14 to 18 present the correlation analyses between the liquidity and indebtedness variables, in order to establish whether there is a relationship between indebtedness and liquidity risk.

	rowname	AT	WK	CT	CR	AR	GM	OM	NM	RA	RE	TI	FI	TL
1	AT													
2	WK	0.18												
3	CT	0.036	0.37**											
4	CR	0.18	0.85****	0.5****										
5	AR	-0.0096	0.08	-0.23*	0.18									
6	GM	0.079	-0.1	-0.031	-0.005	0.4***								
7	OM	-0.056	0.04	0.27*	0.088	0.13	0.1							
8	NM	0.16	0.24*	0.42***	0.31**	0.069	0.14	0.7****						
9	RA	-0.039	0.29*	0.34**	0.23*	-0.0096	0.0012	0.55****	0.81****					
10	RE	0.0039	0.18	0.22	0.11	0.097	-0.075	0.37**	0.63****	0.82****				
11	TI	-0.28*	-0.13	-0.26*	-0.21	0.17	0.027	-0.16	-0.31**	-0.18	0.21			
12	FI	-0.18	0.063	-0.029	0.016	0.16	0.26*	0.22	-0.013	-0.018	-0.13	0.16		
13	TL	-0.35**	-0.054	-0.18	-0.13	0.2	0.16	-0.019	-0.17	-0.021	0.16	0.84****	0.23*	
14	FL	-0.24*	0.067	-0.074	-0.014	0.15	0.17	0.21	-0.065	0.0023	-0.082	0.25*	0.95****	0.32**

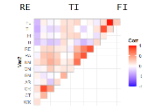


Figure 14. Bogota Correlation & Significance matrix
Source: Own elaboration by using R Studio 4.4.1

Before analyzing the results in Figure 10 to 14, it is important to note that these are presented at the 0.01 ** and 0.05 * levels of bilateral significance. In this order of ideas, when analyzing the relationship between the liquidity and indebtedness variables of the companies of the lodging sector in Bogota, it is observed that in the case of the Acid Test - AT, it presents significant negative correlations at 0.01 with the Total Leverage indicator - TL (-.35), and significant negative correlations at 0.05 with the Total Indebtedness - TI (-.28) and Financial Leverage - FL (-.24) indicators. On the other hand, when analyzing the Cash Ratio - CR, there is a significant negative correlation at 0.05 with the Total Indebtedness - TI indicator (-.26). The Working Capital Ratio - WK, Current Ratio - CR and Accounts Receivable Rotation - AR do not have a negative correlation with the debt indicators.

Regarding the analysis of the relationship between the liquidity and indebtedness indicators of the SMEs of the lodging sector in Valle, the AT indicator presents significant negative correlations at 0.05 with the TI (-0.43). With respect a negative correlation significant at 0.01 is observed between the indicators WK and TI (-1). Finally, AR presents a positive relationship significant at 0.05, with the indicators FI (0.41).

Regarding the analysis of the relationship between the liquidity and indebtedness indicators of the SMEs of the lodging sector in Risaralda, the AT indicator presents significant positive correlations at 0.05 with the TL (0.82). On the other hand, a negative correlation significant at 0.01 is observed between the indicators WK and TI (-1).

	rowname	AT	WK	CT	CR	AR	GM	OM	NM	RA	RE	TI	FI	TL	FL
1	AT														
2	WK	0.43*													
3	CT	0.78****	0.3												
4	CR	0.98****	0.4	0.77****											
5	AR	0.23	0.089	-0.049	0.22										
6	GM	-0.048	0.038	-0.14	-0.08	0.4									
7	OM	0.5*	0.32	0.55**	0.58**	-0.083	0.054								
8	NM	0.46*	0.37	0.47*	0.5*	-0.078	0.024	0.87****							
9	RA	0.51*	0.21	0.45*	0.52*	-0.024	0.034	0.73****	0.88****						
10	RE	0.5*	0.15	0.4	0.51*	0.019	0.068	0.7***	0.85****	0.98****					
11	TI	-0.43*	-1****	-0.3	-0.4	-0.089	-0.038	-0.32	-0.37	-0.21	-0.15				
12	FI	0.1	-0.2	-0.082	0.18	0.41*	0.15	0.21	0.28	0.32	0.4	0.2			
13	TL	-0.18	-0.4	0.0045	-0.19	-0.21	-0.059	-0.24	-0.22	-0.11	-0.028	0.4	-0.076		
14	FL	0.1	-0.41	-0.0045	0.12	0.33	0.015	-0.024	0.12	0.26	0.27	0.41	0.75****	-0.088	

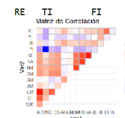


Figure 15. Valle Correlation & Significance matrix
Source: Own elaboration by using R Studio 4.4.1

	rowname	AT	WK	CT	CR	AR	GM	OM	NM	RA	RE	TI	FI	TL	FL
1	AT														
2	WK	0.41													
3	CT	0.16	0.31												
4	CR	0.89*	0.09	-0.16											
5	AR	0.18	-0.43	0.18	0.21										
6	GM	0.31	0.091	0.45	0.2	0.76*									
7	OM	0.63	-0.31	0.055	0.63	0.61	0.24								
8	NM	0.96**	0.31	0.34	0.86*	0.32	0.45	0.67							
9	RA	0.79*	-0.036	0.25	0.79*	0.54	0.36	0.79*	0.86*						
10	RE	0.79*	0.064	0.43	0.68	0.63	0.54	0.81*	0.88**	0.95***					
11	TI	-0.41	-1****	-0.31	-0.09	0.43	-0.091	0.31	-0.31	0.036	-0.064				
12	FI	0.13	-0.47	-0.16	0.13	0.67	0.16	0.79*	0.13	0.36	0.43	0.47			
13	TL	0.82*	0.72	0.4	0.61	-0.29	0.11	0.18	0.79*	0.46	0.49	-0.72	-0.36		
14	FL	0.039	-0.38	0.04	-0.059	0.37	-0.14	0.7	0.039	0.26	0.33	0.38	0.88**	-0.26	

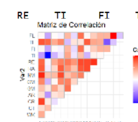


Figure 16. Risaralda Correlation & Significance matrix
Source: Own elaboration by using R Studio 4.4.1

	rowname	AT	WK	CT	CR	AR	GM	OM	NM	RA	RE	TI	FI	TL	FL
1	AT														
2	WK	0.45**													
3	CT	0.63****	0.36*												
4	CR	0.99****	0.47**	0.62****											
5	AR	0.31*	-0.0067	-0.16	0.27										
6	GM	0.08	0.13	-0.25	0.08	0.28									
7	OM	0.37*	0.18	0.26	0.35*	0.2	0.16								
8	NM	0.41**	0.15	0.28	0.39**	0.15	0.34*	0.78****							
9	RA	0.21	-0.11	0.1	0.18	0.11	-0.12	0.57****	0.56****						
10	RE	0.21	-0.28	0.16	0.18	0.065	-0.26	0.36*	0.35*	0.78****					
11	TI	-0.45**	-1****	-0.36*	-0.47**	0.0067	-0.13	-0.18	-0.15	0.11	0.28				
12	FI	-0.088	-0.0064	0.14	-0.11	-0.0082	-0.12	0.33*	0.13	0.18	0.049	0.0064			
13	TL	-0.23	-0.069	-0.22	-0.21	-0.25	-0.11	-0.17	-0.22	-0.19	-0.1	0.069	-0.1		
14	FL	-0.1	-0.064	0.16	-0.11	-0.071	-0.36*	0.1	-0.1	0.18	0.36*	0.064	0.73****	0.11	

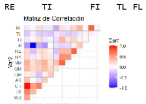


Figure 17. Antioquia Correlation & Significance matrix
Source: Own elaboration by using R Studio 4.4.1

	rowname	AT	WK	CT	CR	AR	GM	OM	NM	RA	RE	TI	FI	TL	FL
1	AT														
2	WK	0.76****													
3	CT	0.7****	0.69****												
4	CR	0.97****	0.67****	0.7****											
5	AR	0.38*	0.49**	0.2	0.38*										
6	GM	0.047	0.23	-0.0085	-0.032	0.47*									
7	OM	0.32	0.42*	0.38*	0.27	0.39*	0.47*								
8	NM	0.42*	0.52**	0.57**	0.38*	0.37	0.38*	0.88****							
9	RA	0.26	0.45*	0.53**	0.27	0.38*	0.34	0.58***	0.71****						
10	RE	-0.018	0.22	0.17	0.014	0.27	0.2	0.15	0.3	0.7****					
11	TI	-0.41*	-0.33	-0.68****	-0.4*	-0.12	-0.077	-0.56**	-0.57**	-0.3	0.34				
12	FI	-0.5**	-0.44*	-0.39*	-0.43*	0.067	-0.11	0.086	-0.21	-0.24	-0.035	0.15			
13	TL	-0.42*	-0.34	-0.68****	-0.4*	-0.12	-0.076	-0.56**	-0.57**	-0.31	0.33	1****	0.16		
14	FL	-0.63***	-0.57**	-0.52**	-0.55**	-0.13	-0.2	-0.14	-0.4*	-0.36	-0.093	0.28	0.9****	0.29	

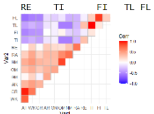


Figure 18. Bolivar Correlation & Significance matrix
Source: Own elaboration by using R Studio 4.4.1

Regarding the analysis of the relationship between the liquidity and indebtedness indicators of the SMEs of the lodging sector in Antioquia, the AT indicator presents significant negative correlations at 0.01 with the TI (-0.45). On the other hand, a negative correlation significant at 0.01 is observed between the indicators WK and TI (-1). In the same way, a negative correlation significant at 0.01 is observed between the indicators CR and TI (-0.47). Finally, CR presents a negative relationship significant at 0.05, with the indicators TI (-0.36).

Following the previous, the null hypothesis is rejected, and the researchers' hypothesis is accepted since there is a negative correlation between the variables analyzed: AT, at 99% confidence; and TI and FI, at 95% confidence, as explained, which leads to corroborate the existence of a positive relationship between capital structure and liquidity risk.

Regarding the analysis of the relationship between the liquidity and indebtedness indicators of the SMEs of the lodging sector in Bolivar, a negative correlation significant at 0.01 and 0.05 is observed between the indicators mentioned, except between the liquidity variable WK and the indebtedness variables TI and TL. In this order of ideas, the AT indicator presents significant negative correlations at 0.01 with the FI (-0.05) and FL (-0.63) indicators, as does the relationship between WK and FL (-0.57), CT and the TI (-0.68), TL (-0.68) and FL (-0.52) indicators, and finally the relationship between CR and FL (-0.55). With respect to the negative relationships significant at 0.05, the behavior between AT and the indicators TI (-0.41) and TL (-0.42), WK and FI (-0.44), CT and FI (-0.39), and finally CR and the indicators TI (-0.4), FI (-0.42) and TL (-0.4) was observed.

3.5 Multivariate analysis: technology and profitability in departments

The analysis corresponds to a logistic regression, which considers as independent variable the adoption of technologies by the companies and as explained variables the

TCN	Odds Ratio	Std. Err.	z	P>|z|	[95% Conf.	Interval]
GM	1.117856	.6848489	0.18	0.856	.336435	3.714242
OM	1.652084	1.048908	0.79	0.429	.4759969	5.73403
NM	1.070089	.1423391	0.51	0.611	.8245111	1.388812
RA	19.49117	50.33395	1.15	0.250	.1235085	3075.947
RE	.9032762	.8453434	-0.11	0.913	.144282	5.654955
DEPARTAMENTO						
VALLE	2.379621	1.19046	1.73	0.083	.8926366	6.343674
RISARALDA	1.717115	1.408542	0.66	0.510	.3440033	8.571093
ANTIOQUIA	3.367482	1.455573	2.81	0.005	1.443374	7.856548
BOLIVAR	5.47779	2.909515	3.20	0.001	1.934157	15.51383
_cons	.5008874	.2536987	-1.37	0.172	.1856128	1.351675

Figure 19. Logistic regression TGN~ departments, GM, OM, NM. RA , RE
Source: Own creation using Stata software

TCN	Odds Ratio	Std. Err.	z	P>|z|	[95% Conf.	Interval]
GM	1.408862	.8918571	0.54	0.588	.4074076	4.872005
OM	.7033381	.4276339	-0.58	0.563	.2136133	2.315794
NM	1.024056	.1466484	0.17	0.868	.7734441	1.355873
RA	316611.4	1794738	2.23	0.025	4.736089	2.12e+10
RE	.5819148	.7849793	-0.40	0.688	.0413641	8.186448
_cons	.3179293	.1860457	-1.96	0.050	.1009776	1.001005

Figure 20. Logistic regression Bogota TGN~ GM, OM, NM. RA , RE
Source: Own creation using Stata software

TCN	Odds Ratio	Std. Err.	z	P>|z|	[95% Conf.	Interval]
GM	.321153	.9350107	-0.39	0.696	.0010678	96.58631
OM	2794.285	11632.98	1.91	0.057	.7991085	9770927
NM	.2843828	1.126184	-0.32	0.751	.0001211	667.9512
RA	1.91e-11	1.80e-10	-2.62	0.009	1.79e-19	.0020473
RE	3510.431	18822.07	1.52	0.128	.0958133	1.29e+08
_cons	7.01155	15.67962	0.87	0.384	.0875608	561.4594

Figure 21. Logistic regression Antioquia TGN~ GM, OM, NM. RA , RE
Source: Own creation using Stata software

departments, profitability indicators. The results show that there is a statistical relationship between technology and the departments of Antioquia and Bolivar, indicating that these departments are between 3.3 and 5.5 times more likely to adopt technologies in the companies than the others (Fig. 19).

In this multivariate model there is no evidence of a relationship between profitability indicators and technology in all the departments studied except Antioquia and Bolivar; however, when analyzing the individual results, important relationships between the return on assets (RA) and technology in the departments of Bogota (Fig. 20) and Antioquia (Fig. 21) are found.

4. Discussion and Conclusions

It was found that the relationship between liquidity risk and its financial structure is higher in Bolivar than in Bogota, which constitutes a challenge for lodging companies when applying for loans or leveraging the growth of their operations. However, when analyzing the relationship between the technological transformation processes and the increase in the company's profitability or liquidity, it is observed that there is no correspondence whatsoever, which highlights the fact that those companies interested in betting on new technologies that decide to leverage such growth through financial indebtedness, will be involved in risk levels that may lead them to incur not only in crisis but also in the possibility of bankruptcy.

This is in line with what was established by [4,39], for whom financial equilibrium is one of the most important aspects regarding the financial and economic stability of an entity, and its long-term financial sustainability. In line with the above, some researchers argue that ICT adoption is a competitive advantage factor, as it improves customer experience, which can increase hotel performance [15,16,1,2].

Although some authors suggest that SMEs are increasingly resorting to the adoption of Information and Communication Technologies (ICT) as a strategic means to compete with large companies [9,10,40,41] , or as a crucial factor to foster growth and innovation [42], the results of the present study show the opposite.

Regarding the T-test, no statistically significant differences were found between financial sustainability and the application or not of technological transformation processes in the companies analyzed. The above coincides with what has been stated by [41-3,28-30], for whom the adoption of ICTs cannot increase hotel performance, since it is not directly aimed at improving productivity, but rather these innovative systems are intended to improve customer service and increase the number of services offered.

However, when analyzing the individual results supported by multivariate analysis, significant relationships were found between return on assets (RA) and technology in the departments of Antioquia and Bogota.

On the other hand, although the literature on the significant positive influence of ICT on business performance is extensive, especially in SMEs [12-14,43-45], in the hotel sector this relationship is not so evident [42]. This coincides with the findings of the authors, who reflect that there is little research on financial sustainability and digital transformation processes in SMEs in Colombia, unlike in other parts of the world.

This motivates research and business strengthening in this field of study, and the creation of synergies between the business and academic sectors.

For future research, multivariate analyses should be carried out to establish relationships and find causes of the risks derived from decisions related to investments in technologies, as well as their effect on the profitability and sustainability of companies in the hotel sector.

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Analysis of the Intentionality and usability of business intelligence in the context of Industry 5.0 and its impact on Colombian international trade

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Abstract
In Colombia, integrating educational technology (EdTech) is crucial for enhancing educational quality and efficiency, especially in the post-pandemic context. Researchers [1] highlight the significant role of online platforms, yet challenges persist, such as the need for robust technological infrastructure and comprehensive teacher training. With 55.3% of universities adopting these platforms, reliance on external technologies and insufficient investment in local EdTech hinder innovation, as noted by [2]. [3] advocate for investing in local EdTech to improve education and stimulate economic development. In the industrial sector, under Industry 5.0, Business Intelligence (BI) is vital for boosting international trade through data analysis and informed decision-making. [4] emphasizes tools like Power BI for competitiveness, while DANE data indicates that 40.1% of companies outsource technology management, highlighting the need to develop local expertise to ensure sustainable growth and align BI with national economic goals.

Keywords: Industry 5.0; online platforms; educational quality; technological infrastructure; local development.

Análisis de la Intencionalidad y usabilidad de la inteligencia de negocios en el contexto de la Industria 5.0 y su impacto en el comercio internacional Colombiano

Resumen
En Colombia, la integración de la tecnología educativa (EdTech) es crucial para mejorar la calidad y eficiencia educativa, especialmente en el contexto postpandemia. Los investigadores [1] destacan el papel significativo de las plataformas en línea; sin embargo, persisten desafíos como la necesidad de una infraestructura tecnológica robusta y una capacitación docente integral. Con un 55.3% de universidades que adoptan estas plataformas, la dependencia de tecnologías externas y la insuficiente inversión en EdTech local obstaculizan la innovación, como señalan [2]. [3] abogan por invertir en EdTech local para mejorar la educación y estimular el desarrollo económico. En el sector industrial, bajo la Industria 5.0, la Inteligencia de Negocios (BI) es vital para impulsar el comercio internacional a través del análisis de datos y la toma de decisiones informada. [4] enfatiza herramientas como Power BI para la competitividad, mientras que los datos del DANE indican que el 40.1% de las empresas subcontratan la gestión tecnológica, destacando la necesidad de desarrollar experiencia local para asegurar un crecimiento sostenible y alinear la BI con los objetivos económicos nacionales.

Palabras clave: Industria 5.0; plataformas en línea; calidad educativa; infraestructura tecnológica; desarrollo local.

1 Introduction

1.1 Paper size, margins, columns and paragraphs

In the dynamic landscape characterizing Industry 5.0 today, international trade is defined as a rapidly evolving terrain, emphasizing the crucial importance of conscious and well-founded decision-making for companies to maintain their competitiveness. Furthermore, the relationship between humans and machines is essential for achieving successful outcomes, as [15] mention in their study on human-machine interaction in Colombian international trade. In this context,

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the implementation of Business Intelligence emerges as a vital catalyst, equipping Colombian organizations with the capability to analyze essential data and extract valuable information to guide their strategies, according to [8] in his analysis of business intelligence in the era of Industry 5.0.

Data management and Artificial Intelligence (AI) are fundamental in Industry 5.0, with applications such as Power BI playing a crucial role [4]. This analysis delves into the intent and usability of Business Intelligence within the framework of Industry 5.0, focusing specifically on its impact on Colombian international trade. The subsequent sections will explore the strategic objectives motivating the adoption of BI, evaluate the usability of available tools, and thoroughly examine how this transformative technology influences operational efficiency, decision-making, and competitiveness on a global scale.

This analysis aims to understand the current state of Business Intelligence (BI) implementation in Colombia while also projecting future opportunities and addressing present challenges. [5] highlights the integration of artificial intelligence within industrial processes as a key revolution in Industry 5.0, whereas [6] investigate the impact of digital transformation on international trade. As we progress toward an increasingly interconnected business landscape, the ability to leverage business intelligence becomes a crucial differentiator. [7] highlight the significance of implementing BI strategies in emerging economies as essential for fostering growth and development. This document aims to illustrate this process by offering valuable content and analysis for companies striving to enhance their presence and success in international trade within the framework of Industry 5.0.

2 Theoretical framework

Currently, Industry 5.0 is evolving towards the integration of humans and machines, with the goal of improving efficiency and personalizing production processes. This era is founded on synchronized collaboration between human intelligence and advanced technological capabilities, promoting a more adaptive and transformative work environment.

Furthermore, Business Intelligence (BI) plays a vital role in this context by providing tools and techniques for collecting, analyzing, and presenting business data. According to [8] BI empowers organizations to convert large volumes of data into valuable information that informs strategic decisions. Tools like Power BI, as noted by [4] are indispensable for data analysis and visualization, aiding in the identification of key trends and patterns.

Therefore, International trade, which entails the exchange of goods and services between nations, necessitates that companies quickly adapt to shifting global conditions. Implementing BI can significantly bolster companies' ability to compete internationally by optimizing supply chain management, identifying new markets, and understanding consumer preferences, as argued by [5].

In the Colombian context, specific challenges in adopting BI include a heavy reliance on external technologies and limited internal technological infrastructure. [9] reports that only 17.2% of Colombian companies utilize new technologies internally, while 40.1% depend on external providers. This dependency can hinder companies' ability to develop internal competencies in data analysis. The importance of fostering local technological development is underscored in the studies by [6] and [10].

For this reason, the integration of emerging technologies, such as the Internet of Things (IoT) and Big Data, with business intelligence (BI) tools presents innovative opportunities to enhance operational efficiency and supply chain management. [11] assert that these technologies significantly transform logistics operations, while [12] highlight the value of detailed data analysis in fraud prevention and improving financial security. Business intelligence in Industry 5.0 provides valuable tools to enhance competitiveness in international trade, particularly in the Colombian context, where the effective adoption of these technologies can revolutionize business management and optimize performance in a dynamic global environment.

2.1 Colombia in the domain of business intelligence and Industry 5.0

According to statistics from [9] at the start of the third decade of the 21st century, 17.2% of companies in the commerce sector employed new technologies internally, while 40.1% utilized these technologies in collaboration with external parties. These figures indicate a significant trend toward outsourcing the management of new technologies, suggesting a considerable delegation of essential functions for financial optimization and detailed data analysis [9]. The high reliance on external providers for managing advanced technologies implies that many Colombian companies are not allocating the necessary attention and resources to develop a robust internal technological infrastructure. This situation may hinder their ability to perform rigorous data analysis and continuous process optimization, which are vital for maintaining a competitive edge in a dynamic global environment [13]. According to these authors, Colombian manufacturers that have adopted advanced technologies internally have achieved positive outcomes, underscoring the importance of a proactive approach to internal technological development. Data study and analysis play a crucial role in the ongoing improvement of business processes. [14] contend that, particularly in the context of the COVID-19 pandemic, the capacity to adapt and respond to global changes has heavily relied on the effective use of big data tools and platforms such as Power BI. These technologies enable companies to gather, analyze, and utilize data in ways that allow them to anticipate trends, optimize operations, and make informed decisions [14].

Due to the effective implementation of Business Intelligence (BI) and emerging technologies such as Power BI, within the framework of Industry 5.0, presents a significant opportunity for Colombian companies to enhance their global competitiveness. Integrating BI into business operations not only fosters a deeper understanding of market dynamics but also enables improved supply chain management, the identification of new markets, and analysis of consumer preferences on a global scale ([8,15]. However, to fully realize these benefits, it is essential that Colombian companies invest in developing internal technological capabilities and do not rely solely on external solutions [16,17].

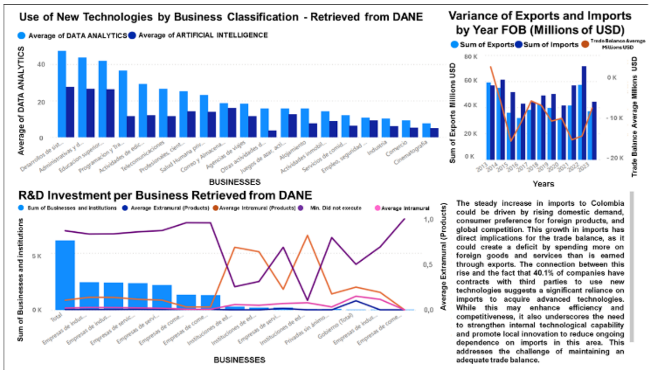

Figure 1. Uses of new technologies by company classification.
Source: Retrieved from DANE, 2023.

In summary, the considerable dependence on external technologies and the absence of a strategic focus on internal technological development could restrict the growth potential and competitiveness of Colombian companies within Industry 5.0. It is crucial to adopt policies and strategies that encourage local technological development to ensure sustainable growth and active participation in the global economy [18,19]. The ability of companies to excel in the adoption and application of advanced technologies will be fundamental to their success in an increasingly competitive and technologically advanced environment.

Thus, although forecasts indicate a favorable outlook for Colombian international trade, there is a risk of a regulated or negative impact if local technological development is not actively promoted. Over-reliance on external technologies could hinder Colombia's ability to innovate, respond swiftly to changes, and sustain a robust competitive position in Industry 5.0. It is crucial that future strategies tackle this challenge and aim to bolster internal technological capacity to ensure sustainable growth and engagement in the global economy, as shown in Fig. 1.

2.2 Intentionality and usability of business intelligence in Industry 5.0: effects on the performance of Colombian international trade

The research question centers on understanding the intentionality and usability of Business Intelligence (BI) within the context of Industry 5.0 and its effects on Colombian international trade. Firstly, intentionality pertains to the goals and objectives that Colombian companies strive to achieve through the implementation of BI in the framework of Industry 5.0. The adoption of BI aims not only to optimize data management but also to enhance strategic decision-making and boost competitiveness in the global market. The technologies of Industry 5.0, which encompass advanced integration of artificial intelligence, automation, and big data analysis play a vital role in the evolution of these intentions. The capacity to analyze large volumes of data and extract valuable insights allows companies to anticipate market trends, adjust their strategies, and respond more swiftly to the demands of international trade [8,4].

On the other hand, the usability of BI tools is crucial for these intentions to materialize effectively. Usability evaluates how practical and efficient these tools are in integrating and analyzing complex data. In the context of Industry 5.0, where emerging technologies require high processing and analytical capabilities, the usability of tools like Power BI is vital for facilitating successful implementation. Ease of use, customization options, and integration with other technologies are factors that determine how Colombian companies can fully leverage BI capabilities. The assessment of these tools focuses on their direct impact on operational efficiency and the ability of companies to manage their business operations more effectively [14,21]. The proposed Boolean search equation—“Business Intelligence” AND “Industry 5.0” AND “Colombian International Trade” AND “Analysis” AND “Usability” AND “Impact”—aids in identifying relevant studies that explore the intersection of BI, Industry 5.0 technologies, and Colombian international trade. This search facilitates the identification of research addressing how the implementation of BI within the framework of Industry 5.0 influences the performance of international trade in Colombia. Furthermore, by incorporating terms such as “Analysis,” “Usability,” and “Impact,” it ensures the acquisition of information regarding the effectiveness and efficiency of BI tools and their influence on the global competitiveness of Colombian companies [16,19].

Therefore, this research on the intentionality and usability of BI within the framework of Industry 5.0 offers a thorough perspective on how these emerging technologies can revolutionize Colombian international trade. Assessing companies' intentions to adopt BI, alongside the usability of the tools, enhances the understanding of the potential effects on their global performance and their ability to compete in a dynamic and technological landscape.

2.3 Impact of BI on Colombian and global international trade

The integration of Business Intelligence (BI) in international trade is transforming business strategies and providing significant competitive advantages. According to [20] in the context of Cemex, despite possessing advanced knowledge, the company has not fully optimized its use of BI due to ineffective implementation. This case underscores a critical gap between theoretical capability and practical application, highlighting the necessity for a more strategic adoption of BI technologies to maximize their commercial benefits. Similarly, [20] analyzes the challenges faced by Command Alkon Colombia SAS, where insufficient BI integration restricts operational performance and illustrates how the lack of a robust strategy can impede improvement opportunities.

In [22] presents a pertinent case involving a fruits and vegetables company in Valencia, where effective use of BI has revolutionized logistics and supply chains. By employing advanced BI tools for data analysis, the company has streamlined its processes and enhanced decision-making, resulting in a significant increase in its competitiveness. This study illustrates the potential of BI to produce positive operational outcomes when applied appropriately and strategically.

In other matters, in the financial sector, data mining has proven vital for detecting fraud and enhancing security in commerce. [12] explore how comprehensive data analysis through Business Intelligence (BI) can identify irregularities and prevent financial fraud, emphasizing the importance of BI tools in preserving financial integrity.

In international trade, the ability of BI to identify niche markets and business opportunities is crucial. In [23] investigates how data analysis facilitates the identification of opportunities in green supply chains, improving sustainability and efficiency in product replenishment. This research demonstrates how the strategic use of BI can optimize supply chain management and generate a competitive advantage in the global market.

The impact of Big Data and advanced data analytics on international logistics is a highly relevant topic. In [14] emphasize how Big Data enables better logistical control in supply chains, facilitating more efficient and precise management. Furthermore, the integration of emerging technologies from Industry 4.0 and 5.0, such as the Internet of Things (IoT), has the potential to significantly transform supply chain management. Finally, in [11] underline how these advanced technologies can enhance the efficiency and sustainability of logistical operations, providing companies with a competitive edge in an interconnected global environment.

Additionally, in [24] focuses on the impact of BI in Colombia, particularly in the area of imports. This analysis highlights how the use of BI tools can optimize business processes in the Colombian context, bolstering the country's competitiveness in international trade. The research also emphasizes the need for policies that promote local technological development to maximize the benefits of Business Intelligence (BI) and ensure sustainable, competitive growth. The importance of strengthening local technological development in Colombia is supported by [10] who argue that internal technological development is crucial for emerging markets to compete effectively on the global stage. This approach is essential to ensure that the benefits of BI translate into sustainable economic growth and a strong competitive position.

3 Methodology

The analysis of the impact of Business Intelligence (BI) on Colombian international trade, within the context of Industry 5.0, was conducted using a comprehensive and multifaceted methodology. Thus, this methodology combines qualitative and quantitative approaches to offer a nuanced and holistic perspective on the subject. The key phases of the methodology employed are detailed below.

3.1 Extensive literature review

The first phase involved an extensive review of relevant academic and technical literature. This process included examining previous studies on Business Intelligence, Industry 5.0, and their impact on international trade. Journals, books, and doctoral theses were consulted to gain a thorough understanding of current theories and approaches. In particular, the contributions of recognized authors in the field were reviewed, such as [25] who analyzed the implementation of BI in the era of Industry 5.0, and Travez [15], who studied the relationship between humans and machines in international trade. Studies on the integration of BI tools, such as Power BI, in business data analysis and their influence on strategic decision-making were also included [4,14].

3.2 Analysis of secondary data

A detailed analysis of secondary data provided by official sources and government agencies was conducted. This included a review of statistics from the National Administrative Department of Statistics (DANE) and the Ministry of National Education regarding the adoption of technologies and BI platforms in Colombia. DANE data (2020) offered insights into the adoption and outsourcing of new technologies by Colombian companies, providing a quantitative basis to evaluate reliance on external technologies and internal technological development capacity. Additionally, reports on technological infrastructure and teacher training were analyzed to understand current needs and challenges related to BI implementation.

3.3 Detailed case studies

The analysis included comprehensive case studies of companies both in Colombia and internationally that have adopted BI tools. Representative cases were chosen to illustrate various aspects of BI adoption and usage. Among the case studies reviewed were Cemex [20] which demonstrated how inadequate BI implementation can hinder operational performance, and Command Alkon Colombia SAS ([21] which underscored challenges and opportunities in BI integration. Additionally, the case of a fruit and vegetable company in Valencia [22] was examined, showcasing how effective BI utilization transformed logistics and supply chains while providing concrete examples of success and areas for enhancement.

3.4 Critical evaluation of BI tools

A thorough evaluation of the BI tools available in the market was performed, with a particular emphasis on Power BI. This evaluation encompassed a review of technical features, usability, and effectiveness of the tools, as well as their adaptation to the specific needs of Colombian international trade. Previous studies and implementation data were analyzed to identify best practices and areas for improvement in the use of Business Intelligence (BI). This analysis facilitated an assessment of how these tools can support informed decision-making and enhance operational efficiency.

3.5 Interviews and surveys with experts

Interviews and surveys were conducted with experts in educational technology and professionals from companies employing BI tools. These interviews provided qualitative insights into practical experiences with BI implementation, the challenges encountered, and the strategies adopted to address those challenges. The qualitative information gathered complemented the quantitative data and enabled a deeper understanding of the factors influencing the success of BI implementation in Colombia.

3.6 Comparative and critical analysis

A comparative and critical analysis of the collected data, both quantitative and qualitative, was performed. This analysis helped identify patterns and trends in the adoption and use of BI, as well as evaluate the impact of these technologies on operational efficiency and global competitiveness. The results obtained were compared with findings from the reviewed literature and case studies to draw conclusions about the influence of BI on Colombian international trade and to formulate recommendations for enhancing its adoption and use.

4 Results

The implementation of Business Intelligence (BI) has significantly transformed how Colombian companies approach strategic decision-making. Tools like Power BI have proven essential by enabling companies to analyze large volumes of data with a level of detail and accuracy that was previously unattainable. This capability has facilitated a more precise identification of patterns and trends in the market, leading to improved strategic planning and adaptation to the dynamics of the global environment [4,14]. The ability to anticipate changes in demand and adjust strategies accordingly has become a key differentiator for companies striving to remain competitive in a constantly evolving market.

In terms of operational efficiency, the adoption of BI has allowed for a notable optimization of internal processes and a reduction in operational costs. Companies that have integrated BI have successfully enhanced coordination in their supply chains and resource management. For instance, the case of a fruit and vegetable company in Valencia illustrates how the effective use of BI can transform logistics and supply processes, resulting in a greater capacity to meet deadlines and satisfy market demand [22]. This confirms the idea presented by [23] regarding how data analysis facilitates the identification of opportunities in green supply chains, improving sustainability and efficiency.

However, one of the persistent challenges in the implementation of Business Intelligence (BI) in Colombia is the high dependence on external providers for managing advanced technologies. According to statistics from [9] a significant percentage of Colombian companies outsource the management of new technologies, which may hinder the development of the internal competencies necessary for rigorous analysis and continuous process optimization [13]. This dependence can restrict companies' ability to develop a robust internal technological infrastructure, limiting their capacity to adapt and evolve in the global market.

Case studies, such as that of Command Alkon Colombia SAS, illustrate how poor BI implementation can constrain operational performance. This case underscores the need for a strong strategy for integrating BI, as the lack of proper planning can lead to underutilization of available tools [21]. Despite the challenges, it is clear that BI tools have the potential to significantly enhance efficiency and decision-making when implemented correctly.

To overcome these challenges, it is crucial to strengthen local technological development. Investing in internal capabilities and technological infrastructure is essential for reducing reliance on external solutions and improving competitiveness [19]. Policies that promote internal technological development and encourage innovation are vital to ensure sustainable and competitive growth in international trade.

The integration of emerging technologies, such as the Internet of Things (IoT) and Big Data, with Business Intelligence (BI) has significantly impacted the transformation of business operations. These advanced technologies enable more precise and real-time management of the supply chain, offering competitive advantages by enhancing operational efficiency and adaptability [11]. Research by [14] highlights how Big Data facilitates improved logistical control and more efficient supply chain management, supporting the idea that the combination of BI and emerging technologies can revolutionize business management.

Advanced data analytics through BI has also enhanced companies' ability to manage financial risks. The capacity to identify anomalies and prevent fraud is a crucial advantage that adds an additional layer of financial security [12]. Research by [10] underscores the importance of bolstering internal technological development in emerging markets to ensure that the benefits of BI translate into sustainable economic growth and a robust competitive position.

The implementation of BI in Colombia has proven to be a powerful tool for boosting competitiveness and business efficiency. However, to fully harness these benefits, it is essential to continue developing technological infrastructure and fostering an environment that encourages innovation and the adoption of emerging technologies. The evolution of BI within the Colombian context indicates a pathway toward a more competitive and adaptable future, but it necessitates a sustained commitment to technological development and continuous improvement.

5 Discussion

To start, response to the research question, the aim of Business Intelligence (BI) in Industry 5.0 is to enhance strategic decision-making by utilizing data analytics to anticipate trends and optimize processes. According to [26] BI acts as a vital catalyst, enabling organizations to analyze complex data and extract valuable insights to inform their strategies. Furthermore, [27] highlight the essential role of tools like Power BI in this endeavor. The effectiveness of BI lies in its capacity to provide accessible and adaptable information to meet business needs in Colombia, seamlessly integrating with emerging technologies, which is crucial for international trade [28].

Table 1.
Summary of Trade Metrics by Year.

Year	at	ct	Xt	It	Zt
2024	50,33	45,33	555,63	495,63	60
2025	50,36	45,36	606,36	536,36	70
2026	50,39	45,39	657,09	576,09	81
2027	50,42	45,42	707,72	615,72	92

Source: Authors.

In the realm of international trade, BI can enhance competitiveness by improving supply chain management, identifying new markets, and facilitating the understanding of consumer preferences on a global scale, thereby contributing to business performance in a dynamic and technologically advanced environment [29]. This influence is significant for examining how BI tools and data analytics can affect operational efficiency and competitiveness in Colombian international trade.

Linear programming and projections derived from data indicate a gradual increase in Colombian exports and imports over the next four years. While this forecast suggests steady growth in international trade, it is crucial to consider how these outcomes may impact the local context, particularly in the absence of a substantial boost to internal technological development. Applying the principle of Ceteris Paribus, which means "keeping everything else constant," simplifies the analysis and focuses on specific variables of interest, as demonstrated in methods like Ordinary Least Squares [19].

The linear programming procedure commenced with the formulation of the problem, defining the variables of interest and establishing the objective function to maximize the trade balance. The coefficients, based on assumed initial values, incorporate an annual increase of 3%, enabling projections of exports, imports, and the trade balance for the years 2024-2027 (see Table 1).

The results of the linear programming were presented in a table, highlighting the coefficients along with the projections for exports, imports, and the trade balance for each projected year. The analysis of the results concentrated on interpreting the projections in relation to the context of Colombian international trade and Industry 5.0. Potential positive impacts and challenges were assessed, underscoring the significance of local technological development. The anticipated increase in exports could suggest a higher demand for Colombian products in the international market, reflecting a positive adaptation to global trends [29]. However, this growth may be constrained if it is not bolstered by local technological advancements. Dependence on external technologies could lead to vulnerability, as the ability to innovate and maintain competitive quality might hinge on external factors [18].

The rise in imports may indicate a deeper integration of foreign products and technologies into the Colombian economy. While this could facilitate the adoption of advanced practices, it also carries the risk of over-dependence on foreign technologies [19]. Without concurrent support for local technological development, Colombia might find itself at a disadvantage regarding autonomy and the capacity to adapt to unforeseen changes in the international landscape [28].

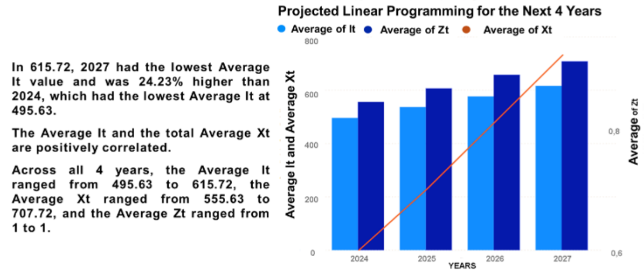

Figure 2. Projected linear programming for the next four years.
Source: DANE, 2023.

The notable percentage of companies outsourcing the management of new technologies (40.1%) may imply a lack of investment or internal capability to spearhead technological advancements. This could lead to a gap in innovation capacity and challenges in maintaining strategic control over business operations [16].

The Fig. 2 show a projected linear programming for the next four years.

6 Conclusions

In the analysis of economic projections and the application of linear programming to Colombian international trade, a potential increase in exports, imports, and trade balance has been identified for the upcoming years. This growth is grounded in a linear trend and specific assumptions regarding the future behavior of these variables [19]. The use of linear programming on economic data indicates a gradual rise in these indicators, reflecting a positive outlook for Colombian international trade. However, when this outlook is combined with the reliance on external technologies, as evidenced by the significant percentage of companies outsourcing the management of new technologies, the urgent need to bolster local technological development is underscored [16,17]. Fig. 2 illustrates the linear programming projection for the next four years (2024-2027), highlighting a steady increase in Colombian exports (Xt) and imports (It). The It values are projected to rise from 495.63 to 615.72, while Xt values are expected to grow from 555.63 to 707.72, ensuring a positive trade balance (Zt). This linear growth indicates promising prospects for Colombian international trade, although sustaining it will require advancements in local technology within the framework of Industry 5.0.

Fig. 3 demonstrates the fluctuating trends of Colombia's imports and exports of goods and services as a percentage of GDP, emphasizing the persistent gap where imports consistently surpass exports. Despite a recovery in both metrics after 2020, challenges such as high domestic demand, reliance on imports, and limited adoption of advanced technologies contribute to this imbalance. This underscores the need for enhanced Business Intelligence (BI) adoption to optimize trade operations, support local production, and align with Industry 5.0 to improve competitiveness in international markets.

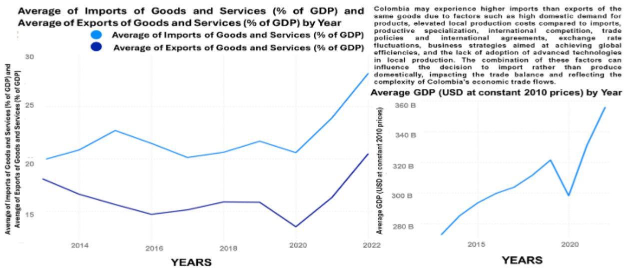

Figure 3. Average Imports of Goods and Services (% of GDP) and Average Exports of Goods and Services (% of GDP) by Year.
Source: Retrieved from DANE, 2023.

The implementation of emerging technologies, such as Business Intelligence (BI) within the framework of Industry 5.0, presents significant opportunities to enhance decision-making and operational efficiency in international trade. BI enables organizations to analyze large volumes of data to gain strategic insights that can optimize processes and business strategies [26]. The capability of BI tools to deliver accurate, real-time information is crucial for competing in an increasingly complex and competitive global environment [30].

However, a lack of a strategic approach to local technological development could hinder Colombia's ability to lead in innovation and adapt to global changes [29,31]. An overreliance on external technologies may create significant vulnerabilities, where improvements in economic projections do not translate into sustainable and competitive growth. Local technological autonomy becomes essential to maximize the positive impact of commercial trends and ensure that Gross Domestic Product (GDP) growth is driven internally [18,4].

The high reliance on external technologies, evident in the 40.1% of Colombian companies that outsource the management of new technologies, highlights a significant gap in the internal capacity to develop and lead technological innovations [28]. This situation may lead to a lack of strategic control and a deficiency in adaptability and innovation capabilities [3]. Investing in local technological development is not only vital for enhancing the quality of education and operational efficiency but also for promoting economic development and job creation in the technology sector [19].

The analysis underscores that while forecasts indicate a positive outlook for Colombian international trade, there is a considerable risk if internal technological development is not actively promoted. An overreliance on external technologies could hinder Colombia's ability to lead in innovation, swiftly adapt to changes, and sustain a robust competitive position in Industry 5.0 [26,17]. It is crucial that future strategies confront this challenge and aim to enhance internal technological capabilities to ensure sustainable growth and active engagement in the global economy [30,18].

To address these challenges, it is vital for the country to implement policies and strategies that foster internal technological development as a core component of its long-term vision for international trade. Sustainable economic success does not merely depend on numerical forecasts but also on the capacity of companies and the nation to excel in the adoption and application of advanced technologies, thus ensuring equitable and resilient GDP growth [29,31]. Collaboration among the government, private sector, and educational institutions will be essential in cultivating an innovative and competitive ecosystem that enables Colombia to remain at the forefront of the global economy [32,4].

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Quantification of cadmium in samples of Venezuelan *Theobroma cacao* almonds

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Abstract
Since the European Union regulations on the maximum permissible content of heavy metals came into force in 2019, there has been a growing interest in quantification these metals in Venezuelan cocoa. In the present study, Cd was quantified in nine samples of cocoa beans from different areas of the national territory, analyzing the shell and nib separately. Atomic absorption spectroscopy with flame atomization using a continuous source spectrophotometer in fast sequential mode was utilized. A sample digestion process was optimized through the implementation of a factorial design. Measurements were evaluated by calculating the percentage recovery for inter-day and intra-day precision determination. The cadmium concentration in the samples ranged from 1.4 to 7.2 mg kg^{-1}, exceeding the European Union's established limit of 0.6 mg kg^{-1}.

Keywords: cadmium; food safety; heavy metals; Venezuelan cocoa.

Cuantificación de cadmio en muestras de almendras *Theobroma cacao* venezolano

Resumen
Desde la entrada en vigencia de la normativa de la Unión Europea en 2019 sobre los límites máximos permitidos de metales pesados, ha aumentado el interés por la cuantificación de estos elementos en el cacao venezolano. En este estudio, se determinó la concentración de cadmio (Cd) en nueve muestras de granos de cacao provenientes de distintas regiones del país, analizando por separado la cáscara y el nib. Se optimizó un proceso de digestión de muestras mediante un diseño factorial y se empleó para la cuantificación espectroscopia de absorción atómica con atomización por llama, utilizando un espectrofotómetro de fuente continua en modo secuencial rápido. La precisión del método se evaluó a través del cálculo del porcentaje de recuperación en determinaciones inter-diarias e intra-diarias. Los resultados arrojaron concentraciones de cadmio en un rango de 1,4 a 7,2 mg kg^{-1}, superando el límite establecido por la normativa europea de 0,6 mg kg^{-1}.

Palabras clave: cadmio; cacao venezolano; seguridad alimentaria; metales pesados.

1. Introducción

El cacao, es un fruto tropical necesario e insustituible para la producción de chocolate, que proviene del árbol "cacaotero" perteneciente a la familia *Malvaceae* [1,2]. Su nombre científico, *Theobroma cacao*, deriva del griego "*Theobroma*", que significa "alimento de los dioses", mientras que la palabra "cacao" es una adaptación del *nahua* "*cacáhua*", que significa fruto.

Debido a sus múltiples beneficios para la salud, el cacao ha generado un gran interés global, siendo reconocido como un superalimento [1,3]. Entre estos beneficios se destacan los

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reportados por Vicentim y Hassoun [4,5], quienes encontraron que el cacao puede actuar como un agente terapéutico en el tratamiento de lesiones vasculares causadas por la diabetes mellitus. Además, Baharum et al. [6] demostraron la eficacia de los compuestos bioactivos del cacao en procesos fisiológicos y fisiopatológicos [7]. El cacao es rico en antioxidantes como flavonoides, catequinas, epicatequina, endorfinas, procianidinas y polifenoles [8], los cuales ayudan a reducir radicales libres, prevenir enfermedades infecciosas y autoinmunes, contribuyen a regular la presión sanguínea y tienen propiedades anticancerígenas. Estudios en mujeres de edad avanzada han mostrado que el chocolate puede mejorar la osteoporosis [9,10].

El creciente interés en el consumo de chocolate ha incrementado la demanda mundial de cacao [11], impulsada por el mercado global de productos de confitería. Según la Organización Internacional del Cacao, la oferta anual de cacao alcanzó los 3.8 millones de toneladas en 2015/16, siendo Costa de Marfil, Ghana e Indonesia los principales productores, representando el 70,7 % de la producción mundial [12]. Los principales consumidores de productos derivados del cacao se encuentran en Europa, Estados Unidos, Australia y Japón [13]. En Venezuela, se está desarrollando la denominación de origen para certificar la calidad específica del cacao, destacándose el "Cacao de Chuao" como la primera denominación de origen reconocida por el Servicio Autónomo de la Propiedad Intelectual (SAPI) en el 2000.

Se han detectado concentraciones elevadas de metales pesados en muestras de cacao y sus derivados, lo que ha llevado al establecimiento de controles estrictos sobre los niveles permitidos [14-16]. En Venezuela, aún no se han realizado investigaciones exhaustivas sobre concentración de metales pesados en el cacao, por lo que, determinar estas concentraciones es crucial dado su valor internacional. En la presente investigación se cuantificó cadmio (Cd) en almendras de cacao venezolano mediante espectroscopia de absorción atómica, abarcando tanto el nib como la cáscara de semillas fermentadas. Se seleccionó el análisis de Cd debido a los graves daños que este metal puede causar en la salud humana, incluso en niveles traza, tales como alteraciones metabólicas, neurológicas, mentales y genéticas [17]. La ingesta de Cd se produce mayormente a través de alimentos como paté, champiñones, mariscos, mejillones, algas secas y cacao. Estudios previos han mostrado que el chocolate puede contener trazas de este metal pesado. Yanus et al. [9] encontraron una relación lineal entre el contenido de metales pesados en el chocolate procesado y los sólidos de cacao. Por otro lado, Chávez et al. [10] estudiaron la determinación de Cd en el sur de Ecuador en muestras de suelo y plantas de cacao, atribuyendo la contaminación a actividades antropogénicas.

2. Metodología

Reactivos

Se utilizaron los siguientes reactivos: ácido nítrico (HNO_3), Fisher Chemical, Ottawa, Canada, ACS certificate, CAS# CAS 7697-37-2, PubChem CID: 944; peróxido de hidrógeno (H_2O_2), Fisher Chemical,Ottawa, Canada, Certified ACS, CAS# 7722–84–1, PubChem CID: 784; ampolla marca Titrisolde $CdCl_2$ para preparar solución madre de 1000 ppm de Cd, agua nanopura de 18 MΩ , gases: aire y acetileno.

Materiales y equipos

Papel de filtro marca Whatman Nro. 42, pipetas automáticas de 10-100 μL marca Dragon Lab, pipeta de 100-1000 μL marca accumax A modelo AV-600 y pipeta de 1-10 mL marca Socorex modelo Acura 835, balanza analítica de cuatro cifras marca A&D modelo GR-120, digestor de microondas marca Berghof modelo Speedwavefour, baño de ultrasonido marca Cole-Parmer modelo 8854, espectrofotómetro de absorción atómica marca Analitik Jena modelo contrAA 700 y destilador Marca Barnstead.

Muestras

Para obtener una variabilidad adecuada se seleccionaron tres regiones diferentes de producción de cacao en Venezuela: Miranda, Ocumare y Carúpano. Dentro de cada región, se seleccionaron dos plantaciones de cacao diferentes. De cada plantación, se recolectó al azar 1 kg de semillas de cacao fermentadas, tomando muestras de distintas áreas dentro de cada plantación. En la Tabla 1 se listan el tipo y procedencia de las muestras analizadas.

Tratamiento de muestras

Descascarillado

Se removió manualmente la cáscara que recubre la almendra tostada y fermentada de cacao. Se almacenaron por separado las cáscaras y el nib, en bolsas de plástico con cierre hermético.

Homogeneización de las muestras

Dado el origen natural y la variabilidad inherente de las muestras, se llevó a cabo un proceso de homogeneización para garantizar la representatividad y reproducibilidad de los resultados analíticos. Para ello, las almendras de *Theobroma cacao* fueron sometidas a un proceso de secado a temperatura ambiente durante 48 horas para reducir la humedad residual y evitar interferencias en la cuantificación de cadmio. Posteriormente, las almendras secas se trituraron utilizando un mortero de cerámica y un pistilo hasta obtener un material de granulometría homogénea. Para minimizar la

Tabla 1.
Tipos de muestras y procedencia.

#	Tipo de muestra	Procedencia
1	Híbridos internacionales	Padrón. Troncal 9. Estación experimental Miranda
2	Carenero Superior	Barlovento, comunidad de Curiepe-Mango de Ocoita. Estado Miranda
3	Cacao de Cumboto	Central de beneficio 6 de julio. Ocumare de La costa. Edo. Aragua
4	Sur del Lago	UPS Pedregal y Palmira. Estado Mérida.
5	Ocumare 61	Carúpano, Estado Sucre
6	Carenero	Carúpano, Estado Sucre
7	Sur del Lago	Carúpano, Estado Sucre
8	Canoabo	Carúpano, Estado Sucre
9	Rio Caribe Superior	Carúpano, Estado Sucre

Fuente: Los autores.

contaminación cruzada, el mortero y el pistilo se limpiaron rigurosamente entre cada muestra con una solución de HNO_3 al 10 % (v/v) y se enjuagaron con agua ultrapura. El polvo obtenido se tamizó utilizando un tamiz de malla 250 µm para garantizar la uniformidad en el tamaño de partícula. Las muestras trituradas se almacenaron en bolsas de polietileno estériles y herméticas, protegidas de la luz y la humedad hasta su posterior digestión y análisis.

Digestión por microondas

Se pesaron 0,500 g de muestra y se ingresaron a un tubo de teflón, utilizando un embudo de vidrio diseñado especialmente para garantizar que la muestra quede depositada en su totalidad en la parte inferior del tubo y no en las paredes del mismo. La digestión del material orgánico se realizó utilizando HNO_3 y H_2O_2. El proceso de digestión con HNO_3 se asocia a la siguiente reacción: $(CH_2)_n + 2HNO_3 \rightarrow CO_2 + 2NO + 2H_2O$ y la reacción de descomposición con H_2O_2, para aumentar el potencial de oxidación y suprimir la formación de óxidos de nitrógeno (de color amarillo) a: $2H_2O_2 \rightarrow 2H_2O + O_2$. Se utilizaron las siguientes condiciones: envases de teflón de 60 mL, modelo DAP-60+, presión 40 bar (580 psi), temperatura 230 ºC, 500 mg de muestra y 5 mL de ácido; además, de un elemento de seguridad de aluminio como indicador de fuga de gases. A continuación, el tubo se introdujo en el digestor por microondas y se inició el programa de digestión.

Digestión por ultrasonido

Para la digestión asistida por ultrasonido, se pesó con precisión 1,0 g de muestra homogeneizada y se transfirió a un tubo de digestión de vidrio, el cual estaba equipado con un condensador de 50 cm de altura para evitar la pérdida de volátiles. Los tubos de digestión se colocaron en una estructura metálica dentro del baño de ultrasonidos (Fig. 1), asegurando una distribución uniforme de la energía ultrasónica. Una vez correctamente ubicados, se cerraron con sus respectivos condensadores, y se activó el flujo continuo de agua para la refrigeración del sistema. La digestión por ultrasonido se llevó a cabo aplicando una frecuencia ultrasónica de 40 kHz con una potencia de 120 W durante un tiempo previamente optimizado en el diseño experimental. Este proceso favorece la disrupción de la matriz orgánica y la liberación de metales pesados en la solución, reduciendo el tiempo y la severidad de las condiciones en comparación con otros métodos de digestión.

Filtrado de la muestra

Luego de la digestión de las muestras, las soluciones resultantes se filtraron para eliminar cualquier material particulado que pudiera obstruir los capilares del espectrofotómetro de absorción atómica modelo contrAA 700 (Analytik Jena). Para ello, se utilizó filtración por gravedad mediante embudos de vidrio y papel de filtro de celulosa de porosidad media (Whatman N° 42). Las soluciones filtradas se recolectaron en matraces aforados de 25 mL en el caso de las muestras digeridas por microondas y de 50 mL para aquellas digeridas por ultrasonido. Posteriormente, las soluciones se almacenaron en frascos de polietileno de alta densidad (HDPE) y se mantuvieron en refrigeración a 4 °C hasta su análisis.

Figura 1. Montaje de digestión con ultrasonido.
Fuente: Los autores.

Diseño factorial

Para la optimización de las condiciones de digestión, se diseñó un experimento factorial completo, en el que se evaluaron los efectos de tres variables principales: temperatura, tiempo de digestión y proporción de reactivos**.** Como muestra de control, se emplearon híbridos internacionales de *Theobroma cacao*, cuya composición química es bien caracterizada en estudios previos. En las Tablas 2 y 3 se detallan los niveles de cada variable y las condiciones experimentales utilizadas para cada método de digestión. Este diseño experimental permitió identificar las condiciones óptimas para maximizar la eficiencia de digestión y minimizar la degradación de la muestra, asegurando una recuperación cuantitativa del cadmio presente en la matriz de cacao.

Tabla 2.
Diseño factorial para la digestión por microondas.

Digestión	**T/ ºC**	**t/ min**	**HNO_3:H_2O_2**
1	190	30	6:0
2	190	45	6:0
3	190	30	4:3
4	190	45	4:3
5	170	30	6:0
6	170	45	6:0
7	170	30	4:3
8	170	45	4:3

Fuente: Los autores.

Tabla 3.
Diseño factorial para la digestión por ultrasonido.

Digestión	T/ºC	t/ min	HNO_3:H_2O_2
1	45	60	6:0
2	45	60	4:3
3	60	120	6:0
4	60	120	4:3
5	60	60	6:0
6	60	60	4:3
7	45	120	6:0
8	45	120	4:3

Fuente: Los autores.

La exactitud de las medidas, se reportan como porcentajes de recuperación: $\% R = \frac{valor\ experimental}{valor\ teórico}\ x\ 100$; utilizando una cantidad conocida de patrones Cd. Para la digestión por ultrasonido a las muestras del nib se añadieron 0,025 mg de Cd y a las de cáscara 0,020 mg. Para la digestión por microondas se añadieron 0,012 mg de Cd a las muestras de nib y 0,010 mg a las de cáscara. El criterio aceptado fue valores de % R entre 90 -105 % [19-21].

Para el análisis de repetibilidad se utilizó la muestra etiquetada con el número 1 en la Tabla 2. El estudio se realizó en un día a las siguientes horas: 8:30 am, 10:30 am, 1:30 pm, 3:30 pm y 5:30 pm. En cuanto a las mediciones inter-diarias se realizaron en un intervalo de siete días, medidas diarias entre las 10:30 am y las 11:00 am y se evaluaron parámetros adicionales de temperatura, humedad y precipitaciones; para evaluar la relación entre las medidas y estos parámetros.

Cuantificación de cadmio por espectroscopia de absorción atómica de llama

Para las medidas de absorbancia se utilizó un espectrofotómetro contrAA700 de *Analitik Jena* de alta resolución con fuente continua. Las muestras se inyectaron al equipo mediante un auto muestreador y los análisis de Cd se realizaron de modo secuencial rápido y simultáneo. Para la construcción de curvas de calibración, Fig. 2, se prepararon patrones de Cd de 50 mL, (0,05 a 1,5 mg L^{-1}) a partir de soluciones madre de 1000 mg L^{-1}. La longitud de onda de trabajo, de mayor sensibilidad, fue de 228 nm. Se utilizó acetileno como combustible a un flujo de 50 L h^{-1} y aire como oxidante a 470 L h^{-1}. Adicionalmente, se programó el equipo para que realizara seis réplicas para cada medida. El límite de detección fue calculado directamente por el software del equipo contrAA700, el cual suministra los datos automáticamente a partir de la curva de calibración realizada. El límite de detección obtenido fue de 0,0279 mg L^{-1}.

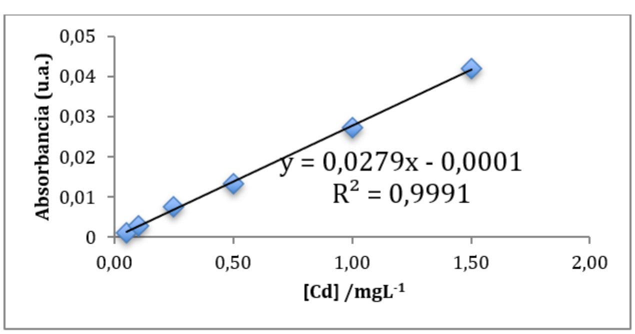

Figura 2. Curva de calibración.
Fuente: Los autores.

3. Resultados y Discusión

Efecto del tipo de digestión en la cuantificación de cadmio

En las Tablas 4 y 5 se presentan las concentraciones de Cd determinadas en muestras de híbridos internacionales de *Theobroma cacao*, obtenidas mediante cada uno de los procesos de digestión, según las condiciones establecidas en el diseño factorial.

Mediante digestión de las muestras por microondas, la concentración máxima de Cd en el nib fue de 4,9 ± 0,1 mg kg^{-1}, la cual se obtuvo realizando la digestión con una relación 4:3 (mL) de HNO_3:H_2O_2, respectivamente; mientras la concentración máxima de Cd obtenida en la cáscara fue de 8,60 ± 0,03mg kg^{-1}, utilizando HNO_3:H_2O_2 6:0 (mL); ambos resultados obtenidos a 170 ºC y 45 min. De acuerdo a la observación experimentales, en las digestiones realizadas con proporción de HNO_3:H_2O_2 de 6: 6 (mL) se generaron gases que aumentaron considerablemente la presión en el tubo de digestión, lo que resultó en el rompimiento del plástico de seguridad. Por otro lado, por digestión con baño de ultrasonido se obtuvieron concentraciones de Cd entre 2,6-3,6 mg kg^{-1} para el nib y 5,6-7,0 mg kg^{-1}, utilizando una proporción 4:3 (mL) de HNO_3:H_2O_2 por 120 minutos y 60 ºC.

Con ambos métodos de digestión las mayores concentraciones de Cd se obtuvieron con una proporción 4:3 (mL) de HNO_3:H_2O_2. Sin embargo, para la digestión por ultrasonido se necesitó de mayor tiempo y temperatura. Los resultados mostrados son soportados por los valores de % R (Tabla 6), donde con digestión por ultrasonido se obtuvo un menor % R, entre 73-93 %, los cuales están por debajo del rango aceptado.

Tabla 4.
Concentración de Cd en las muestras de híbridos internacionales de *Theobroma cacao,* de acuerdo al diseño factorial para digestión por microondas.

	HNO_3 /mL	H_2O_2 /mL	H_2O/ mL	T /ºC	t/min	Cd] /mg Kg^{-1}
Nib	6	0	6	190	30	2,8±0,1
Cáscara	6	0	6	190	30	6,6±0,1
Nib	4	3	5	190	30	2,1±0,2
Cáscara	4	3	5	190	30	6,4±0,4
Nib	4	3	5	190	45	3,6±0,1
Cáscara	4	3	5	190	45	7,5±0,1
Nib	6	0	6	190	45	3,471±0,003
Cáscara	6	0	6	190	45	7,06±0,04
Nib	4	3	5	170	45	4,9±0,1
Cáscara	4	3	5	170	45	8,3±0,2
Nib	6	0	6	170	45	4,4±0,2
Cáscara	6	0	6	170	45	8,60±0,03
Nib	6	0	6	170	30	4,42±0,05
Cáscara	6	0	6	170	30	8,45±0,04
Nib	4	3	5	170	30	4,7±0,2
Cáscara	4	3	5	170	30	8,04±0,04

Fuente: Los autores.

Tabla 5.
Concentración de Cd en las muestras de híbridos internacionales de *Theobroma cacao,* de acuerdo al diseño factorial para digestión por ultrasonido.

	HNO_3 /mL	H_2O_2 /mL	H_2O /mL	T/ºC	t/min	[Cd] /mg Kg^{-1}
Nib	12	0	12	45	60	2,6±0,1
Cáscara	12	0	12	45	60	6,86±0,05
Nib	8	6	10	45	60	2,84±0,06
Cáscara	8	6	10	45	60	5,6±0,1
Nib	12	0	12	60	120	2,82±0,06
Cáscara	12	0	12	60	120	6,7±0,2
Nib	8	6	10	60	120	3,6±0,2
Cáscara	8	6	10	60	120	7,01±0,06
Nib	8	6	10	60	60	3,1±0,1
Cáscara	8	6	10	60	60	5,81±0,04
Nib	12	0	12	60	60	3,11±0,01
Cáscara	12	0	12	60	60	5,8±0,1
Nib	8	6	10	45	120	2,6±0,2
Cáscara	8	6	10	45	120	6,2±0,1
Nib	12	0	12	45	120	3,01±0,08
Cáscara	12	0	12	45	120	5,8±0,1

Fuente: Los autores.

Tabla 6.
Porcentaje de recuperación para cada método de digestión.

	[Cd] / %	
Método	**Nib**	**Cáscara**
Digestión con ultrasonido	93 ± 1	79,6 ± 0,9
Digestión con microondas	96 ± 2	94 ± 1

Fuente: Los autores.

Dado que el sistema de digestión por ultrasonido consiste en un tubo con un sistema de condensación (Fig. 1), se descartó la posible pérdida de analito por volatilización durante la digestión. Por otro lado, debido al tamaño del tubo y el aforo para la solución de 50 mL se entorpece el proceso de trasvasado y lavado, por lo cual se concluyó posible pérdida de analito puede ocurrir en esta etapa.

En el caso de la digestión con microondas los % R estuvieron entre 94-104 %, valores dentro del rango de aceptación. Estos resultados indican que el horno de microondas utilizado para la digestión de la muestra mantiene en solución la totalidad del analito y garantiza los resultados con mayor exactitud, por lo que fue seleccionado como el método de digestión para los ensayos presentados en las próximas secciones (HNO_3:H_2O_2 4:3 (mL),170 ºC y 45 min).

Evaluación de la precisión inter-día e intra-día de las medidas

Utilizando digestión por microondas, se evaluó la repetibilidad inter-día e intra-día de las absorbancias obtenidas. Para la repetibilidad intra-día se realizaron medidas de la misma muestra un mismo día a distintas horas. En la Tabla 7, se reportan las absorbancias promedio y las condiciones ambientales de temperatura, presión y humedad del laboratorio donde se realizaron las medidas. Se obtuvo en promedio una absorbancia de 0,00222 para el nib y 0,0048 para la cáscara; con un coeficiente de variación promedio de 3 % para ambas muestras. Valores de coeficientes de variación menores de 1 % en un análisis de repetibilidad son considerados aceptables según la Conferencia Internacional sobre Armonización (ICH) [22], por lo que se procedió a evaluar los posibles efectos externos que pudieran generar diferencia entre las mediciones.

Tabla 7.
Resultados del estudio de repetibilidad intra-día.

Hora	Absorbancia (Nib)	Absorbancia (Cáscara)	T/ºC	Humedad /%	Presión(mbar)
8:30 am	0,0021±0,0002	0,0048±0,0002	23,1	83	1020,6
10:30 am	0,00226±0,00001	0,0049±0,0002	23,8	80	1020
1:30 pm	0,00217±0,00002	0,0049±0,0003	24,7	64	1017,7
3:30 pm	0,0021±0,0001	0,0046±0,0002	25,1	62	1015,7
5:30 pm	0,00222±00009	0,0049±0,0003	24,9	85	1015,9
Promedio	0,00222	0,0048			
Desviación estándar	0,00007	0,0001			
Coeficiente de variación (%)	3,29	2,71			

Fuente: Los autores.

Tabla 8.
Resultados del estudio de precisión inter-diaria.

Fecha	Absorbancia (Nib)	Absorbancia (Cáscara)	T / ºC	Humedad /%	Presión/mbar
27/09/2016	0,00221±0,00005	0,00461±0,00006	23,8	80	1020
28/09/2016	0,0020±0,0002	0,0042±0,0001	24,1	76	1019,8
04/10/2016	0,00221±0,00007	0,0040±0,0003	22,9	69	1019,1
07/10/2016	0,00215±0,00005	0,0043±0,0002	23,7	71	1015,1
10/20/2016	0,00217±0,00009	0,0045±0,0002	24,2	79	1015,8
Promedio	0,00215	0,0043			
Desviación estándar	0,00008	0,0002			
Coeficiente de variación	3,79	5,35			

Fuente: Los autores.

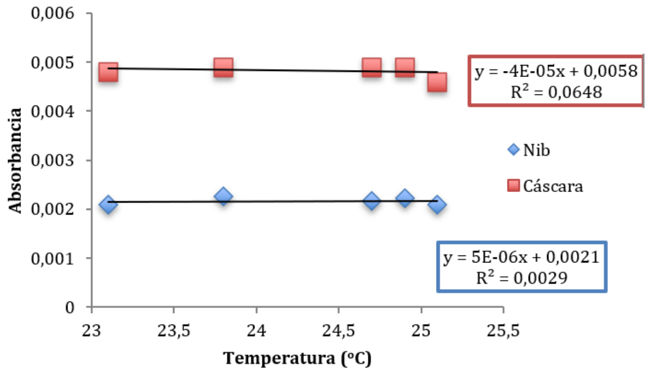

Figura 3. Evaluación del efecto de la temperatura ambiente en las mediciones de absorbancia en el estudio intra-diario.
Fuente: Los autores.

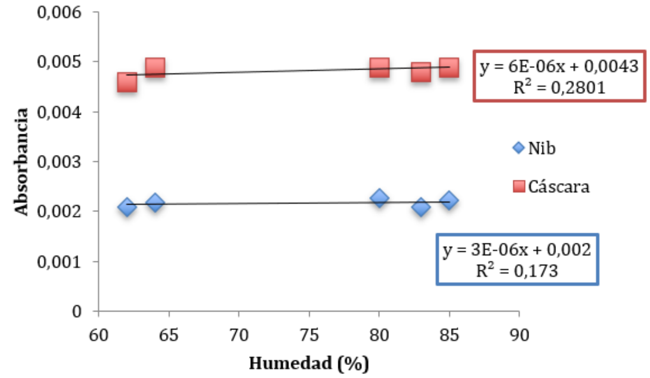

Figura 4. Evaluación del efecto de la humedad en las mediciones de absorbancia en medidas intra-diario.
Fuente: Los autores.

La relación entre la temperatura y las medidas de absorbancia se presenta en la Fig. 3, donde se puede observar un coeficiente de determinación R^2 menores de 0,1 con pendientes que tienden a cero, por lo que las mediciones realizadas son prácticamente independientes de la temperatura. Igualmente, en las Figs. 4 y 5, se puede observar que no hay relación de dependencia entre las absorbancias medidas y las variables externas presión y humedad. De acuerdo a estos resultados se consideró que las mediciones son bastante precisas y las leves variaciones detectadas no tienen relación alguna con variables como la temperatura, presión o humedad del ambiente.

Bajo el mismo procedimiento descrito se realizaron las mediciones de absorbancia en la solución de una única muestra variando en diferentes días. Los resultados se resumen en la Tabla 8.

Los valores establecidos como aceptables por la ICH es un coeficiente de variación promedio por debajo de 2 %, para el análisis de precisión intermediaria. En la presente investigación se obtuvo un coeficiente de variación promedio de 4,6 % por lo que se procedió a evaluar los posibles efectos externos que generaron las diferencias en las medidas de absorbancia. Los resultados (no mostrados), indicaron que no hay efecto apreciable entre las variables estudiadas y la absorbancia.

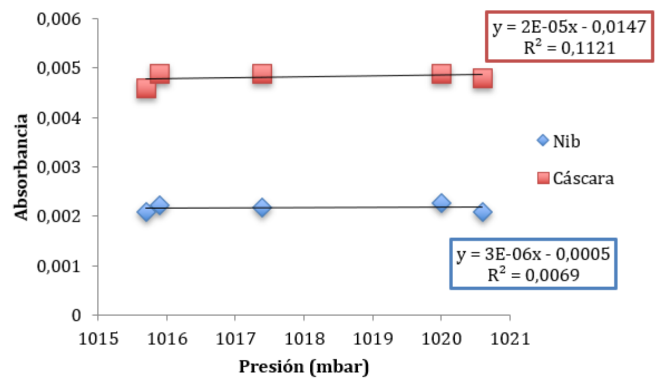

Figura 5. Evaluación del efecto de la presión en las mediciones de absorbancia en estudio intra-diario.
Fuente: Los autores.

Tabla 8.
Resultados del estudio de precisión inter-diaria.

Fecha	Absorbancia (Nib)	Absorbancia (Cáscara)	T / º C	Humedad /%	Presión/mbar
27/09/2016	0,00221±0,00005	0,00461±0,00006	23,8	80	1020
28/09/2016	0,0020±0,0002	0,0042±0,0001	24,1	76	1019,8
04/10/2016	0,00221±0,00007	0,0040±0,0003	22,9	69	1019,1
07/10/2016	0,00215±0,00005	0,0043±0,0002	23,7	71	1015,1
10/20/2016	0,00217±0,00009	0,0045±0,0002	24,2	79	1015,8
Promedio	0,00215	0,0043			
Desviación estándar	0,00008	0,0002			
Coeficiente de variación	3,79	5,35			

Fuente: Los autores.

Determinación de cadmio en muestras de Theobroma cacao venezolano

En la Tabla 9 se reportan los resultados obtenidos de concentración de Cd para cada muestra analizada. No se detectó Cd en las muestras provenientes de Cumboto de la región Ocumare de la Costa y la variedad Ocumare 61 procedente de la población de Carúpano, mientras que en las otras muestras la presencia de Cd fue evidente.

La prueba de Kruskal-Wallis mostró diferencias significativas en los niveles de Cd entre las siete muestras de *Theobroma cacao* en las que se detectó el metal ($p < 0{,}01$). Sin embargo, no se observaron diferencias significativas en el contenido de Cd entre nib y cáscara en las muestras de Carenero – Carúpano y Sur del Lago – Carúpano ($p = 0{,}2105$ y $p = 0{,}1034$, respectivamente). En contraste, en las muestras provenientes de las demás regiones sí se encontraron diferencias significativas en la concentración de Cd entre nib y cáscara.

Los resultados presentados en la Fig. 6, indican que la muestra con mayor concentración de Cd fue la proveniente de Padrón en la estación experimental Miranda. En todas las muestras donde se detectó Cd la concentración se encuentra por encima de 0,6 mg kg^{-1} (valor indicado por la línea verde sobre el gráfico), límite permisible fijado por Unión Europea y la Organización Internacional de Cacao durante el "Taller internacional sobre el cadmio en productos de cacao y chocolate" en el año 2019. Además, se encontró que la mayor concentración de Cd en las muestras estudiadas está en la cáscara; resultado contrario a lo encontrado por Chávez et al. [18], quienes reportaron que en muestras de cacao proveniente de distintas zonas de Ecuador la mayor concentración de Cd se encontró en el nib.

Tabla 9.
Concentración de cadmio en las diferentes muestras. N=6.

#	Muestra	[Cd] en nib (mg Kg^{-1})	[Cd] en cáscara (mg Kg^{-1})
1	Híbridos internacionales-Miranda	3,6±0,3	7,2±0,2
2	Carenero superior-Miranda	2,6±0,5	5,7±0,2
3	Cumboto-Ocumare	N/D	N/D
4	Sur de lago-Mérida	1,7±0,2	2,0±0,3
5	Ocumare 61- Carúpano	N/D	N/D
6	Carenero- Carúpano	2,86±0,07	3,0±0,1
7	Sur del lago- Carúpano	2,0±0,3	2,0±0,1
8	Canoabo-Carúpano	1,7±0,1	2,46±0,04
9	Rio Caribe Superior- Carúpano	1,40±0,08	2,3±0,2

*N/D = no detectado.
Fuente: Los autores.

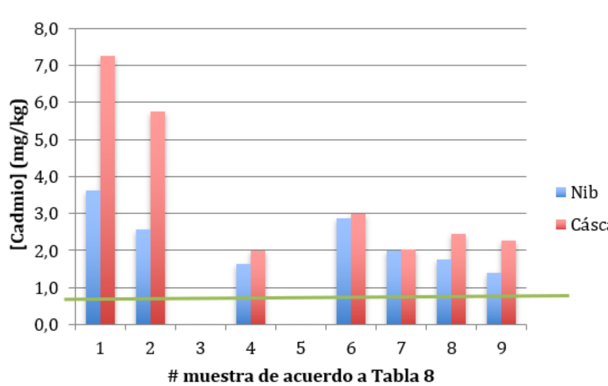

Figura 6. Resultados obtenidos para las diferentes muestras.
Fuente: Los autores.

La mayor concentración de Cd en la cáscara puede ser indicador de fuente de contaminación externa durante el proceso de fermentación, secado o tostado; sin embargo, los valores altos encontrados en el nib no descartan la posibilidad que la contaminación ocurra durante el crecimiento de la planta y, por lo tanto, el metal provenga de suelo o agua contaminada [24]. Por otro lado, se indago sobre posibles fuentes de contaminación en la zona de la muestra con mayor concentración de Cd y no se encontraron, por lo cual sería valioso profundizar en estudios de suelo y agua.

Un resultado relevante en la presente investigación, fue el obtenido en las muestras etiquetadas en la Tabla 9 como 5,6,7,8 y 9, las cuales son diferentes tipos de cacao que provienen de una misma plantación de la población de Carúpano; en estas muestras la concentración de Cd varía entre 1,4 y 2,9 mg kg^{-1} sin embargo, existe una de ellas (muestra 5) cuya concentración de Cd no pudo ser detectada y se asumió que la concentración se encuentra por debajo del límite de detección de la técnica. En esta plantación los diferentes tipos de cacao se encuentran geográficamente separados en terrenos bien delimitados por lo que, realizar estudios de suelos aportaría valiosa información.

La presencia de Cd en las almendras de cacao es un aspecto que se ha estudiado alrededor del mundo en países productores de cacao; por ejemplo, se han detectado altas concentraciones de Cd en muestras provenientes de Ecuador, Malasia y Perú [14], reportes que coinciden con los resultados obtenidos en esta investigación.

1. Conclusión

Se cuantificó Cd en nueve tipos de muestras de almendras de cacao venezolano fermentadas, secas y tostadas, analizando por separado el nib y la cáscara. La concentración de Cd osciló entre 1,4 y 7,2 mg kg^{-1}, destacándose la muestra de híbridos internacionales de la estación experimental Miranda con la mayor concentración tanto en el nib como en la cáscara. Los resultados indicaron una tendencia en todas las muestras de mayor concentración de Cd en la cáscara en comparación con el nib, lo que sugiere la existencia de fuente de contaminación externa durante los procesos de fermentación, secado o tostado. La mayoría de las muestras excedieron el límite establecido por la Unión Europea de 0,6 mg kg^{-1} de Cd, con la excepción de las muestras de Ocumare 61-Carúpano y Carenero – Carúpano.

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Trends in financial inclusion for the social transformation of micro-businesses: a systematic literature review

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Abstract
The financial and credit implications for the household well-being of small businesses or micro-businesses are crucial to understanding their social transformation and business expansion. Therefore, this article aims to examine the research landscape of microfinance, microcredit and financial inclusion and their impact on the entrepreneurial development of small businesses or micro-businesses, considering social, economic and productive conditions. To this end, a bibliometric analysis and a systematic literature review are carried out based on the Business category journals classified from Q1 to Q4 by Scimago. Through the application of PRISMA and VOSviewer, bibliometric networks are constructed and mapped. Among the main findings, it is that micro-businesses mainly located in emerging countries have a significant relationship with women's empowerment and financial education.

Keywords: micro-business; microfinance; small business; PRISMA; social progress; systematic literature review.

Tendencias en inclusión financiera para la transformación social de los micronegocios: revisión sistemática de literatura

Resumen
Las implicaciones financieras y de crédito para el bienestar de los hogares de las pequeñas empresas o micronegocios son cruciales para entender su transformación social y la ampliación de sus negocios. Por esto, este artículo tiene como objetivo examinar el panorama de las investigaciones de las microfinanzas, el microcrédito y la inclusión financiera y su impacto en el desarrollo empresarial de las pequeñas empresas o micronegocios, teniendo en cuenta las condiciones sociales, económicas y productivas. Para esto, se ejecuta un análisis bibliométrico y una revisión sistemática de literatura a partir de las revistas de la categoría Administración (Business) clasificadas de Q1 a Q4 por Scimago. Mediante la aplicación de PRISMA y de VOSviewer se realiza la construcción y mapeo de redes bibliométricas. Entre los principales hallazgos, se encuentran que los micronegocios principalmente ubicados en países emergentes tienen una relación significativa frente al empoderamiento de la mujer y la educación financiera.

Palabras clave: micronegocios; microfinanciación; pequeña empresa; PRISMA; progreso social; revisión sistemática de literatura.

1 Introducción

El microcrédito, las microfinanzas y la inclusión financiera influyen de manera directa en el desarrollo empresarial de los micronegocios y, a su vez, en sus condiciones sociales, económicas y productivas. No obstante, según Estrada & Hernández [1], estos mecanismos dan cuenta de que no necesariamente representan un cliente con un alto riesgo a razón de la recuperación de cartera, sino que también implica oportunidades en cuanto a estímulos financieros y tributarios, generación de empleo, entre otros [2]. Las micro, pequeñas y medianas empresas (MiPymes) [3] son determinantes en la mayoría de los países emergentes porque contribuyen a la generación de empleo y al desarrollo económico. Las pequeñas empresas o micronegocios se ven expuestas a asumir y afrontar riesgos de crédito. Por esto, el microcrédito surge con el fin de incrementar la posibilidad de acceder a mejores condiciones

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para iniciar o mantener un negocio para las personas en calidad de pobreza o que sean trabajadores independientes [4]. Muhammad Yunus extiende este término hacia el mejoramiento de las condiciones de vida de las personas más pobres [5,6]. El microcrédito, como concepto en evolución, es un mecanismo para el desarrollo de los pequeños negocios como los préstamos [7].

En cuanto a las microfinanzas, han ido cambiando en distintas fases desde la euforia financiera y la entrada de esta herramienta hasta hoy [8]. La microfinanciación se entiende como el efecto de los servicios financieros en la vida de las poblaciones más vulnerables y su entorno familiar, así como una herramienta para el desarrollo empresarial [9,2] y una estrategia de lucha contra la pobreza [10]. Se consideran que las políticas de inclusión financiera [11] son la clave para un despliegue con mayor alcance como herramienta para el desarrollo, la reducción de la pobreza y un sistema financiero sólido. Como expresa Das & Saha [12], la microfinanciación ha tenido un impacto relevante en el desarrollo de la India donde se busca ayudar a las comunidades desfavorecidas económicamente a lograr mayores niveles de desarrollo de la riqueza y de seguridad de los ingresos, tanto para los hogares como para las comunidades enteras. A su vez logra ayudar a los pequeños prestatarios a comenzar actividades microempresariales, lo que fomenta su autonomía financiera, conduciendo a una mejor sociedad y el crecimiento del país.

Para Ali et al [12], el alivio de la pobreza es un problema global y la microfinanciación es una herramienta de mitigación. Su estudio está relacionado con las instituciones financieras, la tecnología financiera y el crowdfunding provenientes de Estados Unidos y en cuanto a las tendencias incluyen la educación financiera y el uso de minería de datos. Otra investigación es la revisión de 25 años de literatura en Microfinanzas usando el software R, la técnica de análisis de redes de Gephi y el software VOS viewer [13]; y un estudio similar de Gutiérrez-Nieto & Serrano-Cinca [14] es el más citado en la base de datos Scopus. Por su parte, Brito & Visano [15] consideran que los pequeños préstamos y los programas de microcrédito pueden ayudar a los negocios en sus etapas de incubación y desarrollo. Si bien su modelo está aplicado en ciudades pequeñas de Canadá, país de ingresos altos, las categorías de variables captan la atención para esta investigación a razón de los limitados estudios que tienen lugar en países de ingresos medios o bajos. Cabe destacar dos aspectos: la exclusión de las personas en pobreza del sistema financiero formal en especial en los países menos desarrollados [16] y que la inclusión financiera juega un papel relevante para llevar a cabo la dimensión del desarrollo financiero sostenible de pequeñas empresas o micronegocios.

Por lo tanto, es necesario involucrar en su estudio conceptos como finanzas personales, conocimiento financiero, educación financiera, como también otros que implican nuevos desafíos como alfabetización financiera, género y planificación de jubilación [17]. En la revisión de literatura de Duvendack & Mader [18], encuentran en 5 de los 11 meta-estudios una relación positiva entre acceso a servicios financieros y pobreza, siendo una de las más citadas en Scopus. No obstante, las expectativas en inclusión financiera se pueden ver afectadas por la calificación por parte de las agencias calificadoras de riesgo y las crisis financieras como la presentada en 2008. Cabe señalar que algunos países emergentes tienen contextos locales que moldean la política doméstica [19] como Colombia donde en los últimos años, se han concentrado en afrontar el conflicto armado, o el caso de Rusia y Ucrania [20], también están la inestabilidad política, el narcotráfico [21] y la migración [22]. De aquí que uno de los principales desafíos para mitigar la vulnerabilidad socioeconómica [23] se centra en mejorar la educación financiera, convirtiéndose en una alternativa viable para el mejoramiento de su calidad de vida. El microcrédito [24], las microfinanzas [14,25,26] y la inclusión financiera [27-29] se han estudiado mediante un análisis bibliométrico por separado. Por esto, el presente estudio es único al utilizar este conjunto de términos aplicados a pequeñas empresas o micronegocios, lo que conduce a una comprensión original del avance de la investigación en estos temas y ofrece nuevas oportunidades para futuras investigaciones acerca de su impacto en la dimensión social [30].

Este trabajo tiene como objetivo examinar el panorama de los estudios e investigaciones de las microfinanzas, el microcrédito y la inclusión financiera e identificar las tendencias de investigación asociadas al desarrollo de pequeñas empresas articuladas a las decisiones financieras empresariales en economías emergentes. Se plantea la pregunta de investigación: ¿cuáles son las tendencias de investigación asociadas a los micronegocios? No obstante, por la ausencia de estudios en este tema, es necesario plantear preguntas complementarias ¿cómo ha evolucionado el volumen de publicaciones sobre el tema analizado en los últimos años? ¿cuáles revistas, artículos, autores y países son los más influyentes en la investigación sobre el papel de los microcréditos y las microfinanzas en la inclusión financiera de los micronegocios? Para esto, se realiza un análisis bibliométrico partiendo de un conjunto de 9,107 documentos publicados en Scopus que comprenden artículos, capítulos de libro, revistas, documentos de conferencia, entre otros, y su posterior filtro para encontrar trabajos especializados en el tema propuesto.

La presente investigación se justifica por la ausencia de estudios recientes alrededor de este conjunto temático en torno a un análisis profundo de los más especializados y citados autores. Se parte de las palabras clave seleccionadas de la ecuación de búsqueda y del hecho de que los estudios bibliométricos están recibiendo una importante atención por parte de la comunidad científica para estudiar el estado del arte y la tendencia de desarrollo de un campo de investigación como el de las decisiones financieras empresariales para el desarrollo social en países emergentes. De este modo, los académicos pueden utilizar la revisión sistemática de literatura para identificar tendencias en el rendimiento de artículos y revistas, patrones de colaboración entre investigadores y explorar la estructura intelectual de un ámbito específico en la literatura existente. Este artículo está organizado en tres secciones. En la sección 2, se detalla la parte metodológica, métodos e instrumentos para la selección y procesamiento de los documentos y artículos científicos objetos de estudio.

En la sección 3, se presentan los resultados, seguido en la sección 4 se expone la discusión. Por último, se presentan las principales conclusiones y tendencias de futuras líneas de investigación en decisiones financieras para los micronegocios en países emergentes.

2 Metodología

La investigación académica sobre microfinanzas, microcrédito e inclusión financiera se ha multiplicado en los últimos años y se observa por parte de diferentes autores el interés en ampliar el conocimiento evidenciado en el aumento de las publicaciones en revistas académicas de alto impacto. De tal forma que, para tener un conocimiento comprehensivo del avance científico en microcréditos, microfinanzas e inclusión financiera en las pequeñas empresas o micronegocios, se utiliza el análisis bibliométrico como método de investigación. Este método analiza la evolución de las publicaciones y temáticas de investigación, ofrece un panorama de revistas, autores, conexiones y cooperación, y determina las tendencias en publicaciones [31]. Para esto, se utiliza la herramienta de VOSviewer, es un software de acceso abierto que cuenta con una interfaz gráfica y visualización mediante mapeo. Cabe señalar que las bases de datos principales para la literatura científica son Google Scholar, Web of Science (WoS), Redalyc, Scielo y Scopus. Esta última ofrece la mayor cantidad de publicaciones en artículos, capítulos de libro, revistas, documentos de conferencia, entre otros, con un contenido de calidad y herramientas de análisis, seguimiento y visualización de por áreas de conocimiento, razón por la que se selecciona como base de datos principal.

Asimismo, se considera que una revisión sistemática apoya esta investigación debido a que analiza de forma sistematizada y objetiva la eficacia de las intervenciones de modo que responde a preguntas principales sobre lo que funciona [32]. Este tipo de revisiones se clasifica como investigación de la investigación, o investigación secundaria. Se define como un resumen de evidencias que utiliza un proceso riguroso para minimizar los sesgos e identifica, evalúa y sintetiza estudios para responder a la pregunta de investigación y extrae conclusiones sobre los datos recopilados. Por esto, el presente estudio utiliza la declaración PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) [33]. Se parte de la actualización de Page et al [34] principalmente para la revisión sistemática de literatura y de Urrútia y Bonfill [33], quienes consideran la importancia de los cambios introducidos a la versión de 2009, entre estos se destacan la disminución del riesgo de sesgo a razón del conocimiento previo de los investigadores y el grado de arrojar resultados y conclusiones con validez y fiabilidad.

2.1 Datos y muestra

El desarrollo del análisis bibliométrico utiliza la base de datos Scopus debido que cuenta con amplia cobertura global y regional de revistas científicas, actas de congresos, y libros y capítulos. Es la mayor base de datos de resúmenes y citas de la literatura revisada por pares, cuyas herramientas inteligentes permiten controlar, analizar y visualizar la investigación académica lo que permite obtener un corpus teórico adecuado para dar respuesta al problema planteado. La sincronización del análisis comprende el periodo de enero de 2012 a diciembre de 2023. En el presente estudio, se sigue el proceso diseñado por Ramírez y García Peñalvo [35] para la revisión sistemática de literatura (SLR) mediante 3 fases:

Fase I. Planificación. Según Kitchenham [36], esta etapa de planificación se orienta en la búsqueda de bases de datos a partir de palabras claves mediante la elección de bases de datos especializadas y criterios de delimitación de búsquedas. En primera medida, se seleccionan las palabras clave, se realizan búsquedas sistemáticas, así como resúmenes para posteriormente identificar y clasificar los resultados de los estudios sobre los temas de análisis.

Fase II. Conducción. En esta etapa se da respuesta a la pregunta planteada mediante la evaluación y extracción de los datos de los artículos, siguiendo las recomendaciones de Higgins y Green [37], se utiliza un protocolo de objetivos de la revisión y piloteados para cada nueva revisión. La primera búsqueda integró las palabras claves en la base de datos Scopus (BD-S); en la segunda se seleccionaron únicamente los que estaban en revistas de acceso abierto, en relación con los criterios de inclusión y exclusión y se eliminaron los duplicados.

Fase III. Informe de resultados. En esta fase se ordena la información clave de los trabajos en cuestión como la métrica, autores más representativos, fechas, contexto, objetivos de las investigaciones, métodos, resultados y conclusiones. Según el Centre for Reviews and Dissemination de York University [38], se validan criterios relacionados con calidad y pertinencia de los documentos seleccionados como inclusión y exclusión de la revisión de literatura, el alcance de los estudios y su pertinencia con relación al tema objeto de estudio.

2.2 Selección de los términos de búsqueda

Siguiendo el proceso planteado para la revisión sistemática de literatura, en la fase de planificación, este estudio se centró en contestar las preguntas de investigación:

- ¿Cuántos estudios hay en la base de datos Scopus acerca de microcréditos, microfinanzas e inclusión financiera desde enero de 2012 a diciembre de 2023?
- ¿Cuáles revistas, artículos, autores y países son los más influyentes en la investigación sobre el papel de los microcréditos y las microfinanzas en la inclusión financiera de los micronegocios?
- ¿Cómo ha evolucionado el volumen de publicaciones sobre el tema analizado en los últimos años?
- ¿Cuáles son las tendencias de investigación asociadas a los micronegocios?

Teniendo en cuenta los atributos de la revisión sistemática: estructurada, transparente e integral de Hiebl [39], se procede con el protocolo para la revisión y las pautas de selección y evaluación de los estudios pertinentes:

- Recursos de búsqueda: Base de datos Scopus (BD-S)
- Categorías y palabras clave: Microcrédito (microcredit), microfinanzas (microfinance) e inclusión

financiera (financial inclusion).

- Criterios de inclusión y exclusión: período de tiempo: de enero de 2012 a diciembre de 2023; tipo de documento: artículos, capítulos de libro, documentos de conferencia, libros, revisión de conferencia entre otros; tipo de revista: open Access, Gold, Hybrid Gold, Bronze, Green; campo delimitado de estudio: ciencia abierta; idioma: inglés.

Se tiene la estrategia de búsqueda para Scopus: *TITLE-ABS KEY (microfinance OR microcredit OR "Financial inclusion")* cuyo resultado arroja 9,107 documentos encontrados. Siguiendo con los criterios de inclusión y exclusión y en relación con la variable dependiente considerada como el desempeño de los micronegocios, se incorpora: *TITLE-ABS-KEY (microfinance OR microcredit OR "financial inclusion" AND microbusiness OR microfirms OR microenterprises)*, arrojando 232 publicaciones en las áreas de Negocios y Economía. Se limita la búsqueda al periodo de 2012 a 2023, arrojando como resultado 127 documentos sobre el tema de investigación abordado, donde 61 son publicaciones finales. Enseguida se escogieron los documentos tipo artículos con un resultado de 52 documentos, esto evidencia una gran cantidad aún de publicaciones sobre el tema de investigación. Finalmente, se aplicaron otras ecuaciones de búsqueda delimitando por el área temática de *(Economics, Econometrics and Finance) AND (Business, Management and Accounting)* y de *open access* con un resultado de 29 y 15 documentos, respectivamente.

A partir de lo anterior, se aplica la declaración PRISMA para el análisis y sistematización de los estudios y extractos de datos y también para identificar tendencias futuras de investigación. Por esto, en la Fig.1 se plantea su aplicación para la revisión sistemática.

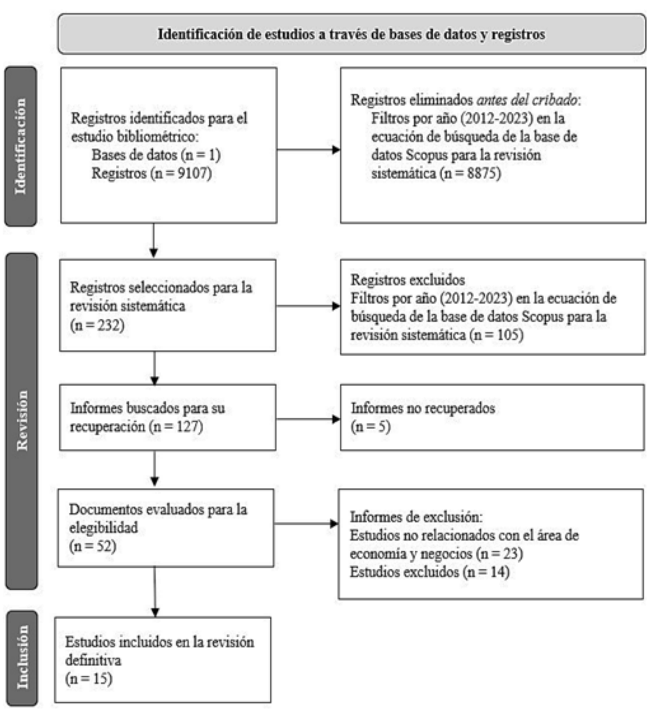


Figura 1. Diagrama de flujo PRISMA por niveles, a partir de Page et al [34].
Fuente: Elaboración propia.

2.3 Identificación de revistas académicas y científicas

Siguiendo la *Fase II de Conducción*, en relación con las revistas y los indicadores científicos, el Scimago Journal Rank (SJR) es un portal que parte de la información contenido en Scopus para proporcionar un índice de calidad relativo, el Scimago Journal Rank (SJR), y un ranking de revistas que cada vez se utiliza con mayor frecuencia para evaluar y analizar las publicaciones científicas. El indicador SJR se realiza sobre el cálculo de las citas recibidas por las revistas en un periodo de tres años, otorgando un peso mayor a las citas procedentes de revistas de alto prestigio (aquellas con altas tasas de citación y baja autocita) y teniendo en cuenta el campo temático, su cálculo utiliza el algoritmo PageRank de Google.

SCImago Journal & Country Rank, además del SJR, ofrece el Índice H de la revista, los cuartiles en los que está situada, el tipo de documento, número de documentos, número de referencias, número de citas, número de documentos citables, citas por documento y referencias por documento y país. Este indicador de citación influye de manera sistémica como comparativo o punto de referencia para las revistas a nivel global, su algoritmo prácticamente involucra un nivel de prestigio alcanzado tanto para la revista como para el artículo o autor citados. El SJR organiza las revistas por áreas temáticas donde el microcrédito, las microfinanzas y la inclusión financiera se encuentran en *Business, Management and Accounting*.

Del cálculo del indicador SJR que refleja prestigio, en el cuartil Q1 hay 95 revistas para el año 2023, entre las que se encuentran Academy of Management Journal (Estados Unidos) con 223 documentos en los últimos 3 años; y seguidos por revistas de Reino Unido en su orden: Journal of International Business Studies con 260; R and D Management con 138; International Journal of Entrepreneurial Behaviour and Research con 306; y Journal of Common Market Studies con 317. No obstante, en la Tabla 1, se observa que solo 10 corresponde a acceso abierto para el año 2023, los principales países de afiliación son Reino Unido, Países Bajos, Suiza, Alemania, República Checa y Malasia.

En cuanto a las revistas que publican más artículos con las palabras claves del presente estudio *(Microfinance, Financial inclusion y microcredit)* están Enterprise Development And Microfinance (Reino Unido) con 164 artículos, World Development (Reino Unido) con 139, Journal of International Development (Reino Unido) con 116 y Small Enterprise Development (Reino Unido) con 91.

Tabla 1.
Revistas SJR Q1 de Administración 2023

Rank Q1	Rank OA*	Título	SJR	Cuartil Q1 SJR	Índice H	Total Docs. (2023)	Total Docs. (3años)	Total Refs.	Total Cites (3años)	Docs. Citables (3años)	Citas / Doc. (2años)	Ref. / Doc.	País
45	1	Schmalenbach Journal of Business Research	1,188	Q1	33	23	108	1698	621	99	1,85	73,83	Alemania
48	2	Journal of Applied Structural Equation Modeling	1,153	Q1	11	10	32	953	263	32	4,1	95,3	Malasia
51	3	Eurasian Business Review	1,142	Q1	31	35	82	2780	430	82	5,7	79,43	Suiza
53	4	International Journal of Health Geographics	1,109	Q1	89	38	122	2398	557	120	3,23	63,11	Reino Unido
56	5	BRQ Business Research Quarterly	1,008	Q1	41	39	91	3386	403	89	4,33	86,82	Países Bajos
59	6	Intereconomics	0,98	Q1	29	57	206	801	548	142	2,62	14,05	Polonia
66	7	Journal of Competitiveness	0,934	Q1	37	44	120	2590	811	120	5,79	58,86	República Checa
70	8	Journal of Theoretical and Applied Electronic Commerce Research	0,892	Q1	47	113	297	8356	2139	290	7,11	73,95	Suiza
71	9	Digital Business	0,89	Q1	13	19	47	1686	303	46	6,29	88,74	Países Bajos
74	10	Humanities and Social Sciences Communications	0,871	Q1	35	950	926	62623	3966	887	4,06	65,92	Reino Unido

Fuente: Elaboración propia, datos obtenidos de SJR.
*OA: Ranking de acceso abierto. Doc: Documento (s).

1 Resultados

El panorama de las investigaciones sobre micronegocios asociados con los tres términos clave en su conjunto: microfinanzas, el microcrédito y la inclusión financiera, en Scopus, incluye la identificación de los principales autores y su afiliación, el ranking de su Índice *H* y la cantidad de documentos publicados del conjunto de términos en mención. Asimismo, se identifican los documentos más citados y las revistas que más publican sobre el tema de este estudio, y las tendencias en producción del periodo 2012-2023, las palabras clave, y la co-citación de autores con el ánimo de visualizar y mapear dichos términos y la distribución geográfica de los autores. En este sentido, continuando con la fase de resultados, cabe señalar que es necesario identificar los principales autores desde su Índice *H* y de los 127 documentos seleccionados [40]. Se encuentra que encabezando el ranking está Vincent Blok de Países Bajos, con un Índice *H* de 36, seguido por Sefa Awaworyi Churchill, con un Índice *H* de 30 del College of Business and Law de Australia, y Md. Mahmudul Alam de la Universiti Utara de Malaysia, con un Índice *H* de 25.

Asimismo, entre las 10 revistas con mayor producción sobre el tema de la presente investigación se encuentran Enterprise Development and Microfinance con 6 documentos, International Journal of Social Economics con 4 artículos, Asian Social Science con 3 publicaciones.

En la Fig.2 se observa la cantidad de documentos publicados en el periodo estudiado. En los años 2012 y 2013 se muestra un fuerte crecimiento de la producción relacionada con el resultado de búsqueda de las palabras *microfinance OR microcredit OR financial inclusion* en Scopus. El nivel de producción anual desde 2014 presenta un decrecimiento significativo, particularmente en 2019, aunque con incremento en 2020 y 2022 de 13 y 18 documentos, respectivamente.

Teniendo en cuenta la co-ocurrencia de palabras claves, la Fig.3 muestra los términos más representativos: en el clúster verde, los conceptos de pobreza, economía, empoderamiento de la mujer, renta, hogar, investigación cualitativa; en el clúster amarillo destacan desarrollo económico, crecimiento económico, desarrollo financiero, inclusión financiera digital, desigualdad de ingresos; en el clúster azul, están los términos inclusión financiera, finanzas, países emergentes, servicios financieros, economía y efectos sociales, banca móvil; el clúster rojo visualiza los conceptos de servicios financieros, banca, sistema financiero, concesión de créditos, India, Bangladesh, Nigeria, género, ahorro, situación de la mujer, convirtiéndose así en los conceptos más relevantes de este estudio bibliométrico.

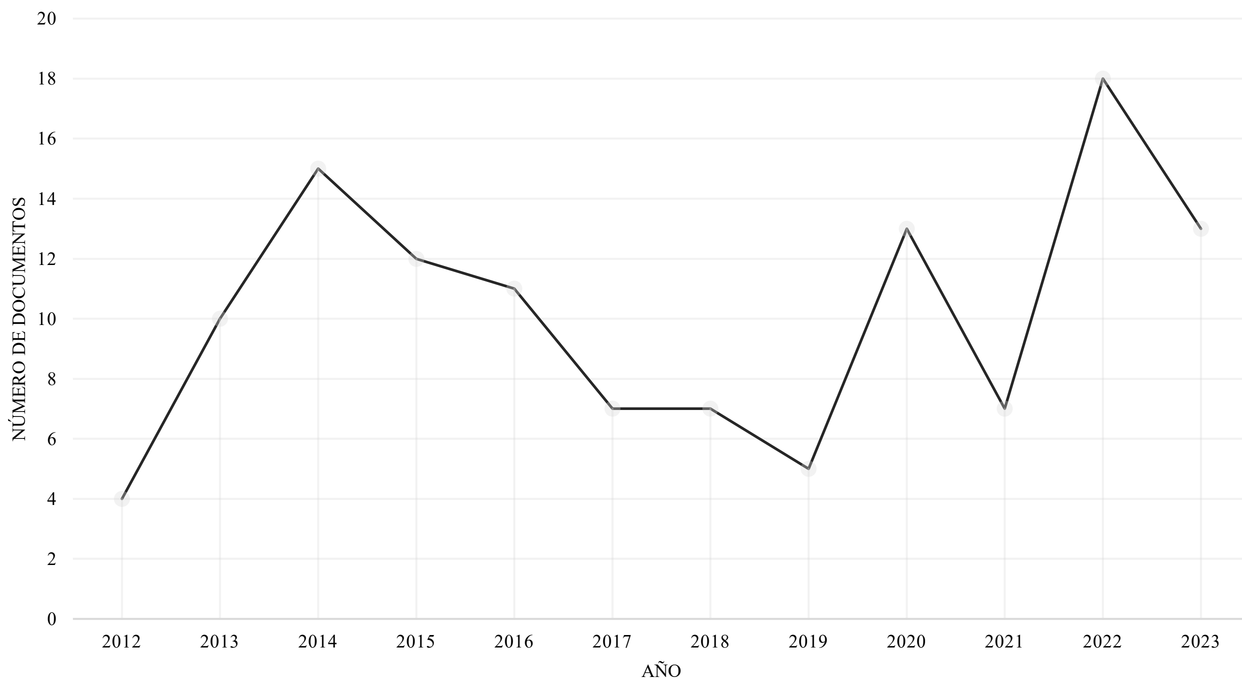
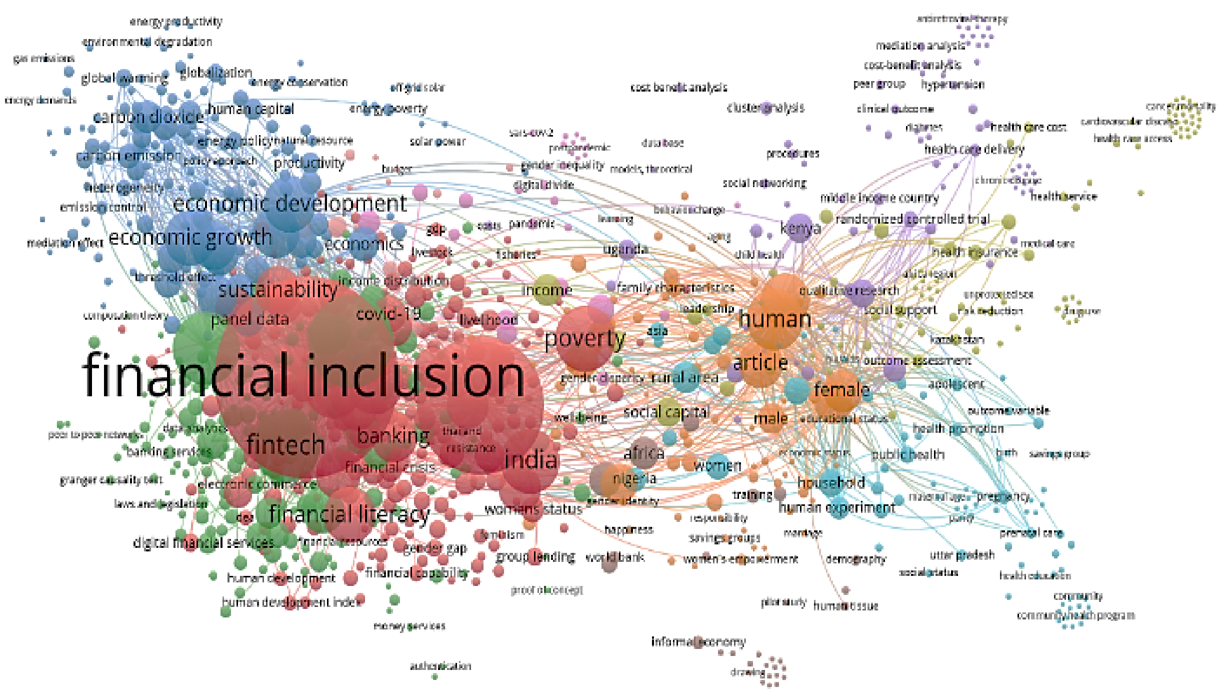


Figura 2. Producción científica 2012 – 2023 en microfinance OR microcredit OR financial inclusion
Fuente: Elaboración propia, datos obtenidos de SJR.



VOSviewer

Figura 3. Co-ocurrencia con todas las palabras clave
Fuente: Elaboración propia.

El acoplamiento bibliográfico es un mecanismo de visualización de áreas temáticas específicas que permite explorar la literatura producida y consumida en una comunidad científica. De este modo, se señala la presencia de tres grandes grupos de autores con un representativo entre ellos. El primer grupo está dominado por Roy Mersland, Marek Hudon, Robert Lensink, Dean Karlan, Jonathan Morduch, Shahidur R. Khandker, Robert Cull y Abhijit Banerjee, autores que han abordado temas microfinanzas, inclusión financiera, desarrollo y economía en sus publicaciones.

El segundo grupo contiene una mayor representación de Asli Demirguc-Kunt, Leora Klapper, James Robinson, Ross Levine, Mandira Sarma y M. Kabir Hassan que han escrito sobre desarrollo financiero, acceso de las empresas a la financiación, crédito, microcrédito, finanzas islámicas, regulación y la inclusión financiera. En el tercer grupo se destacan autores como Muhammad Shahbaz, M. Hashem Pesaran, M Mohsin, que han revisado temas sobre finanzas verdes, Macroeconomía, inclusión financiera y políticas de financiación.

Se encuentra que los países con mayor producción científica asociada al tema de estudio es Estados Unidos, India, Malasia y Reino Unido. No obstante, se presenta un creciente número de autores de países emergentes de la región Asia Pacífico como China, India, Indonesia, Malasia; de la región Europa, Oriente Medio y África están Sudáfrica y Turquía; y en Américas está Colombia. Cabe señalar que Bangladesh es considerado mercado de frontera, y Nigeria como independiente. La necesidad de aumentar la producción científica de mercados emergentes como México y Perú en esta base de datos es clave para los investigadores y los hacedores de política pública de estos países.

A partir de los 15 documentos resultantes de la ecuación de búsqueda, se realiza un análisis de revisión sistemática cualitativa, organizados por autores, fecha de publicación (año) de la reciente a la más antigua, objetivo del estudio (objetivo), Enfoque del estudio empírico (Enfoque) y metodología utilizada en el estudio (Metodología).

En la Tabla 2, se observa que los investigadores utilizan metodologías tradicionales desde los enfoques descriptivo y exploratorio con métodos cualitativos y cuantitativos de acuerdo con el objeto de estudio. Asimismo, utilizan el caso de estudio como metodología para sus investigaciones. Los autores usan principalmente instrumentos como encuestas y entrevistas y realizan revisiones bibliográficas. Los documentos de Malik *et al* [46], Atmadja *et al* [50] y de Alam *et al* [52] se destacan entre los 10 documentos más citados sobre el tema, con co-ocurrencia de palabras relacionadas con las publicaciones en mención.

Tabla 2.
Matriz de revisión sistemática cualitativa

Autores	Año	Objetivo	Enfoque	Metodología
Luciano Alipio *et al* [41]	2023	Determinar la influencia de la gestión empresarial en el desarrollo de Pymes en zonas mineras en el sur de Perú.	Enfoque cuantitativo, con alcance explicativo, de diseño no experimental	Utilizan SPSS versión 26, y para los resultados inferenciales el modelo de regresión ordinal.
Urueña-Mejía, Gutiérrez & Rodríguez-Lesmes [42]	2023	Explorar la adopción de prácticas empresariales y la influencia en el uso de productos y servicios financieros.	Un modelo de ecuaciones estructurales.	El modelo incluye variables latentes modeladas en forma de análisis factorial confirmatorio. Encuestas a 1542 microempresarios en 10 ciudades colombianas en año 2019.
Tia, Kuunibe & Kwame Nkegbe [43]	2023	Examinar los factores que impulsan la inclusión financiera de los microempresarios en el municipio de Wa, en la región del Alto Oeste de Ghana.	Estudio cuantitativo, con alcance de análisis de corte transversal con alcance exploratorio.	Cuestionario cerrado a 200 microempresarios dedicados al comercio, la fabricación y los servicios, fabricación y servicios, seleccionados mediante técnica de muestreo aleatorio simple. Utilizan modelo de regresión probit binario.
Ramli & Zain [44]	2023	Investigar los efectos de los elementos del microcrédito: el volumen del préstamo, la forma de pago y el apoyo, en el rendimiento de las micro-empresas en Kota Bharu, Kelantan.	Metodología de investigación cuantitativa.	Los datos primarios se recogen mediante cuestionario cerrado, y los cuestionarios estructurados se aplican a prestatarios de AIM y TEKUN.
Bharti & Kumari [45]	2022	Evaluar los resultados de los bancos rurales regionales rendimiento financiero.	Estudio cuantitativo aplicando Modelo de ecuaciones estructurales de mínimos cuadrados parciales (PLS-SEM) y análisis estadístico multivariado.	Análisis Envolvente de Datos (DEA) en rendimiento financiero, rendimiento de los sectores prioritarios, préstamos a los sectores más débiles y financiación agrícola.
Malik *et al [46]*	2020	Determinar las implicaciones para las instituciones microfinancieras locales de Pakistán	Estudio cuantitativo y de corte transversal con alcance exploratorio.	Encuestas telefónicas a 1.000 propietarios de microempresas, encuesta a 200 agentes de crédito de microfinanzas y entrevistas con reguladores y altos representantes de instituciones microfinancieras.
Atmadja, Sharma & Su [47]	2018	Abordar las limitaciones dominadas por las mujeres microempresarias.	Estudio cuantitativo y de corte transversal con alcance exploratorio.	Encuesta a 556 personas de cinco proveedores de microcréditos de la ciudad de Surabaya, utilizan el método probit ordenado.

Autores	Año	Objetivo	Enfoque	Metodología
Mishra & Karunanithi [48]	2017	Explorar las iniciativas de autoayuda y colectividad para la participación de gitanos en sus actividades de desarrollo comunitario.	Estudio cualitativo descriptivo.	Método de observación, descriptivo y datos cualitativos.
Karlan, Osman & Zinman [49]	2016	Medir el impacto de las crisis de liquidez en el gasto.	Estudio cuantitativo y de corte transversal con alcance exploratorio.	Técnica de aleatorización de listas (encuesta indirecta) y análisis contrafactual, con un grupo de control.
Atmadja, Su & Sharma [50]	2016	Examinar el impacto de la microfinanciación en los resultados de las microempresas propiedad de mujeres en Indonesia.	Estudio cuantitativo, con alcance de análisis de corte transversal con alcance exploratorio.	Encuesta realizada en Surabaya, participaron más de 100 PYME. La técnica probit ordenada para estimar el rendimiento en relación con el capital financiero, social y humano.
Hassan, Alam & Abdul Rahman [51]	2015	Evaluar la demanda de microfinanzas entre los microempresarios en el Estado de Selangor, Malasia	Estudio cuantitativo y de análisis de corte transversal con alcance exploratorio.	Encuestas por cuestionario de 550 microempresarios.
Alam, Hassan & Said [52]	2015	Examinar el papel de los programas de microcrédito islámico en base a la Maqasid Al-Shariah.	Estudio cuantitativo y de corte transversal con alcance exploratorio.	Encuesta por cuestionario distribuida entre 393 prestatarios de microcréditos.
Mokhtar & Ashhari [53]	2015	Determinar los problemas y desafíos de los programas de microcrédito en Malasia.	Estudio cuantitativo y de corte transversal con alcance exploratorio.	Encuesta a 100 prestatarios de las instituciones AIM y YUM mediante muestreo estratificado, seleccionaron aleatoriamente a prestatarios de diversos planes de préstamos.
Alam & Molla [54]	2012	Examinar las limitaciones del microcrédito para para la promoción de microempresas en Bangladesh.	Estudio cuantitativo y de corte transversal con alcance exploratorio.	La encuesta sobre el terreno de los prestatarios de microcréditos.
Al Mamun, Adaikalam & Mazumder [55]	2012	Medir el efecto del programa de microcréditos de AIM sobre los activos de las microempresas en las zonas rurales de Malasia peninsular.	Modelo de cartera económica de los hogares (Household Economic Portfolio Model), HHEP.	Recolectan datos de 281 clientes rurales seleccionados en siete sucursales de cinco estados.

Fuente: Elaboración propia.

1 Discusión

El impacto del microcrédito en las diferentes poblaciones vulnerables a donde llega esta herramienta financiera es significativa, explicado por el uso de casos de estudio que propician examinar regiones o ciudades de países emergentes. En el desarrollo del presente estudio, tomado de Scopus, se identifican posturas de diferentes autores sobre microfinanzas, microcrédito e inclusión financiera en función con el desempeño de los micronegocios. Las investigaciones alrededor de estas palabras clave seleccionadas son amplias, aunque cuando se establecen en función de los micronegocios o microempresas o microfirmas se reduce de manera significativa, esto demuestra el número de estudios relacionados con este tema. El periodo de estudio es otro factor determinante, debido a que se reduce la muestra. Esto evidencia que, aunque son más limitadas las investigaciones, implica que las citaciones de estos documentos están en crecimiento. Asimismo, las investigaciones provienen principalmente de países emergentes, así como los casos de estudio. Entre algunos de estos países se destacan India, Malasia, Indonesia, Nigeria, Bangladesh, Sudáfrica, Turquía, China y Colombia.

En el ranking de los autores más citados destacan aquellos que han escrito sobre el impacto del microcrédito y la relación con el rol de la mujer y la lucha contra la pobreza. Resaltan Vincent Blok de Países Bajos, con un índice H de 36 y 2 documentos sobre el tema objeto de esta investigación; Sefa Awaworyi Churchill, con afiliación de Australia sobre temas de inclusión financiera; Md. Mahmudul Alam sobre temas de finanzas sustentables; y Abdullah Al Mamun sobre temas de sostenibilidad en micronegocios y el impacto del microcrédito en el empoderamiento de la mujer. Por otro lado, el autor que más ha escrito sobre el tema de investigación es Nisha Barthi con artículos altamente citados relacionados con la inclusión financiera, el desempeño de las instituciones microfinancieras y el desarrollo de las microempresas en India para la reducción de la pobreza.

Otras tendencias temáticas que surgen están alrededor de los sectores más débiles de algunos países y los servicios de financiación [56]. A saber, Urueña-Mejía, Gutiérrez & Rodríguez-Lesmes [42] exploran cómo la adopción de prácticas empresariales puede influir en el uso de productos y servicios financieros por parte de microempresas en Colombia. Un estudio diferente es el de Bharti & Kumari [45] centrado en evaluar los resultados de los Bancos Rurales Regionales (RRB) en lo que se refiere a su rendimiento financiero, así como en el cumplimiento del objetivo de apoyar la agricultura, la microempresa y la financiación de los sectores más débiles de la India. Si bien la inclusión financiera es determinante para los micronegocios, cabe destacar la palabra Fintech [57] o Financial Technology es un servicio en el cual se entrega recursos monetarios a los usuarios de forma digital, beneficiando principalmente tres grupos: las mujeres que se encuentran en zonas remotas, las pymes y las mujeres emprendedoras, principalmente empoderando a través de plataformas Crowdfunding", entre la co-ocurrencia relacionada entre las palabras clave.

La contribución de Kandie & Islam [58] acerca de los microcréditos, mediante la aplicación de la técnica estadística de Diferencias en Diferencias, conducen a una perspectiva de microfinanciación y proponen el empoderamiento económico como un efecto significativo de pasar de los microcréditos tradicionales a los digitales. Malik *et al* [46] en su estudio denominado COVID-19 y el futuro de la microfinanciación: datos y perspectivas de Pakistán, determinan las implicaciones para las instituciones microfinancieras locales de Pakistán, un país con un sector microfinanciero maduro, que atiende a un gran número de hogares, en contraste con la microfinanciación y rendimiento de las microempresas en Indonesia dominadas por mujeres microempresarias como en el estudio de Atmadja, Sharma & Su [47] en Surabaya-Indonesia.

La distribución geográfica nos indica que la investigación sobre microfinanzas, microcrédito e inclusión financiera es un tema que permea a todos los países y que es de alto interés tanto en países industrializados y desarrollados como también en economías emergentes. El caso de Bangladesh es notorio ya que allí nació el concepto de microcrédito con Muhammad Yunus en 1976. Sin embargo, se observa que los países más productivos no son necesariamente también los más abiertos a las colaboraciones internacionales. Por lo tanto, el resto de los países necesitan una mayor contribución en este tema, y Bangladesh, aunque es pionero en el término, su crecimiento es de mercado de frontera; esta implicación es significativa para los inversionistas y para la creación de nuevos micronegocios.

2 Conclusiones

Las diferentes contribuciones de los autores proporcionan un aumento en la investigación transfiriendo de manera adecuada conocimientos a la comunidad científica en los temas relacionados con inclusión financiera, microcréditos, impacto de las microfinanzas en las poblaciones más vulnerables, empoderamiento de la mujer. En cuanto al área del conocimiento en que se desarrollan las publicaciones consideradas en cada país, se resaltan las distintas regiones donde se producen los documentos científicos asociados al tema de investigación, los 6 primeros países tienen una participación del 55% sobre el total de publicaciones frecuentes: Estados Unidos con una contribución de 26 documentos, India con 18, Malasia con 17, Reino Unido con 11, Australia y Japón con 6 cada uno.

Este estudio identifica las principales tendencias en la investigación de las microfinanzas, el microcrédito y la inclusión financiera asociadas al desarrollo de pequeñas empresas, cabe destacar que nuevos temas surgen a la par de la inclusión financiera como es el empoderamiento de la mujer, la educación financiera, sostenibilidad y evidentemente su relación con la lucha contra la pobreza, resaltan países emergentes como India, Indonesia, Colombia, entre otros. Asimismo, para los tomadores de decisión o hacedores de política pública, está considerar el papel de la mujer en las economías emergentes como determinante para el bienestar de los hogares y la generación de productividad mediante la creación de micronegocios.

La base de datos Scopus como fuente principal en el presente estudio, señala que la investigación realizada en países emergentes es incipiente, siendo una limitación a razón del número reducido de publicaciones, a pesar de ser la mayor base de datos de resúmenes y citas de la literatura revisada por pares; cuenta con herramientas inteligentes que permiten controlar, analizar y visualizar la investigación académica. Scopus ofrece una visión completa del mundo de la investigación" [59]. Por ende, algunas implicaciones es la necesidad de incrementar la producción científica y de publicarla en revistas indexadas Scopus que avalan confianza en la comunidad científica.

En cuanto a las contribuciones al campo disciplinar de la administración, negocios y economía se pueden resaltar que los hallazgos del agrupamiento de tres conceptos clave de enfoque financiero: microfinanzas, el microcrédito y la inclusión financiera, en función del desempeño económico de los micronegocios son significativos. Si bien las pequeñas empresas en las economías emergentes tienen un común denominador que es la participación importante de la informalidad empresarial y laboral, esto impacta directamente en la generación de ingresos familiares y de empleo en sus entornos. Este tipo de negocios juega un papel relevante en las economías principalmente emergentes, por lo que a su vez también constituye una de las principales limitaciones de esta investigación a razón de la dificultad que los distintos investigadores encuentran para tener los datos más fiables al estudiar este campo. Los micronegocios son los que finalmente toman las decisiones entorno a microfinanzas, microcrédito y la inclusión financiera al tener como propósito mejorar las condiciones de sus negocios y contar con estrategias de permanencia empresarial [60].

Finalmente, como futuras líneas de investigación en prospectiva se podría ampliar el acervo investigativo en cuanto a ¿Qué ha sucedido de acuerdo en las investigaciones analizadas en los últimos años en términos de inclusión financiera y emprendimiento? ¿Se aborda con mayor frecuencia a nivel país o a nivel empresarial? ¿En qué tipo de mercados desarrollados o emergentes? Entre las tendencias de investigación, se pueden reconocer que el desarrollo y sostenibilidad empresarial en los países emergentes son temas de interés, en particular en el periodo posterior a la pandemia del Covid-19. La participación de la mujer para el acceso a los microcréditos en relación con el desempeño empresarial es un tema que está en boga por el papel tan representativo que tiene en distintas regiones. Por último, en la parte metodológica se evidencia un creciente uso de métodos cuantitativos que requieren de datos a ser recolectados, del uso de metodologías que involucren software especializado y de la aplicación de modelos econométricos entorno a la temática en mención que representan líneas clave de estudio.

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Physical and mechanical characterization of extruded plastic lumber for its use un civil constructions

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Abstract
The research examined the physical and mechanical properties of extruded plastic lumber for civil construction applications. The tests addressed tensile strength, compression, bending, impact and hardness, together with the volumetric density of the material. The results indicated that these plastic woods possess adequate characteristics to resist significant stresses, loads and impacts, standing out for their ability to withstand adverse conditions in structural environments. In addition, it was demonstrated that the use of recycled plastics in their manufacture offers a sustainable and responsible alternative to conventional woods. These findings underscore the potential of extruded plastic lumber as a viable and efficient option for improving durability and sustainability in the construction industry.

Keywords: physical and mechanical properties; tensile; compression; bending; impact; hardness; volumetric density.

Caracterización física y mecánica de maderas plásticas extruidas para su uso en construcciones civiles

Resumen
La investigación examinó las propiedades físicas y mecánicas de las maderas plásticas extruidas para aplicaciones en construcciones civiles. Los ensayos abordaron la resistencia a la tracción, compresión, flexión, impacto y dureza, junto con la densidad volumétrica del material. Los resultados indicaron que estas maderas plásticas poseen características mecánicas para resistir tensiones, cargas e impactos significativos, destacándose por su capacidad para soportar condiciones adversas en entornos estructurales. Además, se demostró mediante aplicaciones que el uso de plásticos reciclados en su fabricación ofrece una alternativa sostenible y responsable a las maderas convencionales. Los hallazgos cuantitativos referentes a las propiedades físicas y mecánicas subrayan el potencial de las maderas plásticas extruidas como una opción viable y eficiente para mejorar la durabilidad y la sostenibilidad en la industria de la construcción.

Palabras clave: propiedades físicas y mecánicas; tracción; compresión; flexión; impacto; dureza; densidad volumétrica.

1 Introducción

1.1 Contexto y relevancia ambiental

En la actualidad, una de las principales preocupaciones en el ámbito de la investigación es la mitigación del impacto ambiental causado por la acumulación de residuos no biodegradables, como los plásticos, que pueden tardar entre 150 y 400 años en descomponerse, así como otros materiales sintéticos y neumáticos [1]. Este problema ha impulsado la búsqueda de soluciones innovadoras y sostenibles en diversas disciplinas.

De acuerdo con la Organización de las Naciones Unidas, el 85% de los residuos que llegan a los océanos son plásticos, y manifiesta que para 2040 se triplicarán los volúmenes de residuos con una cifra de entre 23 y 37 millones de toneladas [2]. Estos residuos, generados diariamente, representan una grave amenaza para el medio ambiente, contribuyendo a problemas como la proliferación de plagas, el calentamiento global, el efecto invernadero y la propagación de enfermedades.

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El uso excesivo de recursos no renovables ha llevado a la comunidad científica a investigar formas de reutilizar estos materiales, buscando obtener resultados positivos en su reaprovechamiento.

En nuestro país, el desarrollo de materiales nuevos derivados de plásticos reciclados se está consolidando como una alternativa ventajosa, con el potencial de ganar terreno en el mercado de la construcción sostenible y amigable con el medio ambiente. Investigaciones internacionales han mostrado que las maderas plásticas, fabricadas exclusivamente a partir de plásticos reciclados como bolsas de basura, mangueras, cajas plásticas y residuos de industrias de envasado, ofrecen numerosas ventajas. Estas incluyen alta resistencia mecánica, durabilidad ante condiciones ambientales adversas y resistencia a plagas, posicionándolas como un excelente sustituto de la madera tradicional.

No obstante, uno de los retos más significativos para la adopción de estos productos radica en cumplir con los requisitos legales del país. Para autorizar su uso en estructuras, es necesario contar con evidencia obtenida a través de análisis de laboratorio que demuestre su capacidad para cumplir con las normas sismo-resistentes. En respuesta a esta necesidad, el Centro de Diseño e Innovación Tecnológica Industrial ha iniciado un proyecto para acompañar al sector productivo en la caracterización de maderas plásticas.

Este artículo incluye la realización de ensayos de laboratorio bajo metodologías específicas para evaluar las propiedades mecánicas y físicas de: tracción, compresión, flexión, dureza, impacto y densidad volumétrica de las maderas plásticas. Estos ensayos proporcionan una visión integral de las capacidades y limitaciones de este material innovador, ofreciendo datos fundamentales para su implementación efectiva en el mercado. Los ensayos de tracción y compresión son esenciales para comprender el comportamiento del material bajo cargas axiales, mientras que los ensayos de flexión e Izod evalúan su resistencia a fuerzas transversales e impactos y la dureza del material se mide para determinar su resistencia al desgaste y a la deformación superficial. Finalmente, la densidad volumétrica se determina para conocer la relación entre la masa y el volumen del material, lo cual es crucial para el diseño y la ingeniería de estructuras.

La investigación y caracterización de las maderas plásticas no solo aporta al conocimiento existente sobre materiales compuestos, sino que también fomenta su viabilidad como una alternativa sostenible y eficiente. Este estudio busca comprender las propiedades intrínsecas de las maderas plásticas y facilitar la comparación con materiales convencionales, identificando sus ventajas y áreas de mejora.

Estos hallazgos servirán como referencia para investigadores, ingenieros y diseñadores interesados en adoptar materiales innovadores que favorezcan un futuro más sostenible.

1.2 Impacto ambiental y normativas de ensayo para la madera plástica en Colombia

La madera plástica es un producto fabricado a partir de residuos plásticos recuperados y reciclados mediante programas ambientales. Generalmente, la mitad de la materia prima utilizada en su fabricación consiste en polietileno de alta densidad (HDPE), polietileno de baja densidad (LDPE) y polipropileno (PP). El HDPE actúa como un agente aglutinante, encapsulando plásticos de alta fusión y los aditivos incorporados. Durante el proceso de extrusión, se añaden otros aditivos a la mezcla para mejorar la apariencia y el rendimiento del producto [3].

La madera plástica tiene muchos usos como alternativa de reemplazo de las maderas convencionales en diferentes aplicaciones. Diseñada para superar la durabilidad de las maderas tradicionales. Investigaciones indican que ofrece buenas propiedades mecánicas [3], lo que contribuye a construcciones con mejores prestaciones, además de ofrecer ventajas ambientales, funcionales, estéticas y de durabilidad.

Entre las ventajas de la madera plástica destacan su alta durabilidad frente a la intemperie, elevada resistencia al impacto, capacidad para soportar trabajos pesados, impermeabilidad, inmunidad a plagas y bajos costos de mantenimiento, todo en comparación con la madera tradicional. Las maderas plásticas se dividen en dos categorías: Plastic Lumber, fabricada al 100% con plástico reciclado, y Wood Plastic Composite (WPC), compuesta por una mezcla de residuos de madera y plástico reciclado. Estos productos tienen una vida útil mayor que las maderas convencionales y mejoran sus propiedades mecánicas y estructurales [3].

La producción de madera plástica es un proceso ecológico y con poco impacto ambiental adverso que se inicia con la recopilación de plásticos reciclados en plantas de reciclaje. En estas instalaciones, los termoplásticos son separados, triturados, mezclados de manera homogénea y fundidos a través de un proceso de extrusión a alta temperatura.

En la actualidad, Colombia carece de una norma específica que verifique al 100% las propiedades mecánicas de la madera plástica, así como sus características físicas, mecánicas, de durabilidad y térmicas [3]. No obstante, algunas normas pueden ser útiles para lograr una caracterización completa, estas son: NTC 6296 – método de ensayo para evaluar las propiedades a la compresión de madera plástica y perfiles, NTC 595 – método de ensayo para determinar las propiedades de tracción en plásticos, NTC 6355 – métodos de ensayo estándar para la determinación de las propiedades de flexión de madera plástica reforzada y no reforzada y productos relacionados, NTC 943 – determinación de la resistencia de los plásticos al impacto del péndulo de IZOD y NTC 467 – Propiedades del caucho. Determinación de dureza con durómetro. Con el uso de estas normas se permite determinar características mecánicas y físicas de la madera plástica como lo son la resistencia a la tracción, la resistencia a la compresión, la resistencia a los impactos, dureza, y resistencia a las condiciones ambientales.

1.3 Objetivos e importancia de la investigación

La investigación tiene como objetivo principal caracterizar las maderas plásticas extruidas, mediante ensayos de tracción, compresión, flexión, dureza, impacto y densidad volumétrica, para determinar sus propiedades mecánicas y físicas.

Además, la investigación pretende obtener evidencia experimental que demuestre la capacidad de las maderas plásticas para cumplir con los requisitos de las normas sismo-resistentes nacionales, facilitando así su uso en estructuras civiles. Este estudio es crucial para promover la viabilidad de las maderas plásticas como una alternativa sostenible y eficiente en la industria de la construcción, contribuyendo a la reducción de residuos plásticos y a la conservación de recursos naturales.

La importancia de esta investigación radica en la caracterización de la madera plástica, ya que proporcionar información que permita su uso en diversos ámbitos como las construcciones civiles se aborda uno de los principales problemas actuales: la acumulación de residuos plásticos. Al promover el uso de plásticos reciclados en la fabricación de maderas plásticas, se contribuye significativamente a la disminución de estos residuos en el medio ambiente. Las maderas plásticas tienen el potencial de sustituir a los materiales tradicionales en la construcción, ofreciendo propiedades superiores en términos de resistencia mecánica, durabilidad y resistencia a plagas, lo cual puede llevar a una menor dependencia de recursos no renovables.

Asimismo, la caracterización detallada de las maderas plásticas mediante ensayos mecánicos proporciona datos fundamentales para su implementación, fomentando la innovación y el desarrollo de nuevos materiales de construcción. Al demostrar que las maderas plásticas pueden cumplir con la norma de construcción sismo-resistente NSR-10, se facilita su adopción en aplicaciones estructurales, garantizando la seguridad y la integridad de las construcciones. En la Tabla 1 se presentan las propiedades mecánicas de tracción, compresión y flexión con las que deben cumplir las estructuras de maderas convencionales para su uso en construcciones civiles.

2 Fundamentos y Metodología

2.1 Fundamentos teóricos

En esta sección se describen los fundamentos teóricos para cada tipo de ensayo: tracción, compresión, flexión, dureza, impacto y densidad volumétrica. Estos ensayos permiten evaluar las propiedades esenciales del material, proporcionando datos críticos para determinar su comportamiento bajo diversas condiciones de carga.

2.1.1 Ensayo de tracción

La norma NTC 595 – MÉTODO DE ENSAYO PARA DETERMINAR LAS PROPIEDADES DE TRACCIÓN EN PLÁSTICOS es la encargada de suministrar el procedimiento correspondiente para ejecutar los ensayos de tracción en materiales plásticos reforzados y no reforzados. Dentro de la norma se especifica que el espesor de la probeta no debe superar 14 mm, si los supera este debe ser mecanizado a los 14 mm [4]. Las probetas deben tener las dimensiones establecidas en la Tabla (2), la forma de las probetas se muestra en la Fig. (1).

Tabla 1.
Propiedades mecánicas de las maderas convencionales.

Esfuerzos admisibles (Mpa)				
GRUPO	Flexión	Tracción	Compresión vertical	Compresión horizontal
ES1	*29,5*	*21,0*	*23,0*	*6,0*
ES2	*28,5*	*20,0*	*22,0*	*4,3*
ES3	*23,0*	*17,0*	*19,0*	*3,8*
ES4	*17,0*	*12,0*	*15,0*	*2,8*
ES5	*15,0*	*11,0*	*13,0*	*2,0*
ES6	*12,5*	*9,0*	*10,0*	*1,5*

Fuente: NSR-10, 2010.

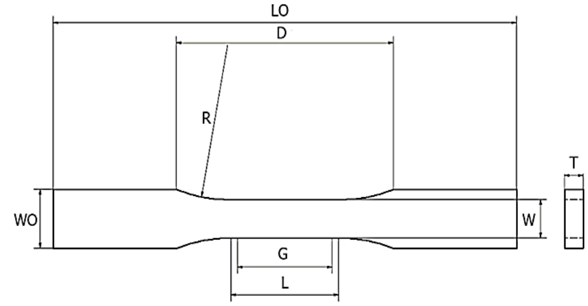

Figure 1. Forma probeta de ensayo de tracción.
Fuente: NTC 595, 2021.

Tabla 2.
Dimensiones establecidas.

Dimensiones Probeta Tracción	
W – ancho de la sección estrecha	19 mm
L – longitud de la sección estrecha	57 mm
WO – ancho total, min	29 mm
LO – longitud total, min	246 mm
G – longitud de referencia	50 mm
D – distancia entre mordazas	115 mm
R – radio del chaflan	76 mm
T – espesor, máx	14 mm

Fuente: NTC 595, 2021.

Además, de acuerdo con las características de la Máquina Universal de Ensayos y cuando la velocidad no se especifica, se utiliza velocidad mínima de la norma de referencia NTC 595:2021 para la geometría de la probeta empleada, la cual produce rotura en un tiempo de ensayo entre 0,5 min y 5 min [4].

Finalmente, el ensayo de tracción en maderas plásticas permite determinar su resistencia a la tracción, que es una medida de la capacidad del material para soportar tensiones sin fracturarse. Esta se calcula dividiendo la carga máxima aplicada durante la prueba por el área de la sección transversal de la muestra. Para el cálculo se utiliza la ecuación (1).

$$\begin{matrix}\mathit{Resistencia\ a}\\ \mathit{la\ tracción}\end{matrix} = \frac{\mathit{Carga\ máxima\ aplicada}}{\mathit{Área\ de\ la\ sección\ transversal}} \quad (1)$$

2.1.2 Ensayo de compresión

La norma NTC 6296 – MÉTODO DE ENSAYO PARA EVALUAR LAS PROPIEDADES A LA COMPRESIÓN DE MADERA PLÁSTICA Y PERFILES es la encargada de suministrar el procedimiento correspondiente para ejecutar los ensayos de compresión en materiales plásticos. Dentro de la norma

se específica que los especímenes de ensayo deben ser cortados del perfil tal como se fabricó la madera plástica, se debe tener precaución en el corte para que las caras expuestas a compresión queden paralelas entre ellas. El único mecanizado

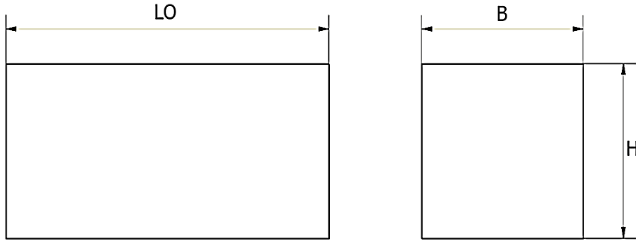

Figure 2. Forma probeta de ensayo de compresión.
Fuente: NTC 6296, 2018.

Tabla 3.
Dimensiones establecidas.

Dimensiones Probeta Compresión	
B – base	$19\ mm$
H – altura	$57\ mm$
LO – longitud total, min	$80\ mm$

Fuente: NTC 6296, 2018.

permitido es para garantizar las caras paralelas. La altura del espécimen debe ser dos (2) veces el ancho o diámetro del producto [5]. Las probetas deben tener las dimensiones establecidas en la Tabla (3), la forma de las probetas se muestra en la Fig. (2).

Además, de acuerdo con las características de la Máquina Universal de Ensayos la velocidad para el ensayo de compresión en maderas plásticas debe producir una velocidad de deformación unitaria de 15 mm/min, con esto se garantiza que el ensayo se realice en el rango de 1 min a 5 min [5].

Por último, En el ensayo de compresión de maderas plásticas se obtiene la resistencia a la compresión, una medida fundamental de la capacidad del material para soportar fuerzas de aplastamiento o corte sin deformarse o romperse. La resistencia a la compresión se calcula utilizando la ecuación (2).

$$\text{Resistencia a la compresión} = \frac{\text{Carga máxima aplicada}}{\text{Área de la sección transversal}} \qquad (2)$$

2.1.3 Ensayo de flexión

La norma NTC 6355 – MÉTODOS DE ENSAYO ESTÁNDAR PARA DETERMINACIÓN DE LAS PROPIEDADES DE FLEXIÓN DE MADERA PLÁSTICA es la encargada de suministrar el procedimiento correspondiente para ejecutar los ensayos de flexión en materiales plásticos reforzados y no reforzados. Dentro de la norma se específica que los especímenes de ensayo deben ser tal y como fueron fabricados, cortar a la longitud suficiente que garantice que sobresalga en la distancia entre apoyos [6]. La longitud entre soportes debe ser de 300 mm. De acuerdo con la sección transversal del material que se va a ensayar la longitud total del ítem de ensayo es de 600 mm; en la Fig. (3) se muestra la configuración del ensayo.

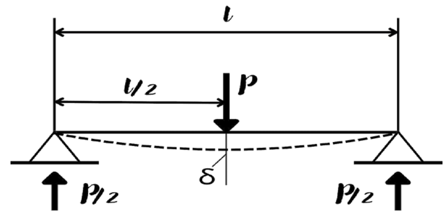

Figure 3. configuración del ensayo de flexión.
Fuente: NTC 6355, 2019.

Además, De acuerdo con las características de la Máquina Universal de Ensayos y las exigencias del ensayo, se debe ajustar la velocidad de ensayo $\frac{3\ mm}{min}$, con esto se garantiza que el ensayo se realice en el rango de 1 min a 5 min. La velocidad real del cabezal no debe diferir en más de +/- 10% [6].

Finalmente, el ensayo de flexión en maderas plásticas permite determinar el módulo de ruptura, una medida fundamental de la capacidad del material para soportar fuerzas de doblado sin fracturarse. Esta propiedad es esencial para evaluar el rendimiento estructural y la integridad del material en aplicaciones donde se espera que soporten cargas flexoras. El módulo de ruptura se calcula utilizando la ecuación (3).

$$Módulo\ de\ ruptura = \frac{3xP_RxL}{2xbxh^2} \qquad (3)$$

Dónde:
P_R**:** fuerza de ruptura
L: longitud de apoyos
b: base sección transversal
h: altura sección transversal

2.1.4 Ensayo de impacto IZOD

La norma NTC 943 – DETERMINACIÓN DE LA RESISTENCIA DE LOS PLÁSTICOS AL IMPACTO DEL PÉNDULO DEL IZOD es la encargada de suministrar el procedimiento correspondiente para ejecutar los ensayos de impacto en materiales plásticos. Dentro de la norma se específica que las probetas deben cumplir con la forma que se muestra en la Fig. (4), y las dimensiones de la Tabla (4), [7].

Además, el ensayo de impacto IZOD no requiere una velocidad específica ni el uso de ecuaciones de ensayo debido a que el equipo está diseñado para garantizar condiciones de prueba constantes. Esta configuración permite una medición directa de la energía absorbida por la muestra, lo que simplifica considerablemente el proceso. Esta metodología asegura que los resultados obtenidos sean reproducibles y consistentes, lo cual es fundamental para aplicaciones prácticas y estudios comparativos de materiales.

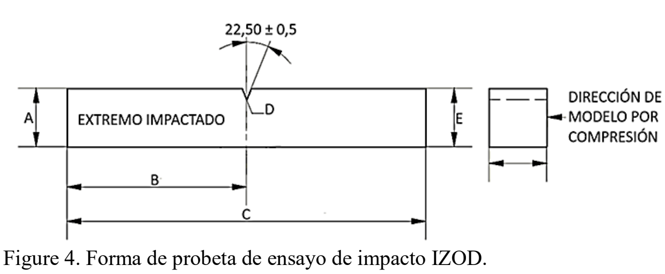

Figure 4. Forma de probeta de ensayo de impacto IZOD.
Fuente: NTC 943, 2003.

Tabla 4.
Dimensiones establecidas.

Dimensiones Probeta IZOD		
Lado	mm	in
A	10,16 ± 0,05	0,400 ± 0,002
B	31,8 ± 1,0	1,28 ± 0,04
C	63,50 ± 2,0	2,500 ± 0,08
D	0,25R ± 0,05	0,010R ± 0,002
E	12,70 ± 0,20	0,500 ± 0,008

Fuente: NTC 943, 2003.

2.1.5 Ensayo de dureza

La norma NTC 467 – PROPIEDADES DEL CAUCHO. DETERMINACIÓN DE DUREZA CON DURÓMETRO es la encargada de suministrar el procedimiento correspondiente para ejecutar los ensayos de dureza en cauchos y materiales plásticos. Dentro de la norma se específica que La muestra de ensayo, debe tener un espesor mínimo de 6,0 mm (0,24 pulgadas), a menos que se demuestre que una probeta más delgada produce resultados equivalentes a los obtenidos con la probeta de 6,0 mm (0,24 pulgadas) [8].

Además, Para realizar un ensayo de dureza Shore D de manera precisa y reproducible, la probeta debe cumplir con condiciones específicas de calidad superficial. La superficie debe ser lisa y plana, libre de rayaduras, surcos, ondulaciones, rebabas y contaminantes como polvo, aceite o grasa. No debe presentar burbujas, grietas, inclusiones ni defectos superficiales que alteren la medición. Los métodos de preparación de la probeta, como corte, lijado o pulido, deben mantener las propiedades superficiales del material.

Por último, en el ensayo de dureza Shore D no se especifica una velocidad particular ni se utilizan ecuaciones de ensayo porque el equipo de medición está diseñado para aplicar la presión de manera uniforme y proporcionar una lectura directa y precisa de la dureza del material, lo que facilita la evaluación de las propiedades del material de manera eficiente y confiable.

2.1.6 Ensayo de densidad volumétrica

Este ensayo se lleva a cabo mediante la medición de la masa de la probeta y sus dimensiones. La masa de la probeta se mide utilizando una balanza analítica con una resolución de 0,01 gr, asegurando que la balanza esté correctamente calibrada para garantizar la exactitud de la medición. La masa se registra en gramos (g). Las dimensiones de la probeta (longitud, ancho y altura) se miden con un pie de rey (calibrador vernier), y es importante que estas mediciones se realicen con cuidado para evitar errores, registrando las dimensiones en milímetros (mm).

Además, la longitud del ítem de ensayo no debe sobrepasar el área efectiva de trabajo de la balanza (200 mm), las caras de la probeta deben ser paralelas planas, para realizar medición en la longitud del ítem de ensayo.

Por último, en el ensayo de densidad volumétrica de maderas plásticas se obtiene la densidad del material, una medida fundamental de la masa por unidad de volumen del material. La densidad es crucial para determinar la calidad y las propiedades mecánicas de la madera plástica, ya que influye en su resistencia, durabilidad y comportamiento bajo cargas [9]. La densidad volumétrica se calcula utilizando la ecuación (4).

$$\varphi = \frac{m}{v} \tag{4}$$

Dónde:
φ: densidad volumétrica del material
m: masa de la probeta
v: volumen de la probeta

2.2 Diseño del experimento

En el ámbito de la investigación científica y la industria, obtener información confiable y valiosa es esencial para el progreso y la toma de decisiones fundamentadas. Sin embargo, la complejidad de los sistemas y procesos, junto con la variabilidad inherente, presenta desafíos significativos. El diseño de experimentos (DOE) es una metodología poderosa que aborda estos desafíos de manera sistemática. El DOE permite a los investigadores planificar y ejecutar experimentos de forma eficiente, maximizando la información obtenida mientras se minimizan los recursos utilizados. Esto facilita la identificación precisa de factores clave que afectan un proceso o producto, revela interacciones complejas y proporciona una base sólida para decisiones informadas. El DOE optimiza procesos, mejora la calidad, ahorra recursos y avanza en la investigación científica.

En nuestro país, el desarrollo de materiales derivados de plásticos reciclados, como las maderas plásticas, se considera una alternativa ventajosa para aplicaciones sostenibles. Estas maderas plásticas, fabricadas con residuos de plástico, presentan ventajas como resistencia mecánica, durabilidad y resistencia a plagas, posicionándolas como un excelente sustituto de la madera convencional. Sin embargo, es crucial cumplir con los requisitos legales nacionales, que exigen evidencia de laboratorio sobre sus capacidades mecánicas para su uso en estructuras.

El Centro de Diseño e Innovación Tecnológica Industrial ha desarrollado un estudio de caracterización de maderas plásticas, incluyendo ensayos de tracción, compresión, flexión, dureza, impacto y densidad volumétrica. Estos ensayos permiten evaluar las propiedades esenciales del material.

La elección de un diseño de experimentos unifactorial se debe a la limitación de disponer de una única condición estándar para la evaluación, minimizando la variabilidad y proporcionando datos precisos. Este enfoque permite establecer una base para entender el comportamiento del material, es eficiente en términos de recursos y proporciona una referencia fundamental para futuros análisis. Los resultados obtenidos pueden generar nuevas preguntas de investigación, impulsando el avance en la comprensión de las propiedades mecánicas de las maderas plásticas.

2.3 Metodología para caracterización de madera plástica: enfoque unifactorial

Para caracterizar las propiedades mecánicas de la madera plástica bajo una única condición estándar, se sigue una metodología estructurada. Se define inicialmente el factor relevante como la "Condición estándar", asegurando un enfoque claro y consistente en todos los ensayos. Se emplea un diseño unifactorial debido a la limitación de disponer de una sola mezcla de madera plástica, lo que minimiza la variabilidad y facilita la interpretación de los resultados. Cada ensayo se repite al menos tres veces para garantizar la robustez de los datos. Esto resulta en un total de tres ensayos por propiedad mecánica evaluada. Posteriormente, se realiza un análisis estadístico detallado que incluye el cálculo de promedios y desviaciones estándar. La interpretación final busca revelar patrones y tendencias que informen sobre el comportamiento del material bajo la condición estándar.

En el contexto de la ingeniería mecánica, la precisión de las mediciones y la fiabilidad de los datos son cruciales para la toma de decisiones informadas en el diseño y análisis de sistemas y componentes mecánicos. Por esta razón, se ha optado por una muestra de 20 ensayos por propiedad a evaluar, lo que asegura una mayor precisión estadística, reducción de errores aleatorios y una detección más efectiva de patrones significativos en los resultados.

3. Resultados y discusión

3.1 Resultados obtenidos en los ensayos de laboratorio

A continuación, se presentan los resultados obtenidos de los ensayos mecánicos y físicos realizados sobre las maderas plásticas extruidas estudiadas. Estos ensayos incluyen pruebas de tracción, compresión, flexión, impacto IZOD y densidad volumétrica. Cada una de estas pruebas proporciona información sobre las propiedades mecánicas y físicas del material, permitiendo una evaluación integral de su comportamiento bajo diferentes tipos de cargas y condiciones.

3.1.1 Resultados ensayo de tracción

Los resultados del ensayo de tracción, realizados conforme a la norma NTC 595, indican que las maderas plásticas extruidas presentan una resistencia a la tracción promedio de 11,5 MPa, con una desviación estándar de 1,08 MPa. La consistencia de los resultados, reflejada en la baja desviación estándar, sugiere una uniformidad en la calidad del material producido. Los resultados se presentan en la Tabla (5).

Tabla 5.
Resultados del ensayo.

Ensayo de Tracción		
Ítem	**Resistencia a la tracción (MPa)**	**Ue***
CDITICL-IE061-2024-LEM	11,98	0,14
CDITICL-IE062-2024-LEM	12,79	0,15
CDITICL-IE063-2024-LEM	12,71	0,64
CDITICL-IE064-2024-LEM	11,31	0,13
CDITICL-IE065-2024-LEM	11,07	0,13
CDITICL-IE066-2024-LEM	12,35	0,15
CDITICL-IE067-2024-LEM	12,35	0,15
CDITICL-IE068-2024-LEM	12,53	0,15
CDITICL-IE069-2024-LEM	12,32	0,15
CDITICL-IE070-2024-LEM	12,85	0,15
CDITICL-IE071-2024-LEM	11,56	0,14
CDITICL-IE072-2024-LEM	11,24	0,13
CDITICL-IE073-2024-LEM	11,09	0,13
CDITICL-IE074-2024-LEM	10,79	0,13
CDITICL-IE075-2024-LEM	9,94	0,12
CDITICL-IE076-2024-LEM	9,91	0,12
CDITICL-IE077-2024-LEM	9,21	0,11
CDITICL-IE078-2024-LEM	12,29	0,15
CDITICL-IE079-2024-LEM	10,23	0,12
CDITICL-IE080-2024-LEM	12,25	0,15
Promedio	11,5	
Desviación estándar	1,08	

Fuente: Elaboración propia.

3.1.2 Resultados ensayo de compresión

En la Tabla (6), se muestran los resultados obtenidos de los ensayos de compresión vertical realizados.

Tabla 6.
Resultados del ensayo.

Ensayo de Compresión Vertical		
Ítem	**Resistencia a la compresión (MPa)**	**Ue***
CDITICL-IE001-2024-LEM	18,1	0,21
CDITICL-IE002-2024-LEM	21,7	0,25
CDITICL-IE003-2024-LEM	21,7	0,25
CDITICL-IE004-2024-LEM	20,3	0,24
CDITICL-IE005-2024-LEM	20,5	0,24
CDITICL-IE006-2024-LEM	15,3	0,18
CDITICL-IE007-2024-LEM	20	0,23
CDITICL-IE008-2024-LEM	18,1	0,21
CDITICL-IE009-2024-LEM	13,4	0,16
CDITICL-IE010-2024-LEM	19,3	0,22
CDITICL-IE011-2024-LEM	15,1	0,18
CDITICL-IE012-2024-LEM	16,7	0,19
CDITICL-IE013-2024-LEM	21,1	0,24
CDITICL-IE014-2024-LEM	24,8	0,29
CDITICL-IE015-2024-LEM	25,4	0,30
CDITICL-IE016-2024-LEM	19,8	0,23
CDITICL-IE017-2024-LEM	21,7	0,25
CDITICL-IE018-2024-LEM	19,9	0,23
CDITICL-IE019-2024-LEM	16,1	0,19
CDITICL-IE020-2024-LEM	22,9	0,27
Promedio	19,6	
Desviación estándar	3,17	

Fuente: elaboración propia.

Tabla 7.
Resultados del ensayo.

Ensayo de Compresión Horizontal		
Ítem	**Resistencia a la compresión (MPa)**	**Ue***
CDITICL-IE021-2024-LEM	8	0,09
CDITICL-IE022-2024-LEM	12,8	0,15
CDITICL-IE023-2024-LEM	10,3	0,12
CDITICL-IE024-2024-LEM	11,7	0,14
CDITICL-IE025-2024-LEM	11,1	0,13
CDITICL-IE026-2024-LEM	7,2	0,08
CDITICL-IE027-2024-LEM	12,8	0,15
CDITICL-IE028-2024-LEM	11,7	0,14
CDITICL-IE029-2024-LEM	6,5	0,08
CDITICL-IE030-2024-LEM	13,2	0,15
CDITICL-IE031-2024-LEM	11	0,13
CDITICL-IE032-2024-LEM	8,5	0,10
CDITICL-IE033-2024-LEM	9,7	0,11
CDITICL-IE034-2024-LEM	15	0,17
CDITICL-IE035-2024-LEM	7,5	0,09
CDITICL-IE036-2024-LEM	15,7	0,18
CDITICL-IE037-2024-LEM	9,9	0,12
CDITICL-IE038-2024-LEM	10	0,12
CDITICL-IE039-2024-LEM	25	0,29
CDITICL-IE040-2024-LEM	17,2	0,20
Promedio	11,7	
Desviación estándar	4,23	

Fuente: Elaboración propia.

Tabla 8.
Resultados del ensayo.

Ensayo de Flexión		
Ítem	**Resistencia a la flexión (MPa)**	**Ue***
CDITICL-IE041-2024-LEM	19,67	0,24
CDITICL-IE042-2024-LEM	19,67	0,24
CDITICL-IE043-2024-LEM	20,39	0,24
CDITICL-IE044-2024-LEM	18,6	0,22
CDITICL-IE045-2024-LEM	18,4	0,22
CDITICL-IE046-2024-LEM	18,86	0,23
CDITICL-IE047-2024-LEM	18,84	0,23
CDITICL-IE048-2024-LEM	20,69	0,25
CDITICL-IE049-2024-LEM	20,83	0,25
CDITICL-IE050-2024-LEM	20,77	0,25
CDITICL-IE051-2024-LEM	20,22	0,24
CDITICL-IE052-2024-LEM	21,14	0,25
CDITICL-IE053-2024-LEM	20,21	0,24
CDITICL-IE054-2024-LEM	20,36	0,24
CDITICL-IE055-2024-LEM	20,0	0,24
CDITICL-IE056-2024-LEM	18,91	0,23
CDITICL-IE057-2024-LEM	18,84	0,23
CDITICL-IE058-2024-LEM	20,47	0,24
CDITICL-IE059-2024-LEM	21,68	0,26
CDITICL-IE060-2024-LEM	22,5	0,27
Promedio	20,1	
Desviación estándar	1,09	

Fuente: Elaboración propia.

En el ensayo de compresión vertical, siguiendo la norma NTC 6296, las maderas plásticas extruidas mostraron una resistencia a la compresión promedio de 19,6 MPa, con una desviación estándar de 3,17 MPa. Este resultado destaca la capacidad del material para resistir fuerzas de aplastamiento aplicadas perpendicularmente a las fibras o capas del material, lo cual es fundamental para su uso en aplicaciones estructurales donde las cargas verticales son predominantes.

En la Tabla (7), se muestran los resultados obtenidos de los ensayos de compresión horizontal realizados.

En el ensayo de compresión horizontal, las maderas plásticas extruidas presentaron una resistencia a la compresión promedio de 11,7 MPa, con una desviación estándar de 4,23 MPa. Este ensayo mide la capacidad del material para resistir fuerzas aplicadas paralelamente a las fibras o capas del material. La resistencia a la compresión horizontal es crucial para aplicaciones donde el material debe soportar cargas distribuidas lateralmente, como en el caso de muros y tabiques.

3.1.3 Resultados Ensayo de flexion

En la Tabla (8), se muestran los resultados obtenidos de los ensayos de flexión realizados.

De acuerdo con la norma NTC 6355, los ensayos de flexión revelaron que las maderas plásticas extruidas poseen una resistencia a la flexión promedio de 20,1 MPa, con una desviación estándar de 1,09 MPa. La alta resistencia a la flexión es un indicador clave de que el material puede soportar cargas transversales significativas sin fracturarse, lo cual es esencial para su uso en componentes que requieren rigidez y estabilidad estructural. La rigidez proporcionada por esta resistencia asegura que los elementos de construcción hechos de maderas plásticas mantendrán su integridad bajo esfuerzos de flexión.

Además, la resistencia a la flexión es crítica para evaluar el comportamiento del material bajo condiciones de carga reales, donde las fuerzas de flexión pueden variar en magnitud y dirección. La baja desviación estándar en los resultados sugiere una alta consistencia en el comportamiento del material, lo cual es vital para aplicaciones estructurales donde la uniformidad en el desempeño puede significar la diferencia entre una estructura segura y una comprometida. Esto implica que las maderas plásticas no solo son robustas sino también fiables, garantizando seguridad y durabilidad en sus aplicaciones.

3.1.4 Resultados Ensayo de impacto IZOD

En la Tabla (9), se muestran los resultados obtenidos de los ensayos de impacto realizados.

Tabla 9.
Resultados del ensayo

Ensayo de Impacto IZOD	
Ítem	**Energía absorbida $\frac{kJ}{m^2}$**
CDITICL-IE063-2024-LMI	2,409
CDITICL-IE064-2024-LMI	2,412
CDITICL-IE065-2024-LMI	2,398
CDITICL-IE066-2024-LMI	2,403
CDITICL-IE067-2024-LMI	2,410
CDITICL-IE068-2024-LMI	2,404
CDITICL-IE069-2024-LMI	2,399
CDITICL-IE070-2024-LMI	2,395
CDITICL-IE071-2024-LMI	2,408
CDITICL-IE072-2024-LMI	2,408
CDITICL-IE073-2024-LMI	2,399
CDITICL-IE074-2024-LMI	2,411
CDITICL-IE075-2024-LMI	2,397

CDITICL-IE076-2024-LMI	2,402
CDITICL-IE077-2024-LMI	2,409
CDITICL-IE078-2024-LMI	2,394
CDITICL-IE079-2024-LMI	2,395
CDITICL-IE080-2024-LMI	2,398
CDITICL-IE081-2024-LMI	2,414
CDITICL-IE082-2024-LMI	2,421
Promedio	2,404
Desviación estándar	0,01

Fuente: Elaboración propia.

Los resultados del ensayo de impacto IZOD, conforme a la norma NTC 943, mostraron una energía absorbida promedio de 2,404 J, con una desviación estándar de 0,01 J. Este ensayo mide la capacidad del material para resistir impactos repentinos, lo que demuestra que las maderas plásticas tienen una buena resistencia al impacto. Esto es especialmente relevante en aplicaciones donde los componentes pueden estar sujetos a golpes o impactos súbitos.

3.1.5 Resultados ensayo de dureza

En la Tabla (10), se muestran los resultados obtenidos de los ensayos de dureza shore D realizados.

El ensayo de dureza, realizado según la norma NTC 467, arrojó un promedio de dureza Shore D de 58,6, con una desviación estándar de 2,46. La dureza es un indicador de la resistencia del material al desgaste y a la deformación superficial. Los resultados sugieren que las maderas plásticas tienen una dureza adecuada para soportar el uso y la exposición en diversas condiciones. Esta propiedad es crucial para aplicaciones en las que el material estará en contacto continuo con otros objetos.

Tabla 10.
Resultados del ensayo.

Ensayo de Dureza		
Ítem	**Shore D**	**Ue***
CDITICL-IE001-2024-LMI	60,4	4,8
CDITICL-IE002-2024-LMI	57	0,9
CDITICL-IE003-2024-LMI	57,9	4,0
CDITICL-IE004-2024-LMI	64,7	4,9
CDITICL-IE005-2024-LMI	59,3	0,6
CDITICL-IE006-2024-LMI	56,2	5,9
CDITICL-IE007-2024-LMI	55,8	4,2
CDITICL-IE008-2024-LMI	56,5	3,2
CDITICL-IE009-2024-LMI	57,4	9,1
CDITICL-IE010-2024-LMI	56,9	3,3
CDITICL-IE011-2024-LMI	53,5	1,1
CDITICL-IE012-2024-LMI	60,7	2,9
CDITICL-IE013-2024-LMI	59,8	0,8
CDITICL-IE014-2024-LMI	58,7	0,5
CDITICL-IE015-2024-LMI	59,4	0,5
CDITICL-IE016-2024-LMI	56,8	1,0
CDITICL-IE017-2024-LMI	61,7	1,2
CDITICL-IE018-2024-LMI	60,3	0,6
CDITICL-IE019-2024-LMI	58,9	0.4
CDITICL-IE020-2024-LMI	59,3	0,6
Promedio	58,6	
Desviación estándar	2,46	

Fuente: Elaboración propia.

Tabla 11.
Resultados del ensayo.

Ensayo de Dureza		
Ítem	**Densidad** $\frac{Kg}{m^3}$	**Ue***
CDITICL-IE084-2024-LMI	176,6	0,000010
CDITICL-IE085-2024-LMI	216,4	0,000011
CDITICL-IE086-2024-LMI	212,1	0,000011
CDITICL-IE087-2024-LMI	181,1	0,000011
CDITICL-IE088-2024-LMI	179,2	0,000011
CDITICL-IE089-2024-LMI	213,3	0,000011
CDITICL-IE090-2024-LMI	231,0	0,000011
CDITICL-IE091-2024-LMI	222,9	0,000011
CDITICL-IE092-2024-LMI	176,7	0,000018
CDITICL-IE093-2024-LMI	235,8	0,000011
CDITICL-IE094-2024-LMI	178,0	0,000013
CDITICL-IE095-2024-LMI	180,6	0,000012
CDITICL-IE096-2024-LMI	183,6	0,000012
CDITICL-IE097-2024-LMI	178,0	0,000012
CDITICL-IE098-2024-LMI	176,0	0,000012
CDITICL-IE099-2024-LMI	182,0	0,000011
CDITICL-IE100-2024-LMI	189,6	0,000011
CDITICL-IE101-2024-LMI	226,0	0,000011
CDITICL-IE102-2024-LMI	175,5	0,000011
CDITICL-IE103-2024-LMI	177,6	0,000011
Promedio	194,7	
Desviación estándar	21,79	

Fuente: Elaboración propia.

3.1.6 Resultados de ensayo de densidad volumétrica

En la Tabla (11), se muestran los resultados obtenidos de los ensayos de densidad volumétrica realizados.

La densidad volumétrica de las maderas plásticas extruidas, medida según las especificaciones detalladas, mostró un valor promedio de 194,7 kg/m³, con una desviación estándar de 21,79 kg/m³. La densidad volumétrica es crucial para entender la relación masa-volumen del material y su implicación en el diseño y la ingeniería de estructuras. Un material con una densidad adecuada garantiza que las estructuras no solo sean robustas sino también manejables en términos de peso. La densidad comparable a la de algunas maderas convencionales sugiere que las maderas plásticas pueden ofrecer un equilibrio entre ligereza y resistencia, favoreciendo su uso en una amplia gama de aplicaciones constructivas.

3.2 Consolidado de resultados

A continuación, en la Tabla (12) se presenta un consolidado de los resultados obtenidos de los ensayos mecánicos y físicos realizados sobre las maderas plásticas extruidas estudiadas.

Tabla 12.
Resultados de los ensayos.

Consolidado de Resultados			
Propiedad	**Unidad**	**Promedio**	**Ue***
Tracción	MPa	11,5	1,08
Dureza (Shore D)	Shore D	58,6	2,46
Compresión Vertical	MPa	19,6	3,17
Compresión Horizontal	MPa	11,7	4,23
Densidad Volumétrica	$\frac{Kg}{m^3}$	194,9	21,79
Flexión	MPa	20,1	1,08
Impacto	$\frac{KJ}{m^2}$	2,4	0,01

Fuente: Elaboración propia.

4. Conclusiones

El estudio detallado de las propiedades físicas y mecánicas de las maderas plásticas extruidas revela un material versátil y prometedor para aplicaciones en la industria de la construcción. Con una resistencia a la tracción promedio de 11,5 MPa, estas maderas plásticas demuestran una capacidad considerable para soportar cargas tensiles, fundamentales para estructuras que requieren robustez y fiabilidad estructural.

Los ensayos de compresión vertical y horizontal indican que estas maderas plásticas pueden resistir compresiones de hasta 19,6 MPa y 11,7 MPa respectivamente, lo cual las posiciona como una opción viable para aplicaciones donde la capacidad de soportar cargas concentradas y distribuidas es crucial.

La resistencia a la flexión promedio de 20,1 MPa subraya su capacidad para resistir deformaciones bajo cargas transversales, siendo adecuadas para vigas y otros componentes estructurales. Además, la alta absorción de energía en el ensayo de impacto IZOD (2,404 J) indica una buena capacidad para resistir impactos repentinos, lo cual es esencial en entornos donde se requiere protección contra daños mecánicos.

Con una dureza Shore D promedio de 58,6, estas maderas plásticas ofrecen una superficie resistente al desgaste y duradera, ideal para aplicaciones donde la integridad estructural a largo plazo es crítica. La densidad volumétrica promedio de 194,7 kg/m³ equilibra eficazmente la resistencia con la ligereza, facilitando su manipulación y transporte en proyectos constructivos.

La utilización de plásticos reciclados en la producción de estas maderas plásticas no solo reduce el impacto ambiental al disminuir la dependencia de recursos naturales no renovables, sino que también promueve prácticas sostenibles dentro de la industria de la construcción. Este enfoque innovador no solo cumple con los estándares técnicos exigentes, sino que también responde a la creciente demanda por materiales de construcción que sean económica y ambientalmente responsables.

Con base en el objetivo de la investigación, que es caracterizar las maderas plásticas extruidas mediante ensayos de tracción, compresión, flexión, dureza, impacto y densidad volumétrica para determinar sus propiedades mecánicas y físicas, al comparar las propiedades mecánicas obtenidas en los ensayos realizados con las de las maderas convencionales consignadas en la Tabla (1) y con referencia en la norma NSR-10, se puede concluir que las maderas plásticas se clasifican dentro del grupo de maderas ES5, debido a que su resistencia a la tracción es la que presenta menor capacidad. Esta clasificación, sin embargo, no desmerece las ventajas significativas que ofrecen las maderas plásticas extruidas. Las propiedades mecánicas y físicas evaluadas demuestran que son adecuadas para diversas aplicaciones en la industria de la construcción, proporcionando no solo rendimiento y durabilidad, sino también contribuyendo de manera significativa a la sostenibilidad global y al manejo responsable de los recursos naturales.

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Reinforced earth elements with the addition of Opuntia ficus-indica and Physalis peruviana

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Abstract
This research incorporated the husk of aguaymanto (Physalis peruviana) in proportions of 0.2%, 0.4%, and 0.6%, and the mucilage of prickly pear (Opuntia ficus-indica) at 6%, 8%, and 10% as stabilizers. The soil used was obtained from the San José district in Lambayeque, Peru, following the selection process established by standard E.080. The most notable results were observed when incorporating 0.2% husk and 10% prickly pear. Compressive strength in the adobe bricks was 16.82 kg/cm2, representing an 8.4% improvement compared to the control sample. Additionally, in the adobe stacks, resistance increased by 35.8%. The tensile test also showed a 22.4% improvement, with a strength of 1.04 kg/cm2. Regarding absorption testing, a value of 13.16% was obtained, improving by 14.6%, and the suction test recorded 12.09%, representing a 30.3% improvement over the standard.

Keywords: adobe; shell, resistance; *Opuntia ficus-indica*; *Physalis peruviana*.

Elementos de tierra reforzada con adición de *Opuntia ficus-indica* y *Physalis peruviana*

Resumen
Esta investigación incorporó cascarilla de aguaymanto (*Physalis peruviana*) en proporciones de 0.2%, 0.4% y 0.6%, y mucílago de tuna al 6%, 8% y 10% (*Opuntia ficus-indica*) como estabilizadores. La tierra usada se obtuvo del distrito de San José, Lambayeque, Perú, siguiendo la norma E.080. Los mejores resultados se lograron con 0.2% de cascarilla y 10% de mucílago. La compresión en adobes fue de 16.82 kg/cm2, mejorando un 8.4% respecto al patrón. La resistencia en pilas de adobes aumentó un 35.8%. El ensayo de tracción mostró una mejora del 22.4% con una resistencia de 1.04 kg/cm2. En el ensayo de absorción, se obtuvo un 13.16%, mejorando un 14.6%, y el ensayo de succión registró 12.09%, una mejora del 30.3% comparado con el patrón.

Palabras clave: adobe; cascara; resistencia; *Opuntia ficus-indica*; *Physalis peruviana.*

1. Introducción

El adobe es una variedad de ladrillo sin cocer que se produce utilizando una combinación de suelo, que se compone en su mayoría de arcilla y arena, y se amalgama con fibras naturales [1].

El empleo de la tierra en las prácticas de edificación es un método que se remonta a los años 10.000 a 8000 a.C. A lo largo de los años, se han modificado diversas técnicas de construcción con tierra, añadiendo estabilizadores como la cal y el cemento y otros materiales como pajilla, para incrementar la resistencia y la estabilidad al agua [2].

Es un elemento crucial en la construcción sostenible debido a su producción de bajo costo y su amplia disponibilidad. Fomenta un ahorro energético significativo, aprovechando principalmente las energías renovables. Ofrece una gran manejabilidad, propiedades mecánicas perfectas para la construcción y se integra sin problemas en el ecosistema al culminar su vida útil [3].

El uso de este material se ha extendido en toda América

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del sur [4], principalmente porque se considera una opción viable para abordar la escasez de viviendas. Pero Las construcciones de adobe son susceptibles a diversos tipos de fuerzas debido a su resistencia limitada y fragilidad, especialmente en situaciones sísmicas.

El Perú está ubicado en una zona con una gran cantidad de actividad sísmica, lo que representa un riesgo constante para las personas que viven en viviendas de adobe. Estas construcciones de tierra son frágiles y pueden sufrir daños significativos durante terremotos de gran magnitud.

Para mejorar la seguridad de las viviendas de adobe, se han investigado diferentes métodos de refuerzo. Uno de ellos es el uso de malla de cuerdas, que ha demostrado ser efectiva en ensayos de simulación sísmica. Se ha creado un diseño de vivienda de dos pisos a escala utilizando adobe, pero frente a fuerzas de la naturaleza siguen siendo muy vulnerables [5].

En los últimos, se ha observado un aumento en el desarrollo de adobes; sin embargo, existe una carencia de investigaciones sobre su comportamiento, por lo cual el objetivo de este artículo es poder explorar materiales alternativos que puedan mejorar las unidades de adobe

Es esencial enfatizar que investigaciones de esta índole han sido llevadas a cabo previamente por investigadores tanto en el ámbito nacional como global.

Incorporan fibras de paja toquilla e Ichu para evaluar propiedades como la capacidad de humedad del elemento, límite líquido, granulometría, compactación de Proctor modificado y clasificación de suelos [6]. Al agregar Paja Toquilla en una proporción de 6%, la tensión incrementó a 29.14 kg/cm^2, mientras que con una proporción de Paja Ichu al 4%, alcanzó los 28.11 kg/cm^2 comparación con el estándar de adobe de 20.18 kg/cm^2. Los resultados demuestran que los adobes elaborados con paja toquilla en su composición supera en resistencia a los que contienen paja Ichu. Además, aquellos adobes que incorporan ambas fibras vegetales (paja toquilla e Ichu) superan el umbral mínimo de resistencia establecido en el RNE.

Asimismo, [7] realizaron a cabo investigaciones utilizando fibras de coco (*Cocos nucifera*) para evaluar el desempeño del adobe, empleando parámetros y ensayos de laboratorio similares. Se prepararon muestras con diversas concentraciones de fibras de coco (0.25%, 0.50%, y 0.75%).

Los resultados fueron favorables debido a que la inclusión de fibras de coco condujo a mejoras a la resistencia de los adobes. La capacidad de resistir la fuerza compresiva experimentó un incremento del 24,40%, alcanzando un valor de 36,83 kg/cm^2 en contraste con los 28,21kg/cm^2 de la muestra estándar. De manera similar, la flexión incremento en 13,68%, alcanzando 8,48 kg/cm^2 en comparación a los 7,32 kg/cm2de la muestra de referencia.

En Piura, realizaron el estudio del extracto de la planta Cabuya (*Furcraea andina*) y como puede actuar como un agente estabilizador para proteger el adobe convencional de los efectos del agua [8]. Para evaluar la resistencia al agua, se realizaron dos pruebas no estándar: una de rociado y otra de inmersión. Los resultados indican que el extracto de cabuya mejora significativamente la resistencia a la flexión, casi duplicando los valores iniciales, con un aumento aproximado del 200% desde una base de 2.06 kg/cm^2. Respecto a la capacidad de compresión, registraron una media de 27.32 kg/cm^2 en los adobes estabilizados, mientras que los adobes sin estabilizar tuvieron un valor de 24.92 kg/cm^2.

En Perú, investigaron “Bloques Sostenibles Reforzados con *Agave americana* L. Fibra y sus propiedades mecánicas”, Las resistencias se determinan a través de tres métodos: compresión simple, tracción mediante la prueba de compresión diametral brasileña y el cálculo del módulo de ruptura [9]. La dosis más efectiva para resistir la fuerza compresiva resultó ser el 0.25% de fibra de agave, lo que se tradujo en un incremento del 13.39% (equivalente a 2.54MPa). Al emplear agave en fibras en proporciones del 1%, el aguante a la tracción aumentó en un 39,13% (0,32MPa). Finalmente, la incorporación del 0.5% de fibra de *Agave Americana* condujo a un incremento del 14.29% (1.44MPa) en la resistencia a la flexión. En resumen, se concluyó que el uso de fibra de *Agave Americana* mejoró de manera notable la resistencia mecánica de los bloques.

Incorporo cáscara de arroz *(Oryza sativa*) y paja de lavanda (*Lavándula*) para mejorar durabilidad del adobe. La mezcla constó de aproximadamente un 60% de piedra caliza y un 20% de arcilla [10]. Se llevaron a cabo pruebas de erosión por humedad, abrasión y resistencia al impacto en probetas de 15x15x15 cm^3. Los resultados revelaron que la adición de paja de lavanda generó un notable aumento en la abrasión, mientras que la inclusión de cáscara de arroz produjo una significativa reducción en la misma. Los ensayos concluyeron que al adicionar la paja de lavanda mejoró la durabilidad del adobe. De manera específica, evidenció una mejora para resistir el efecto de la erosión causada por la humedad debido a la inclusión de paja de lavanda

El uso del jacinto de agua (*Eichhornia crassipes)* en fibras para atribuir mejoras a compresión, flexión, durabilidad y la variación de volumen del adobe [11]. Se incorporaron 3 cm de fibra de jacinto a lo largo de la mezcla de adobe, además, se incorporaron partículas de arena con dimensiones que oscilan entre 2.0 y 0.05 mm, en una proporción del 2.7%, así como limo de partículas menores a 0.002 mm en un 37.8%. Posteriormente, se sometió esta mezcla a ensayos en probetas de 10x10x10 cm3. Los resultados obtenidos revelaron una disminución en resistir la resistencia axial por causa del incremento de humedad en el adobe. Además, se observó una reducción en la contracción del adobe del orden del 31% al 34%, y una disminución en su densidad de aproximadamente un 20%.

Decidieron introducir fibras de yute (*Corchorus olitorius/ Corchorus capsularis*) en el adobe utilizando diversas concentraciones (0.5% y 2%) y medidas de extensión fluctuantes (7mm, 15mm y 30mm), [12]. Previamente, llevaron a cabo un análisis granulométrico utilizando el método del hidrómetro, siguiendo la norma ASTM D7928-17 (Determinación del tamaño de partículas en suelos de grano fino mediante sedimentación). Además, emplearon fibras de yute con un diámetro de 3 mm en el estudio. Los resultados evidenciaron que la inclusión de una concentración del 2.0% en peso de fibras de yute resultó en un aumento notable en la absorción de agua capilar en los materiales de adobe, lo que impactó negativamente en su durabilidad. Asimismo, se observó una significativa reducción del 93% y 62% en la densidad de grietas, investigaron la inclusión de *Saccharum officinarum* (azúcar) empleando el residuo de bagazo, para la elaboración de ladrillos ecológicos, reemplazando parcialmente el 0.5%, 1.5% y 2.5% del lodo utilizado, [13]. El proceso comenzó sumergiendo el bagazo de *Saccharum officinarum* en *agua* caliente a unos 90 °C, y se llevaron a cabo mediciones periódicas del peso del bagazo de caña de azúcar seco. Estos materiales secos mostraron ser fibras frágiles y ligeros, con un peso de 0.09 kg/m^3 y un diámetro de fibra que variaba entre 0.3 y 1.2 mm. Posteriormente, las fibras secas se cortaron a una longitud de 80 mm. Los resultados revelaron que la *Saccharum officinarum* en proporciones razonables podría resultar en una reducción del peso del ladrillo de hasta un 7%, lo que a su vez afectaría el peso de la estructura y la cimentación. Además, se encontró que la absorción de los ladrillos de arcilla utilizados en condiciones climáticas normales no debía superar el 25%. En consecuencia, se observó que las muestras con un 1.5% y 2.5% de *Saccharum officinarum* no cumplen.

El reforzamiento de las muestras de adobe con plumas recicladas del pollo (CFF) en el refuerzo de mezclas de adobe, [12]. Descubrieron que la inclusión de CFF en las mezclas mejoraba notablemente su resistencia al daño y su durabilidad, mientras que sus propiedades físicas y mecánicas se mantuvieron prácticamente inalteradas. Entre los hallazgos más destacados se encuentran una notable disminución en la densidad de las grietas y en la erosión por agua, con reducciones de hasta un 99% y un 44%, respectivamente. Además, se determinó que hubo un aumento al resistir la flexión de hasta un 134%. Esto demuestra el potencial de las fibras de plumas de pollo contribuyen en la durabilidad y la capacidad de resistencia de las mezclas de adobe.

Los siguientes investigadores se centraron en el estudio de materiales autóctonos, poniendo especial atención en los ladrillos de adobe, como una alternativa prometedora para la construcción de estructuras en [14]. Sugerían la estabilización de los ladrillos de adobe con cal para incrementar su resistencia a la retracción. Se experimentó con distintas proporciones de cal (0%, 4%, 7% y 10% del peso total del suelo) para determinar su impacto en las características mecánicas y térmicas del adobe. Los descubrimientos más destacados del estudio incluyeron: Se observó una disminución en la conductividad térmica conforme se aumentaba la proporción de cal, se logró la capacidad de soportar cargas más altas (1,1 MPa) cuando se añadió 7% de cal en la mezcla de adobe.

2. Materiales y métodos

2.1 Materiales

2.1.1 Opuntia ficus-indica

La hoja de tuna o también conocida como nopal en otros países, florece en áreas con ambientes áridos y semiáridos. Este compuesto se ha empleado tradicionalmente para mejorar la firmeza del concreto, actuar como un impermeabilizante y componente en pinturas. Este versátil compuesto también desempeña un papel significativo en la industria alimentaria y en la creación de productos farmacéuticos [15].

2.1.2 Physalis peruviana

La Physalis peruviana Linnaeus, una planta de la familia Solanaceae y endémica de la región andina de Sudamérica son reconocidos por sus efectos beneficiosos contra tumores, diabetes e inflamación. Además, destacan por su riqueza en antioxidantes y compuestos fenólicos [16].

El fruto se caracteriza por tener una cubierta que recuerda al cáliz de la planta, sugiriendo la forma de un pequeño jarro o una campana incompleta, con un tamaño que oscila entre 14 y 20 milímetros. Esta cubierta se vuelve más fina durante el proceso de maduración del fruto, adquiriendo una gama cromática que va del amarillo al naranja claro. Además, el cáliz es notable por sus diez venas principales de tonalidad morada y la multitud de venas secundarias en un verde oscuro [17].

2.2 Metodología

Este estudio ha implementado un enfoque cuantitativo, basado en un diseño experimental. El análisis cuantitativo será llevado a cabo mediante una metodología precisa, utilizando diversos instrumentos de investigación, tales como fichas de observación, videocámaras y hojas de cálculo.

2.1.3 Procedimiento

Selección del suelo

Para la elección adecuada del suelo en la producción de adobes, es indispensable realizar dos pruebas según lo establecido en la normativa peruana (E. 080). La primera condición para la selección indica que se forma una cinta de aproximadamente 20 a 25 cm y se evalúa durante 10 minutos debiendo estar suspendida. La segunda es la prueba de bolitas, que consiste en formar cuatro pequeñas esferas de suelo que deben mantener su forma y resistir la presión de los dedos después de 48 horas [18].

Clasificación del suelo

Para la determinar el tipo del suelo se consideró los sistemas de clasificación SUCS y AASHTO

Además, se utilizaron las siguientes normativas como referencia para la creación y evaluación de los adobes.

Fabricación de unidades de adobe

La fabricación del adobe se realizó conforme a lo indicado a la norma E.080 para unidades rectangulares cuyas medidas son de 30 x 15 x 10 debiéndose cumplir que para el ancho debe ser la mitad del largo y la altura estará entre 8 a 12 cm.

La adición de cascarilla de Opuntia ficus-indica al adobe se realizará en proporciones de 0.2%, 0.4% y 0.6% con respecto al peso total del adobe. Por otro lado, para obtener el mucílago de nopal o tuna, se cortó la hoja de tuna en pequeños trozos y dejarla reposar en agua durante 7 a 14 días. Luego, se debe agrego al adobe en porciones de 6%, 8% y 10%.

El período de secado del adobe sin aditivos y el adobe con cascarilla incorporada es de aproximadamente 7 días. Sin embargo, para los adobes que contienen mucílago de tuna, el tiempo de secado puede extenderse hasta 14 días, considerando una temperatura de 20 grados centígrados.

Los ensayos de resistencia del adobe se llevaron a cabo siguiendo las directrices establecidas por la normativa peruana, y se realizaron después de 28 días de su elaboración.

Resistencia a compresión

Basándonos en la (E.080) [18] normativa peruana la cual indiaca que para determinar la capacidad de resistir la compresión en muretes y cubitos de 10x10x10 los días de secado deben ser de 28 días. En este experimento se utilizaron un total de 48 muretes de adobe. Además, se realizaron 30 adobes para cada una de las muestras (patrón, *Physalis peruviana y Opuntia ficus-indica*) en diferentes porcentajes de adición.

Este ensayo evidencia cómo las unidades de albañilería responden bajo carga axial y el esfuerzo resistente en compresión se determina a por el área de la sección transversal [19].

Absorción y Succión

De acuerdo con la normativa peruana (NTP-399.613), para absorción es necesario sumergir los adobes en agua durante un periodo de 24 horas. Se debe registrar tanto el peso seco del adobe antes de la inmersión como su peso después de haber sido sumergido. En el experimento se utilizaron un total de 48 adobes, con 6 adobe para el patrón y adobes con la inclusión de Physalis peruviana y Opuntia ficus-indica en sus distintas adiciones. Por otro lado, la (NTP-399.613) también indica que para los ensayos de succión debe permanecer en agua no más de 3 horas [20].

Tracción

Conforme establece la Normativa (E.080) para avaluar la capacidad de tracción, las muestras deben ser en probetas equivalente a 6 pulgadas x 12 pulgadas habiendo pasado 28 días, en este ensayo la cantidad de probetas fue de 48 unidades, con 6 adobe para el patrón y adobes con la inclusión de *Physalis peruviana y Opuntia ficus-indica* en sus distintas adiciones [18].

3. Resultados y discusión

3.1 Contenido de humedad

La humedad del suelo analizado para la fabricación de unidades de adobe se ha determinado en un 3.45%, conforme a la metodología descrita en la NTP 339.127 [21].

Tabla 1.
Contenido de humedad de la muestra de tierra

Descripción	UND	01	02	03
C. de humedad	%	21.53	22.79	25.18

Fuente: Elaboración propia.

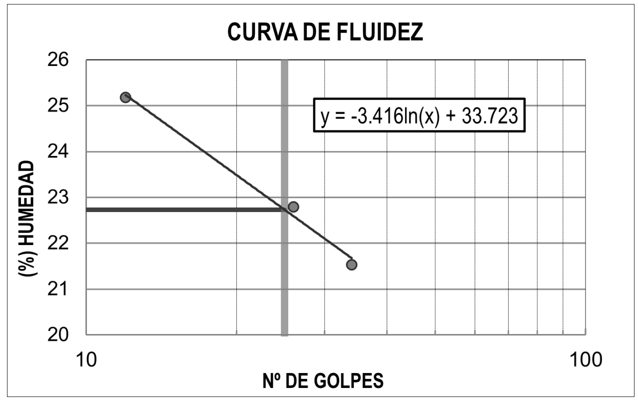

Figura 1. Curva de Fluidez – Análisis del suelo
Fuente: Elaboración propia.

$$\frac{M_w}{M_s}.x.100 \quad (1)$$

dónde:
M_w: peso del agua, en gramos
M_s : peso de las partículas sólidas, en gramos

3.2 Límite líquido (L.L)

Según la Figura 1 el límite líquido determinado correspondió a un 23%.

En la Tabla 1 se visualiza que el mayor contenido de humedad de la muestra alcanzó el 25.18%.

$$LL = W^n\left(\frac{N}{25}\right)^{0.121} \quad (2)$$

dónde:
N = Número de golpes
w^n = Humedad del suelo

3.3 Límite Plástico (L.P)

El límite plástico determinado se registró en un 15% y el índice de plasticidad en un 8%

La Tabla 2 se observa que el límite de plástico del análisis de laboratorio alcanzó el 19.49. Asimismo, en la Tabla 3 se visualiza el valor del índice de plasticidad del análisis de laboratorio con el valor de 8.

Tabla 2.
Límite. Plástico del análisis de laboratorio

Descripción	UND	01	02
C. de humedad	%	19.49	10.16

Fuente: Elaboración propia.

Tabla 3.
Índice de Plasticidad del análisis de laboratorio

Descripción	IP
Índice de plasticidad	8

Fuente: Elaboración propia.

Tabla 4.
Estudio de distribución de tamaños de partículas

Descripción de la muestra	
Material pasante "Malla N° 200"	86.31%
Material pasante "Malla N° 4"	99.42%
Módulo de fineza	0.33
Coeficiente de uniformidad	0.2
Coeficiente de curvatura	1.4

Fuente: Elaboración propia.

Tabla 5.
Resistencia promedio a la compresión de adobes

Descripción	Carga promedio (kg)	Prom. (kg/cm2)
Patrón	1443	15.51
Cascara 0.2%	1515	15.91
Cascara 0.4%	1129	14.79
Cascara 0.6%	1287	13.93
Tuna 6 %	1366	14.80
Tuna 8 %	1421	14.98
Tuna 10 %	1433	15.41
Casca. 0.2% + Tuna 10%	1601	16.82

Fuente: Elaboración propia.

$$IP = LL.LP \qquad (3)$$

dónde:
IP: Índice de plasticidad
LL: Límite líquido
LP: Límite plástico

3.4 Granulometría

Mediante la clasificación SUCS [22] estamos en presencia de una muestra (CL) o arcilla de baja plasticidad. Por otro lado, en la clasificación AASHTO [23] estamos en presencia de un suelo A-4 [9].

Asimismo, se observa los resultados que se obtuvieron de los ensayos en las Tablas 4-13 y Figuras 2-6 respectivamente.

3.5.1 Ensayo de compresion

Fue realizado en cubos de 0.1m x 0.1m y se registró los siguientes valores.

$$F\acute{}b = \frac{Pu}{área} \qquad (4)$$

dónde:
F´b = Resistecia a la compresión axial (kg/cm2)
Pu = Carga (Kg)
A = Área sometida por la carga cm2

3.6 Resistencia a la compresión pilas

Para los ensayos de compresión en adobes de 30 x 15 x 32 se registraron los resultados Tabla 6.

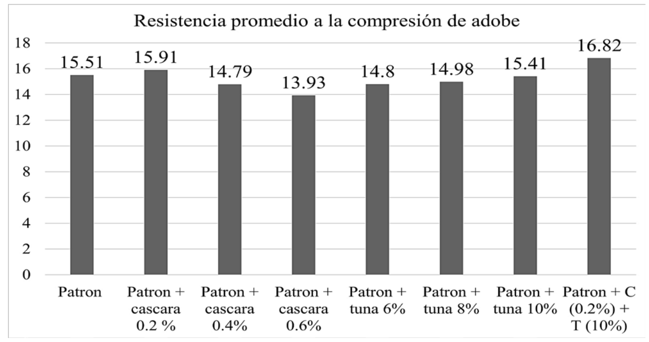

Figura 2. Resistencia promedio a la compresión de adobe
Fuente: Elaboración propia.

Tabla 6.
Resistencia promedio de pilas a comprensión

Descripción	Prom. (kg/cm2)
Patrón	5.50
Cascara 0.2%	7.21
Cascara 0.4%	6.04
Cascara 0.6%	6.16
Tuna 6 %	5.55
Tuna 8 %	5.57
Tuna 10 %	5.92
Casca. 0.2% + Tuna 10%	7.47

Fuente: Elaboración propia.

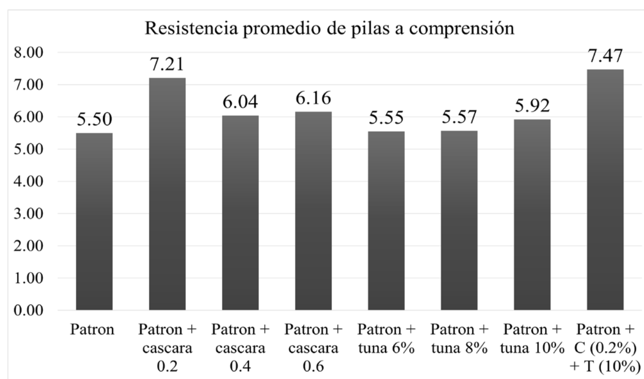

Figura 3. Resistencia promedio de pilas a comprensión
Fuente: Elaboración propia.

Tabla 7.
Resistencia promedio de probetas a tracción

Descripción	Carga promedio (kg)	Prom. (kg/cm2)
Patrón	620	0.85
Cascara 0.2%	640	0.88
Cascara 0.4%	566	0.78
Cascara 0.6%	639	0.88
Tuna 6 %	610	0.84
Tuna 8 %	635	0.87
Tuna 10 %	644	0.88
Casca. 0.2% + Tuna 10%	758	1.04

Fuente: Elaboración propia.

3.7 Ensayo de tracción

Se llevaron a cabo pruebas de tracción en probetas con dimensiones de 15.24 x 30.48 cm (equivalente a 6 pulgadas x 12 pulgadas), y se registraron los resultados de la Tabla 7.

$$T = \frac{2.P}{\pi.D.L} \tag{5}$$

dónde:
P = carga aplicada
D = diámetro de la probeta
L = Longitud de la probeta

3.8 Ensayo de absorción

Fue realizado en adobes 30x15x10 cm, y se registraron los resultados de la Tabla 8.

$$Absorción\% = 100\frac{w_s - w_d}{w_d} \tag{6}$$

dónde:
W_d = Peso seco
W_s = Peso saturado

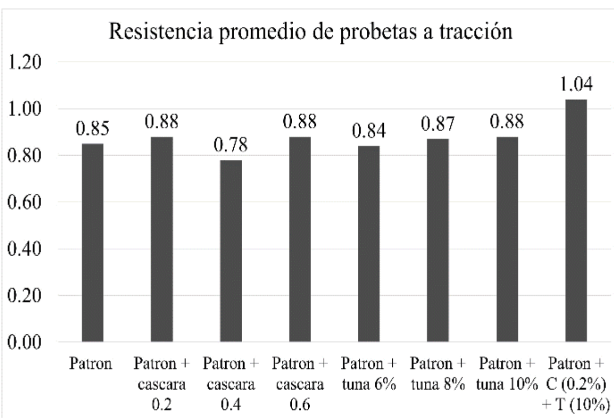

Figura 4. Resistencia promedio de probetas a tracción
Fuente: Elaboración propia.

Tabla 8.
Promedio del ensayo de absorción en adobes

Descripción	Peso Humedo (kg)	Peso Seco (Kg)	Absorción (%)
Patrón	8.123	7.286	11.48
Cascara 0.2%	8.213	7.359	11.60
Cascara 0.4%	8.133	7.374	10.29
Cascara 0.6%	8.228	7.378	11.53
Tuna 6 %	8.163	7.294	11.91
Tuna 8 %	8.156	7.265	12.26
Tuna 10 %	8.2	7.29	12.48
Casca. 0.2% + Tuna 10%	8.183	7.232	13.16

Fuente: Elaboración propia.

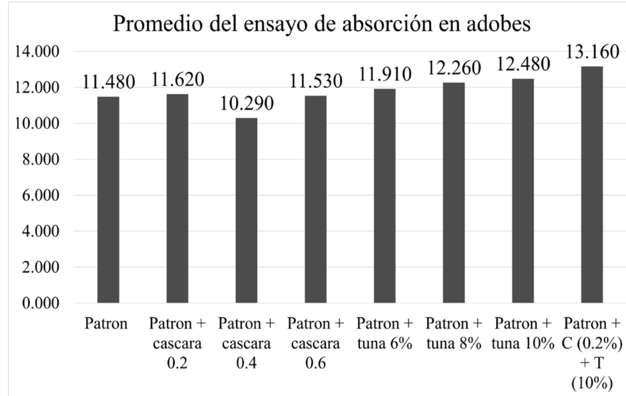

Figura 5. Promedio del ensayo de absorción en adobes
Fuente: Elaboración propia.

3.9 Ensayo de Succión

Fue realizado en adobes 30x15x10 cm, y se registraron los resultados Tabla 9.

$$x = \frac{200.w}{L.B} \tag{7}$$

dónde
X = Diferencia de peso
W= Diferencias de pesos del espécimen (g)
L = Longitud (cm)
B = Ancho (cm)

Tabla 9.
Promedio del ensayo de succión en adobes

Descripción	Peso Saturado (gr)	Peso Seco (gr)	Succión (%)
Patrón	7445	7424	9.28
Cascara 0.2%	7386	7364	9.44
Cascara 0.4%	7250	7230	8.84
Cascara 0.6%	7665	7644	9.56
Tuna 6 %	7665	7643	9.97
Tuna 8 %	7666	7641	10.50
Tuna 10 %	7664	7640	11.61
Casca. 0.2% + Tuna 10%	7666	7640	12.09

Fuente: Elaboración propia

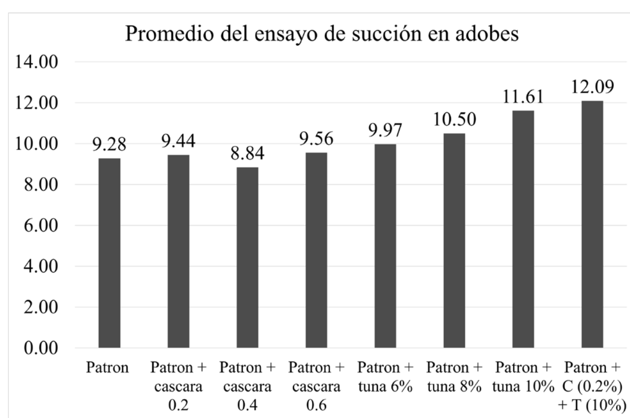

Figura 6. Promedio del ensayo de succión en adobes
Fuente: Elaboración propia.

3.10 Alabeo

Tabla 10.
Promedio del ensayo del alabeo en adobes

Descripción	Cara (A)		Cara (B)	
	Concavo mm	Convexo mm	Concavo mm	Convexo mm
Patrón	2.4	1.6	2.0	3.8
Cascara 0.2%	2.0	3.5	1.7	1.7
Cascara 0.4%	1.8	1.0	1.3	7.0
Cascara 0.6%	2.2	3.8	1.5	1.7
Tuna 6 %	1.0	1.0	2.0	1.8
Tuna 8 %	1.0	3.8	4.5	2.2
Tuna 10 %	1.0	3.8	4.5	2.5
Casca. 0.2% + Tuna 10%	1.0	4.0	4.8	2.5

Fuente: Elaboración propia.

3.11 Variación dimensional

Tabla 11.
Determinación de la Longitud promedio de los adobes

Descripción	Longitud (mm)			
	Longitud estandar	s	Longitud promedio	%
Patrón	300	5.7	294. 3	1.91
Cascara 0.2%	300	1.7	298.3	0.58
Cascara 0.4%	300	2.3	297.7	0.76
Cascara 0.6%	300	0.3	299.7	0.09
Tuna 6 %	300	5.0	295.0	1.65
Tuna 8 %	300	3.5	296.5	1.17
Tuna 10 %	300	3.7	296.3	1.23
Cas. 0.2% y Tuna 10%	300	3.7	296.3	1.22

Fuente: Elaboración propia.

Tabla 12.
Determinación de la anchura promedio en adobes

Descripción	Ancho (mm)			
	Longitud estandar	s	Longitud promedio	%
Patrón	150	0.6	149.7	0.23
Cascara 0.2%	150	1.2	148.8	0.79
Cascara 0.4%	150	0.7	149.3	0.48
Cascara 0.6%	150	6.3	143.7	4.19
Tuna 6 %	150	0.4	149.0	0.26
Tuna 8 %	150	0.5	149.5	0.32
Tuna 10 %	150	0.6	149.4	0.40
Cas. 0.2% y Tuna 10%	150	0.6	149.4	0.37

Fuente: Elaboración propia.

Tabla 13.
Determinación de la altura promedio de los adobes

Descripción	Altura (mm)			
	Longitud estandar	s	Longitud promedio	%
Patrón	100	0.4	99.6	0.42
Cascara 0.2%	100	0.4	99.6	0.42
Cascara 0.4%	100	0.3	99.7	0.30
Cascara 0.6%	100	1.3	98.7	1.25
Tuna 6 %	100	2.3	97.7	2.30
Tuna 8 %	100	2.3	97.7	2.33
Tuna 10 %	100	2.5	97.5	2.5
Cas. 0.2% y Tuna 10%	100	2.4	97.6	2.42

Fuente: Elaboración propia.

3.12 Análisis Gaussiano de la resistencia a la compresión

Se ha calculado la desviación estándar y la variación de la resistencia a la compresión de adobe correspondientes a cada una de las muestras.

3.13 Probabilidad de ocurrencia

Los resultados que se obtuvieron de las probabilidades en los ensayos se visualizan en las Tablas 14-17 y en las Figuras 7-10 respectivamente.

Tabla 14.
Probabilidad de ocurrencia de la muestra patrón

Muestra Patrón			
Desviación estándar	1.337		
Variación	8.617		
Probabilidad	Resistencia (kg/cm2)		
68.20%	14.65	a	16.20
95.20%	13.79	a	16.89
100.00%	12.92	a	17.57

Fuente: Elaboración propia.

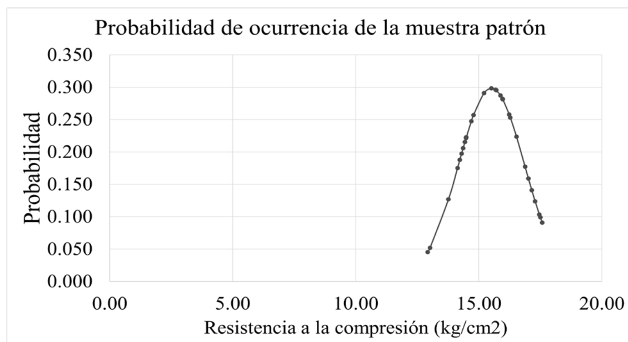

Figura 7. Probabilidad de ocurrencia de la muestra patrón
Fuente: Elaboración propia.

Tabla 15.
Probabilidad de ocurrencia de la muestra patrón + 0.2% de cáscara

Muestra Patrón + 0.2% de cáscara			
Desviación estándar	1.300		
Variación	8.198		
Probabilidad	Resistencia (kg/cm2)		
68.20%	15.30	a	16.92
95.20%	14.69	a	17.94
100.00%	14.07	a	18.95

Fuente: Elaboración propia.

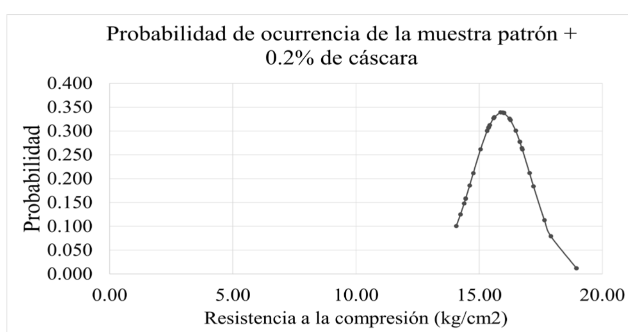

Figura 8. Probabilidad de ocurrencia de la muestra patrón + 0.2% de cáscara
Fuente: Elaboración propia.

Tabla 16.
Probabilidad de ocurrencia de la muestra patrón + 10% de tuna

Muestra Patrón + 10% de tuna			
Desviación estándar	1.054		
Variación	6.842		
Probabilidad	**Resistencia (kg/cm2)**		
68.20%	14.98	a	16.16
95.20%	14.56	a	16.91
100.00%	14.13	a	17.66

Fuente: Elaboración propia

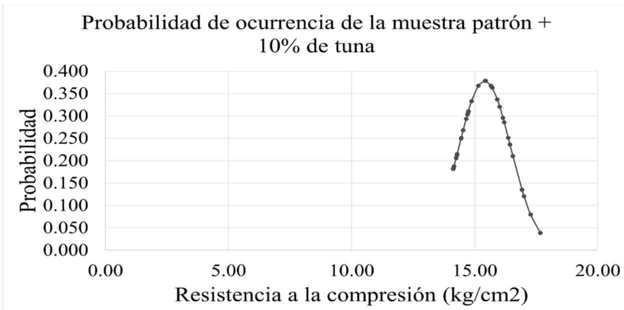

Figura 9. Probabilidad de ocurrencia de la muestra patrón + 10% de tuna
Fuente: Elaboración propia.

Tabla 17.
Probabilidad de ocurrencia de la muestra patrón + 0.2% de cáscara +10% de tuna

Muestra Patrón + 0.2% de cascara + 10% de tuna			
Probabilidad	**Resistencia (kg/cm2)**		
68.20%	16.01	a	17.52
95.20%	15.19	a	18.22
100.00%	14.38	a	18.92

Fuente: Elaboración propia

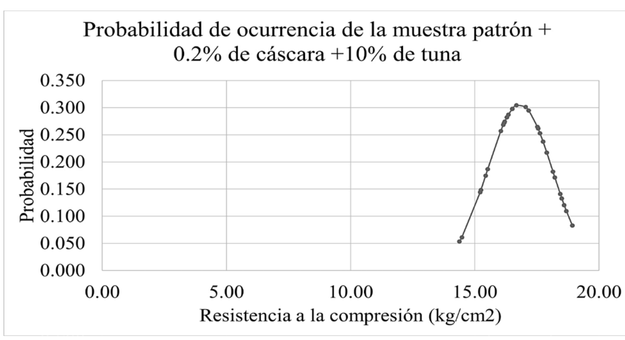

Figura 10. Probabilidad de ocurrencia de la muestra patrón + 0.2% de cáscara +10% de tuna
Fuente: Elaboración propia

Los valores registrados indican que incorporar cascarilla de *Physalis peruviana* en proporciones de 0.2%, 0.4% y 0.6% a los ladrillos de adobe aumenta la capacidad de resistir la compresión en comparación a aquellos que incluyen *Opuntia ficus-indica* en porcentajes de 6%, 8% y 10%. Se observó en la Tabla 5 resistencias de 15.98 kg/cm2, 14.72 kg/cm2 y 13.93 kg/cm2 con la cascarilla de *Physalis peruviana*, frente a 14.80 kg/cm2, 14.93 kg/cm2 y 15.41 kg/cm2 con el *Opuntia ficus-indica*. Al combinar ambos, la resistencia a compresión supera los valores obtenidos individualmente, logrando una resistencia máxima de 16.82 kg/cm2, superado la carga indicada en la norma E.080 de 10.20 kg/cm2 [18].

Comparando las bajas adiciones de *Physalis peruviana* en concentraciones del 0.2%, 0.4% y 0.6% con la investigación realizada por [7], quienes utilizaron fibras de coco en concentraciones similares 0.25%, 0.50% y 0.75%, se evidencia que la compresión soportada es mayor con las fibras de coco. Mientras la cáscara de *Physalis peruviana* presenta una resistencia de 16.82 kg/cm2, la incorporación de fibras de coco alcanza una resistencia de 36.83 kg/cm2. Incluso supera la resistencia obtenida por [6], quienes registraron una resistencia de 29.14 kg/cm2 al incorporar paja toquilla al 6%.

Los adobes deben superar una carga de 6.25 kg/cm2 en pilas. Los datos registrados determinan que adobes con una incorporación de cascarilla del 0.2% y *Opuntia ficus-indica* del 10% alcanzaron una resistencia superior, con 7.47 kg/cm2. Esto es superior a la resistencia del adobe patrón, que registró 5.50 kg/cm2, la cual fue la menor resistencia observada en los ensayos.

Según la norma E.080 [18], se realizó un ensayo de Tracción simple, que evaluó las fibras de agave a las muestras de adobe [9]. Los resultados indican que al incorporar un 0.25% de fibras de agave, habría un aumento del 39.13% en la resistencia, equivalente a (0.32MPa) o 3.26 kg/cm2. En contraste, las muestras de cáscara de *Physalis peruviana* mostraron una resistencia de 1.04 kg/cm2 o (0.10MPa), con un incremento de 22.4% en contraste al adobe patrón de 0.85kg/cm2 [18], habiendo una disminución en la resistencia en comparación con las muestras de agave. Ambos tipos de muestras superaron el nivel de resistencia especificado en la norma E.080, que es de (0.08MPa) o 0.81 kg/cm2.

La absorción de humedad en los adobes, según la Tabla 10, indican que los adobes menos resistentes son aquellos que incorporan cascarilla de aguaymanto. Por otro lado, los adobes que presentaron mayor resistencia son los que contienen tuna en su composición, con una absorción del 12.48%. Este incremento del 8.7% en comparación con la muestra patrón se considera moderado. En contraste, [8], refiere en su investigación que utilizaron el extracto de la cabuya para estabilizar los adobes. Sin la presencia del extracto de la cabuya, se observó un deterioro severo en las unidades, mientras que, con el extracto, el deterioro fue ligero y, en algunas muestras, moderado. Con respecto a la succión en la Tabla 9 muestra que hay mejoría con respecto a los adobes que tienen incorporado cascarilla de *Physalis peruviana* siendo la mejor de 11.61% alcanzando un 25.1% de mejora frente a los 9.28% y la combinación de cascara al 0.2% más incorporación de tuna al 10% mejoro el 30.3%

La variación dimensional en la longitud estándar de los adobes patrón es del 1.91%, lo que resulta menos favorable en comparación con las muestras que incorporan un 0.2% de cascarilla de aguaymanto. Esta diferencia representa un 0.58% y se traduce en una variación de 5.7 mm a 1.7 mm, respectivamente. En cuanto a la anchura estándar, los adobes que incorporan un 0.6% de cascarilla de aguaymanto presentan una mayor variación, con una diferencia de 6.3 mm. Por otro lado, los adobes patrón tienen una variación menor, con un 0.23% en comparación con el 4.19%. Finalmente, en la altura estándar, la variación más desfavorable es de 97.6 mm, lo que representa un 2.5% en comparación con el diseño original de 100 mm

4 Conclusiones

La adición de *Physalis peruviana* a las unidades de adobe podría tener un impacto mínimo en los ensayos que evalúan la resistencia física y mecánica. La proporción óptima de incorporación es del 0.2%. Sin embargo, a medida que se aumenta la cantidad de *Physalis peruviana* en los adobes, la capacidad de resistencia disminuye, como se observa en las Tablas 5, 6 y 7. Aunque las incorporaciones del 0.2%, 0.4% y 0.6% superan lo especificado en la normativa E.0.80, no se aconseja su utilización habiendo materiales que mejoran más las capacidades del adobe.

La incorporación de la tuna en proporciones del 6%, 8% y 10% como agente estabilizador frente al accionar del agua en el adobe resulta en un mejor desempeño. En las pruebas de inmersión, se observa una mejora del 8.7%. Además, en la Tabla 9 en términos de succión, se evidencia un aumento del 7.4%, 13.1% y 25.1%. La combinación óptima de cáscara en un 0.2% y tuna en un 10% mejora en un 30.3%. Por lo tanto, la hoja de *Opuntia ficus-indica* podría funcionar como un impermeabilizante natural.

Los análisis estadísticos de las pruebas de resistencia a la compresión, basados en el control (kg/cm2) basándoos en la normativa ACI 318, proporcionan información valiosa. Tanto para el control en obra como para el control en laboratorio, se establece en la Tabla14 una desviación estándar que varía entre 0.85 y 1.499. En ambos casos, esta condición es excelente, ya que es menor que los valores de referencia: 28.1 para el control en obra y 14.1 para el control en laboratorio. Por otro lado, la variación observada en el control porcentual es deficiente, superando un valor de 6.0 en obra y 5.0 en laboratorio. Según la Tabla 14, los valores oscilan entre 5.6 y 10.05.

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Behavior of an asphalt mixture with the incorporation of plastic for airport pavements

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Abstract
This paper analyzed the physical-mechanical behavior and durability of two P-401 asphalt mixtures manufactured with asphalt modified with plastic waste and polymer. For this purpose, the mixture design was carried out using the Marshall test to determine the optimal asphalt content. Tests were carried out to evaluate the mechanical behavior using monotonic load tests (indirect tensile strength), repeated (resilient modulus, fatigue resistance) and static (static creep). ANOVA statistical analysis was used to determine significant variations between the results of the two mixtures. The results indicate that the incorporation of plastic waste is technically feasible and provides similar mechanical performance and durability in the P-401 asphalt mixture compared to polymer-modified asphalt. Additionally, it provides a final form of environmentally safe disposal of solid waste.

Keywords: hot-mixture asphalt; pavements; airports; modified asphalt; PET.

Comportamiento de una mezcla asfáltica con incorporación de plástico para pavimentos aeroportuarios

Resumen
Este trabajo analizó el comportamiento físico mecánico y la durabilidad de dos mezclas asfálticas tipo P-401 fabricadas con asfalto modificado con residuos de plástico y con polímero. Para tal fin se realizó el diseño de mezclas mediante el ensayo Marshall a fin de determinar el contenido óptimo de asfalto. Fueron realizados ensayos para evaluar el comportamiento mecánico mediante ensayos de carga monotónica (resistencia a la tracción indirecta), repetida (módulo resiliente, resistencia a la fatiga) y estática (fluencia estática). Análisis estadístico ANOVA se emplearon para determinar variaciones significativas entre los resultados de las dos mezclas. Los resultados indican que la incorporación de residuos plásticos es viable técnicamente y proporciona similar desempeño mecánico y durabilidad en la mezcla asfáltica P-401 en comparación al asfalto modificado con polímero. Adicionalmente, proporciona una forma final de disposición ambientalmente segura de residuos sólidos.

Palabras clave: mezcla asfáltica densa en caliente; pavimentos; aeropuertos; asfalto modificado; PET.

1 Introducción

Colombia reporta 253 terminales aéreos o aeropuertos de pasajeros, de los cuales aproximadamente el 67.6% (171), 20.6% (52), 6.3% (16) y 5.5% (14) son administrados por alcaldías municipales, aeronáutica civil, concesionados a cargo de la Agencia Nacional de Infraestructura Colombiana (ANI) y otros, respectivamente, de los cuales, 12 son internacionales [1]. En el año 2019 se reportaron 268 rutas aéreas (165 nacionales y 103 internacionales) que movilizaron aproximadamente 45.5 millones de personas (65.9% destino nacional y 34.1% internacional) [1].

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Tabla 1
Comparación de las características de pavimentos aeroportuarios y de carreteras.

Características	Aeropuertos	Carreteras
Vehículo de diseño	aeronaves	buses y camiones
Carga máxima	500 tf	52 tf
Presión de contacto	200 a 430 psi	85 a 120 psi
Velocidad de operación	260 a 280 km/hora	40 a 100 km/hora
Ancho de la sección	10 a 45 m	6 a 10 m
Largo	Entre 3 a 4 km	Varios km
Acción de frenado	Critico	Despreciable
Impacto vehículo-pavimento	Alto	Bajo
Acción de carga dinámica	Alta	Baja

Fuente: Autores.

Adicionalmente, se reporta la movilización de 808.000 toneladas de carga para el comercio nacional y exterior. En total, para el año 2022 se alcanzaron aproximadamente 1.246.135 y 149.172 operaciones nacionales e internacionales, respectivamente [2]. No se reportan datos de años siguientes, dado que estos valores fueron inferiores en años siguientes debido a la pandemia de Covid-19.

Los pavimentos aeroportuarios son estructuras de materiales que se diseñan y construyen para soportar la acción del tránsito de aeronaves y la incidencia del clima [3]. Estos pavimentos presentan similitud con los pavimentos de carreteras en lo referente a los tipos de materiales [4,5]. Sin embargo, presentan diferencias considerables en la magnitud de carga, presiones, dimensiones, numero de repeticiones de carga, velocidad de aplicación, entre otros [6]. En la Tabla 1 se observa un comparativo entre las principales características de pavimentos aeroportuarios y pavimentos de carreteras.

Los pavimentos aeroportuarios requieren mayor capacidad estructural para soportar la acción dinámica de las aeronaves [5]. Lo anterior implica mayores requerimientos técnicos en los materiales en términos de su rigidez y de espesores de las capas [6]. Adicionalmente, en las pistas de aterrizaje y despegue y rodaje o de aproximaciones se presenta mayor interacción dinámica entre la superficie y la aeronave [4]. Lo anterior implica mayor calidad en los aspectos funcionales del pavimento en términos de mayor resistencia al deslizamiento, rugosidad y menores deterioros superficiales, dado que las velocidades de operación de las aeronaves oscilan entre 260 a 280 km/hora [7,8].

El diseño de mezclas asfálticas para pavimentos aeroportuarios está regulado por las especificaciones de la Administración Federal de Aviación FAA AC 150/5370 [9]. La especificación contempla mezclas tipo P-401 tipo I, II y III, las cuales hacen referencia al tamaño máximo del agregado de 25 mm, 19 mm y 12.5 mm, respectivamente. El diseño se puede realizar por medio del ensayo Marshall o metodología Superpave. El asfalto por utilizar deberá ser calificado por grado de desempeño, por sus siglas en ingles PG Performance Grade según la especificación ASTM D4318. Adicionalmente deberá proporcionar recuperación elástica de 75% obtenida en el ensayo ASTM D6084. De forma general se requiere el uso de características Cementos Asfalticos Modificados CAM con polímeros. La obtención del contenido óptimo de asfalto se establece para garantizar vacíos con aire Va en la mezcla de 3.5%. Asimismo, se debe garantizar la adherencia al daño por humedad inducida en la mezcla asfáltica, la cual es establecida por el parámetro TSR (Tensile Strength Ratio, por sus siglas en inglés) mínimo del 80%. Ese parámetro se obtiene a partir del ensayo ASTM D4867. Adicionalmente, se deben realizar ensayos para evaluar la resistencia a la deformación permanente que se puede evaluar mediante los ensayos de rueda de carga de Hamburg según AASHTO T-324 o el equipo APA (Asphalt Pavement Analyzer) conforme AASHTO T-340, los cuales establecen un valor máximo de desplazamiento final en la mezcla de 10 mm a 20000 y 40000 pasadas de carga a 50ºC y 64ºC, respectivamente.

Por lo anterior, para el diseño de mezclas asfálticas generalmente se requiere el uso de asfaltos modificados, a fin de generar mayor rigidez, resistencia a la deformación permanente y durabilidad de los pavimentos. Usualmente, se emplean modificadores del asfalto que pueden ser polímeros de tipo plastómeros o elastómeros, a fin de generar mayor rigidez o recuperación elástica [10]. En los últimos se investigado el uso de materiales alternativos para la modificación de asfalto. El uso de residuos plásticos para la fabricación de mezclas asfálticas contribuye a la preservación y conservación del medio ambiente por proponer una forma de disposición final de residuos sólidos [11-13]. La incorporación de plástico se puede realizar mediante la vía seca o húmeda, las cuales consisten en la adición sobre los agregados o modificación del asfalto, respectivamente [14]. Algunas investigaciones recomiendan el uso de plástico por vía seca empleando partículas cuadradas de tamaño inferior a 2.36 mm [15 -17]. De forma general, el uso de plástico genera un incremento de la resistencia ante carga monotónica y cíclica, evidenciada por en el ensayo Marshall, resistencia a tensión indirecta, módulo resiliente, deformación permanente, resistencia a la fatiga. en referencia a las mezclas convencionales (sin incorporación de plásticos) [18-22]. En la literatura no se reporta un contenido específico de plástico a incorporar, dado que depende del tipo de asfalto, agregados, granulometrías, tipo de mezcla, entre otras. Sin embargo, los rangos típicos de incorporación oscilan entre 2% a 10% en referencia a la masa del asfalto (vía húmeda) [23]25] y entre 0.1% y 1.0% en referencia a la masa total [15-18]. De forma general, diversos estudios se han realizado -para evaluar la incorporación de residuos plásticos en mezclas asfálticas para pavimentos de carreteras. Sin embargo, pocos estudios se reportan para mezclas asfálticas de pavimentos aeroportuarios.

El objetivo de este estudio fue evaluar el desempeño físico-mecánico de una mezcla asfáltica P-402 tipo II fabricada con cemento asfaltico modificado CAM con residuos de plástico tipo PET para buscar un aprovechamiento de residuos sólidos y contribuir su disposición final y ambientalmente segura. Lo anterior, con el fin de ser comparada con una mezcla convencional elaborada con CAM polímero tipo SBS, la cual es de común uso para la construcción de pavimentos aeroportuarios. Para tal fin fueron realizados los diseños de mezcla según el ensayo Marshall. Fueron realizados ensayos de resistencia ante carga monotónica (resistencia a tracción indirecta RTI), cíclica repetida (módulo resiliente y fatiga a esfuerzo controlado) y estática (fluencia estática). Asimismo, se analizó la durabilidad mediante ensayos de susceptibilidad al agua definida por la relación del RTI en condiciones húmedas/secas y el ensayo cantabro.

2 Materiales y metodología

La metodología de este estudio se fraccionó en tres fases. La primera fase corresponde a la caracterización de materiales empleados para la fabricación de la mezcla asfáltica P401. La segunda fase corresponde al diseño de dos mezclas mediante la metodología Marshall, las cuales fueron denotadas como MDC P-401 CAM plástico y MDC P-401 CAM polímero. Finalmente, la tercera etapa se evaluó el comportamiento mecánico mediante ensayos de carga monotónica, cíclica y estática.

2.1 Materiales

Fueron empleados dos CAMs con residuos plástico tipo PET y con polímero (Ver Fig. 1). Estos materiales fueron denominados como: CAM plástico y CAM Polímero. CAM plástico se empleó el 6% de PET (contenido sobre el peso del asfalto) y Cemento Asfáltico tipo CA 60-70. La modificación se realizó empleando un agitador rotacional, con una velocidad de agitación de 3000 rpm durante 45 minutos a una temperatura de 175 °C. El CAM polímero corresponde a un material manufacturado según los lineamientos del artículo INVIAS 414 2022 [26].

En la Tabla 2 se evidencian los resultados de caracterización física en la condición original y sometida a envejecimiento a corto plazo. Estos indican que los materiales cumplen con los requisitos de calidad dispuestos en el artículo INVIAS 414 2022 [26]. Por otro lado, los agregados pétreos son de origen natural obtenidos de roca triturada en cantera para la ciudad de Bogotá. En la Tabla 3 se exponen los resultados de los ensayos de caracterización física. Según los valores obtenidos, es posible evidenciar que los mismos cumplen con las especificaciones de la Administración Federal de Aviación FAA AC 150/5370 para la fabricación de mezclas asfálticas tipo P-401 para capas de aeropuertos [9].

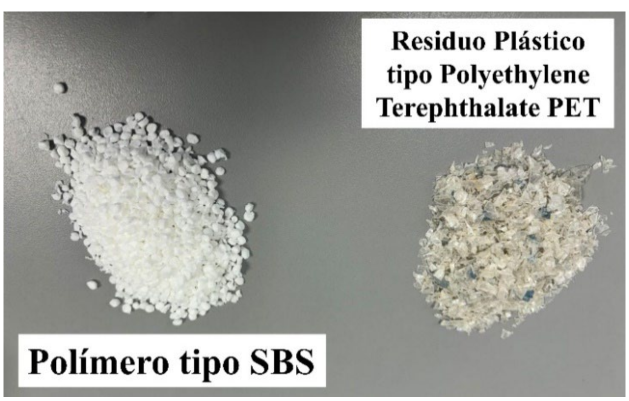

Figura 1. Materiales modificadores del cemento asfáltico.
Fuente: Autores.

Para la fabricación de mezclas asfálticas se empleó la granulometría tipo 2 de especificación AC 150/5370-10H [9] conforme se presenta en la Tabla 4.

Tabla 2.
Caracterización física de CAM plástico y polímero.

Ensayo	Especificación	CAM Polímero	CAM Plástico	Requisitos
Condición original				
Penetración (0.1 mm)	INV-E 706	56	56	55 - 70
Punto de ablandamiento (ºC)	INV-E 712	87	86	mínimo 65
Ductilidad (cm)	INV-E 702	24	31	mínimo 15
Recuperación elástica por torsión (%)	INV-E 727	75	74.4	mínimo 70
Estabilidad al almacenamiento (ºC)	INV-E 726	2.5	5	máximo 5
Punto de ignición (ºC)	INV-E 709	286	294	mínimo 230
Envejecimiento a corto plazo				
Pérdida de masa (%)	INV-E 720	0.4	0.57	máximo 1
Penetración, en referencia al valor original (%)	INV-E 706	67.2	75.4	mínimo 65
Incremento del punto de ablandamiento (ºC)	INV-E 712	5	5	máximo 10

Fuente: Autores.

Tabla 3.
Caracterización de los agregados para el diseño de mezclas.

Ensayo	Procedimiento	Especificación AC150/5370-10H	Resultado
Desgaste en la Maquina de los Ángeles (%)	ASTM C131	Máximo 40	21.2
Solidez en sulfato de Magnesio agregado grueso (%)	ASTM C88	Máximo 18	4.5
Terrones de arcilla en agregado grueso (%)	ASTM C142	Máximo 1	0.5
Caras fracturadas (1 cara)	ASTM D5821	Máximo 85	100
Caras fracturadas (2 caras)	ASTM D5821	Máximo 75	100
Partículas planas y alargadas (Relación 5:1)	ASTM D4791	Máximo 8	4.1
Limite Líquido (%)	ASTM D4318	Máximo 25	NL
Índice de Plasticidad (%)	ASTM D4318	Máximo 4	0
Solidez en sulfato de Magnesio en agregado fino (%)	ASTM C88	Máximo 15	9.5
Terrones de arcilla en agregado fino (%)	ASTM C142	Máximo 1	0.8
Equivalente de arena (%)	ASTM D1073	Mínimo 45	49

Fuente: Autores.

Tabla 4.
Granulometría tipo 2 para MDC P-401.

Tamiz	3/4"	1/2"	3/8"	4	8	16	30	50	100	200
Pasa (%)	100	95	80	63	49	37	28	19	12	4.5

Fuente: FAA AC 150/5370-10H [9]

2.2 Diseño de mezclas asfálticas

Se realizó el diseño de dos mezclas asfálticas MDC tipo P-401 según la especificación INVIAS 748 2013 empleando CAM con plástico y polímero por medio del método Marshall para determinar el contenido óptimo de asfalto. Fueron realizadas briquetas tipo Marshall de aproximadamente 101 mm y 63.5 mm de diámetro y altura, respectivamente. Se realizaron briquetas de 1200 g de material empleando contenidos probables de 5.5%, 6.0%, 6.5%, 7.0% y 7.5%. de CAM. La compactación se realizó mediante la aplicación de 75 golpes por cada cara con el martillo Marshall. Los intervalos de temperatura para la fabricación fueron de 163 a 171°C y 165 a 175°C para las mezclas con CAM plástico y polímero, respectivamente. Para las dos mezclas el rango de temperatura de compactación fue de 150 a 155°C. En total, fueron realizadas 30 briquetas correspondiente a 5 contenidos de asfalto, 2 tipos de mezclas y 3 repeticiones por cada ensayo.

A partir de la fabricación de las briquetas se determinó la composición volumétrica, es decir: vacíos con aire Va; Vacíos en el Agregado Mineral VAM y Vacíos llenos de Asfalto VFA. Luego fueron sometidas en una prensa tipo Marshall a la acción de carga monotónica utilizando una velocidad de 48 mm/minuto hasta la falla. Se determino la Estabilidad, Flujo y relación E/F Marshall sobre briquetas previamente acondicionadas a temperatura de 60 °C durante un tiempo de 35 minutos. Según los protocolos de FAA AC 150/5370, el contenido óptimo de asfalto se definió para Va de 3.5%. A partir de ese valor, se fueron fabricadas briquetas para analizar el desempeño mecánico de las mezclas.

2.3 Caracterización mecánica

2.3.1 Resistencia a la tracción indirecta

Se realizó el ensayo de resistencia a la tracción indirecta RTI según la norma de ensayos INVIAS 725 2013 en condiciones secas y húmedas a fin de analizar la susceptibilidad al agua. las briquetas fueron sometidas a la acción de carga monotónica aplicando una velocidad de deformación de 50 mm/minutos hasta la falla. RTI se calculó con la Ecuación 1, donde P es la carga máxima de ruptura en N, d y h corresponde al diámetro y la altura en mm, respectivamente. Previamente, en condiciones secas las briquetas fueron sometidas a 25 °C durante 1 hora. En condiciones húmedas, las briquetas fueron sometidas a 60 °C en baño María por 24 horas, luego a 25 °C durante 2 horas. La susceptibilidad al agua fue determinada con la Ecuación 2, donde RRTI corresponde a la relación de resistencia a la tracción indirecta, RTIs y RTIh son los resultados de los ensayos en condiciones secas y húmedas, respectivamente. En este estudio las mezclas fueron compactadas con Va entre 3.5+0.2%, dado que el objetivo era evaluar el desempeño de mezclas según los lineamientos FAA AC 150/5370 [9].

$$RTI = \frac{2000.P}{\pi.d.h} \tag{1}$$

$$RRTI = \frac{RTI_h}{RTI_s}100 \tag{2}$$

2.3.2 Ensayo de módulo resiliente y resistencia a la fatiga

Ensayos de caracterización dinámica fueron realizados en una máquina Universal UTM-30. El ensayo de Módulo resiliente por compresión diametral sobre briquetas tipo Marshall se realizó según la norma de ensayo INVIAS 749 2013. Las briquetas fueron sometidas a la aplicación de 100 ciclos de carga de 1200 N asumiendo un coeficiente de Poisson de 0.3. Se utilizaron frecuencias de carga de 2.5 Hz, 5.0 Hz y 10 Hz a temperatura de 20 °C. Los valores obtenidos corresponden al promedio de tres briquetas. El ensayo de fatiga por compresión diametral (esfuerzo controlado) se realizó a 20 ºC empleando carga cíclica (450 kPa) a una frecuencia de 2.5 Hz hasta la falla. Se emplearon 5 muestras por cada tipo de mezcla, a fin de obtener un valor promedio, dada la dispersión del ensayo.

2.3.3 Ensayo de fluencia estática

El ensayo de fluencia estático se realizó según el reporte 465 de Programa de Cooperación Nacional de Carreteras de Estados Unidos NCHRP 2002, por sus siglas en ingles National Cooperative Highway Research Program [27] Para tal fin fue empleada una carga estática de 100 kPa sobre una cara de la briqueta tipo Marshall por 3600 segundos a una temperatura de 20°C. Durante la aplicación del ensayo se determinaron los desplazamientos verticales axiales que experimentó la muestras en dos extremos. Los resultados presentados corresponden al promedio de 3 briquetas por cada tipo de mezcla. Se determinó la velocidad de deformación (vd) en µm/minuto conforme la Ecuación 3, donde dt2 y dt1 corresponden a los desplazamientos verticales presentados en los tiempos 1800 (t1) y 3600 (t2), respectivamente. Los resultados presentados corresponden al promedio de tres briquetas.

$$Vd = \frac{d_{t2} - d_{t1}}{t_2 - t_1} \tag{3}$$

2.3.4 Ensayo Catabro

En ensayo cantabro se realizó con el objetivo de evaluar la durabilidad de mezclas asfálticas. A pesar de ser un ensayo que se realiza para el diseño de mezclas asfálticas drenantes, puede proporcionar un indicador de la durabilidad de las mezclas densas ante desprendimientos de agregados. Para tal fin, cada una de las briquetas fue sometida a 300 giros en la Máquina de Los Ángeles (sin esferas). Como resultado es obtenido el desgaste a la abrasión (D) conforme la Ecuación 4. Donde mi y mf corresponde a la masa inicial y final antes y después del ensayo, respectivamente. Los resultados presentados corresponden al promedio de tres briquetas.

$$D = \frac{m_i - m_f}{m_i}.100 \tag{4}$$

2.4 Análisis estadísticos ANOVA

Se realizaron análisis estadísticos ANOVA a fin de comparar si las variaciones en los resultados son significativas. Para tal fin, se estableció un nivel de confiabilidad de 95%.

3 Resultados

3.1 Ensayo Marshall

Resultados del diseño Marshall para las mezclas MDC P401 se presentan en la Fig. 2.

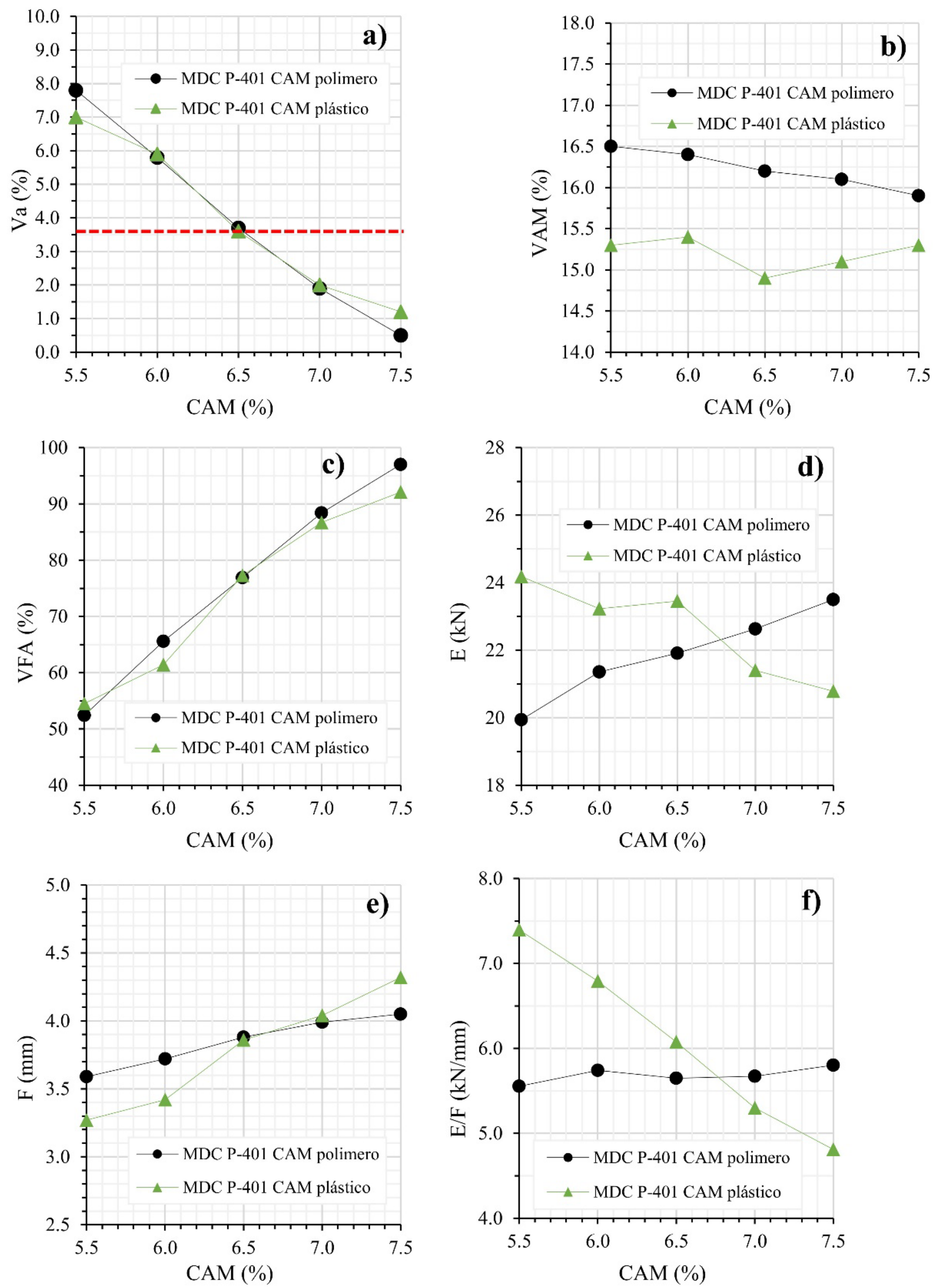

Figura 2. Resultados del diseño de mezclas MDC P-401 con CAM polímero y plástico: a) Va; b) VAM; c) VFA; d) E; e) F; f) E/F Marshall.
Fuente: Autores.

Las evoluciones de Va y VFA para los contenidos de CAM son similares para las dos mezclas, lo cual indica que existen el mismo recubrimiento de las partículas en la MDC P401 al emplear CAM modificado con polímero con residuos plásticos tipo PET. Sin embargo, la mezcla con CAM polímero presenta aumento de VAM en aproximadamente 1% para todos los contenidos de CAM evaluados. Lo anterior, puede indicar que existe un leve incremento de la lámina de recubrimiento del agregado con CAM al emplear polímero. En ambos casos, las mezclas asfálticas cumplen con el valor mínimo establecido en la FAA AC 150/5370 2018 de 15%. En términos de los parámetros de resistencia ante carga monotónica, para 6.5% de CAM se evidencia que la MDC P 401 CAM plástico experimentó un aumento en aproximadamente 7% y 9% de E y rigidez Marshall (E/F), en referencia a la MDC P 401 CAM polímero. Lo anterior, indica que el uso de residuos plásticos puede mejorar levemente la resistencia a la acción de carga monotónica a temperatura de 60°C, es decir, puede contribuir a mejorar la resistencia a la deformación permanente en pavimentos sometidos a climas cálidos. Basados en los lineamientos FAA AC 150/5370 2018 para Va de 3.5%, se estableció que el contenido óptimo de asfalto para la MDC P-401 con CAM modificado con polímero y plástico corresponde a 6.6%.

3.1 Ensayo de tensión indirecta RTI

En la Figura 3 se presentan los resultados de RTI en condiciones secas, húmedas y RRTI para las mezclas MDC P-401 con CAM polímero y plástico.

De forma general, los resultados indican que la MDC P-401 CAM polímero experimentó mayor RTI en condiciones secas y húmedas. Sin embargo, análisis ANOVA reportaron que esas variaciones no son significativas para las condiciones secas (F_o=3.00 < $F_{0.05}$=7.71) y húmedas (F_o=0.88 < $F_{0.05}$=7.71). Lo anterior permite deducir que los valores de RTI son similares, lo cual puede ser explicado por tener el mismo contenido de CAM y la misma composición volumétrica (Va y VFA). Resultados similares se determinaron al analizar la susceptibilidad mediante RRTI. Es decir, el uso de CAM modificado con plástico no afecta la adherencia y susceptibilidad al agua de la mezcla. Adicionalmente, los valores de RRTI cumplen con el valor mínimo establecido por FAA AC 150/5370 de 80% [9].

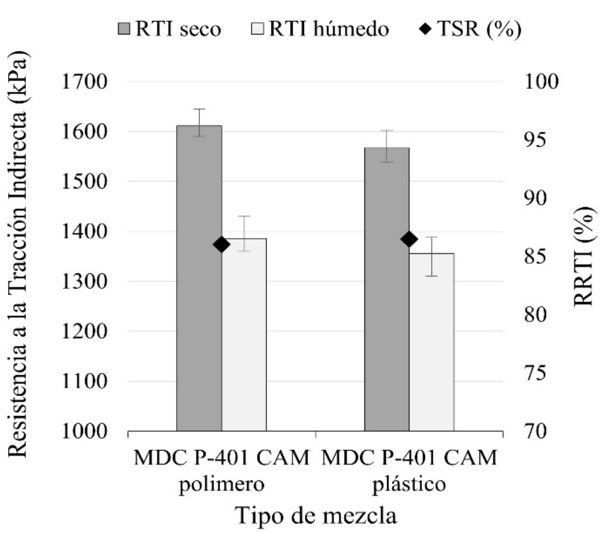

Figura 3. Resultados de ensayos de tensión indirecta.
Fuente: Autores.

3.2 Ensayo de módulo resiliente

En la Figura 4 se presentan los resultados de módulo resiliente para las dos mezclas de estudio a frecuencias de 2.5, 5.0 y 10 Hz a 20°C. De forma general, la MDC P-401 CAM polímero experimentó mayor módulo resiliente para todas las frecuencias analizadas. Resultados ANOVA indican que para las frecuencias de 2.5 y 5.0 Hz no se presentan variaciones significativas entre las dos muestras, dado que Fo=3.35 < F0.05=7.71 y Fo=4.64 < F0.05=7.71, respectivamente. Sin embargo, para frecuencia de 10 Hz las variaciones son significativas Fo=22.24 < F0.05=7.71. Lo anterior indica que la presencia del polímero genera mayor rigidez en la mezcla ante la acción carga repetida cíclica a 10 Hz.

3.3 Ensayo de resistencia a fatiga

En la Figura 5 se exponen los resultados de la resistencia a la fatiga a esfuerzo controlado de 450 kPa.

Los resultados indican que la MDC P-401 CAM polímero experimentó un leve aumento de ciclos hasta de ruptura. Estos resultados son coherentes con los obtenidos en los ensayos de tensión indirecta ante carga monotónica (RTI) y carga repetida cíclica (módulo resiliente). Sin embargo, análisis ANOVA indican que las variaciones de los resultados de las dos mezclas no son significativas (F_o=0.29 < $F_{0.05}$=5.31). Lo anterior indica que la incorporación de los residuos plásticos como material alternativo para CAM no reduce la resistencia al agrietamiento en mezclas asfálticas.

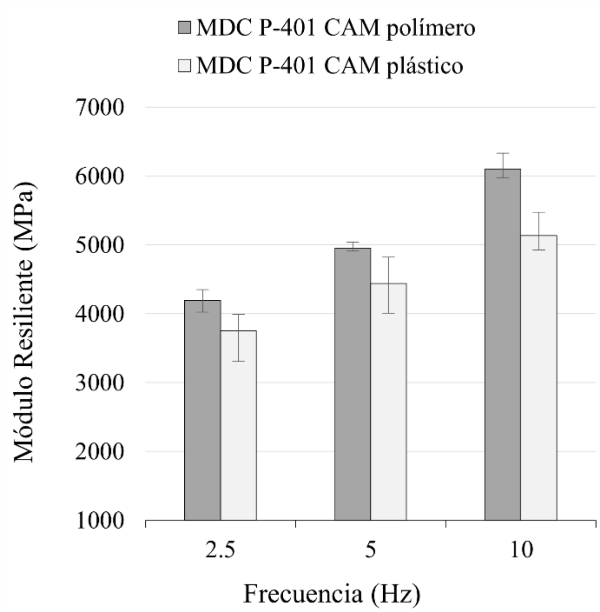

Figura 4. Resultados de ensayos de Módulo Resiliente.
Fuente: Autores.

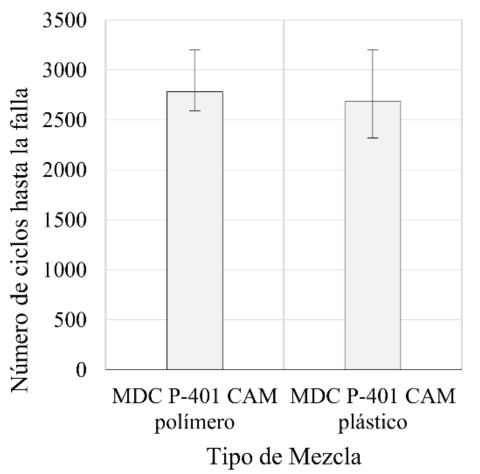

Figura 5. Resultados de ensayos de tensión indirecta.
Fuente: Autores.

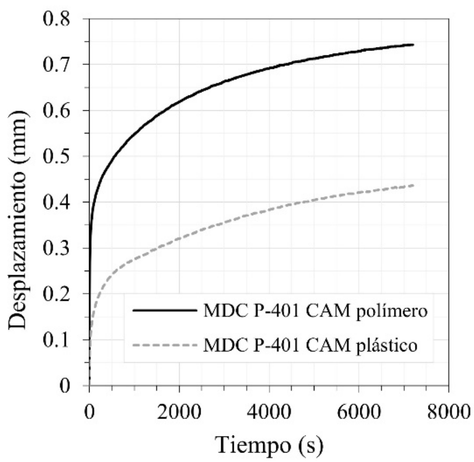

Figura 6. Resultados de ensayos de fluencia estática.
Fuente: Autores.

3.4 Ensayo de fluencia estática

En la Fig. 6 se presentan los resultados del ensayo de fluencia estática para las dos mezclas de estudio.

A partir de los resultados, es posible evidenciar que las briquetas tipo MDC P-401 polímero experimentaron mayor deformación vertical durante el ensayo, lo cual puede indicar menor resistencia a la deformación permanente en referencia a las mezclas con plástico. Lo anterior, también es evidenciado con la velocidad de deformación, dado que la MDC P-401 CAM polímero y con plástico experimentaron valores de 2.267 µm/minuto y 2.067 µm/minuto. Lo anterior indica que la presencia del plástico tipo PET puede mejorar el comportamiento de la mezcla al ser sometida ante carga de compresión. Estos resultados son coherentes con los obtenidos en el ensayo Marshall, donde también se evidenció incremento de E y E/F ante la acción de carga monotónica a compresión.

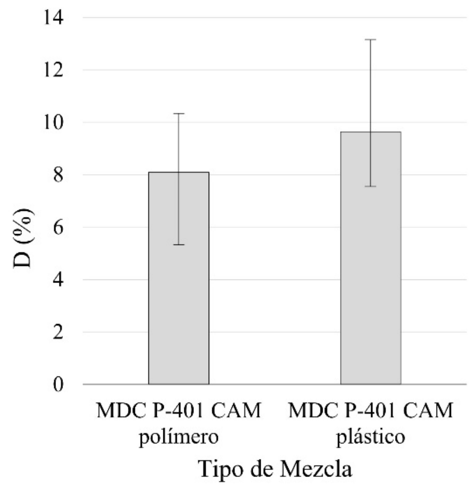

Figura 7. Resultados del ensayo cantabro.
Fuente: Autores.

3.5 Ensayo cantabro

En la Figura 7 se presentan los resultados del ensayo cantabro realizado sobre las mezclas MDC P-401 CAM polímero y plástico. Los resultados muestran que existe aumento en el desgaste a la abrasión en la MDC P-401 CAM plástico, lo cual indica mayor desprendimiento de las partículas durante el ensayo, pudiendo afectar la durabilidad de la mezcla. Estos resultados son coherentes con los evidenciados en los ensayos RTI, RRTI, módulo resiliente y resistencia a la fatiga, donde las briquetas MDC P-401 CAM plástico experimentaron una leve reducción de sus valores en comparación a MDC P-401 plástico. Sin embargo, los análisis estadísticos ANOVA reportan $F_o=0.46 < F_{0.05}=7.70$, lo cual indica que las diferencias entre los ensayos no son significativas.

4 Conclusiones

El objetivo de este estudio fue evaluar el desempeño físico-mecánico de dos mezclas asfálticas tipo P-401 fabricadas con asfalto modificado con residuos de plástico y polímero a fin de ser empleadas para la construcción de capas de pavimentos de aeropuertos. A partir de los ensayos realizados, es posible concluir que:

La utilización de CAM plástico en el diseño de una mezcla tipo MDC P-401 generó el mismo contenido óptimo de asfalto, volumen de vacíos y vacíos llenos de asfalto que la mezcla fabricada con CAM polímero. Adicionalmente, mejoró la resistencia ante la acción de carga monotónica, definido por la estabilidad y rigidez Marshall (E/F). Lo anterior originó incremento de la resistencia a la deformación permanente mediante el ensayo de fluencia estática.}

La MDC P-401 plástico experimentó leve reducción de la resistencia a la tensión indirecta ante carga monotónica y cíclica repetida (módulo resiliente y resistencia a la fatiga). Adicionalmente, se evidenció un leve aumento en el desgaste cantabro. Sin embargo, análisis estadísticos indican que esas variaciones no son significativas. Por lo anterior, el uso del CAM plástico no afecta el desempeño físico mecánico y la durabilidad de la mezcla asfáltica para aeropuertos.

El uso de residuos plásticos tipo PET puede ser viable desde el punto de vista técnico, ambiental, social y económico por permitir la incorporación de materiales reciclados en la fabricación de mezclas de concreto asfáltico para capas de pavimentos aeroportuarios. Adicionalmente, promover prácticas de reciclaje para buscar la disposición final y segura ambientalmente de residuos sólidos. Mayores estudios se deben realizar con el objetivo de mejorar la adherencia entre el asfalto y el plástico, a fin de incrementar la resistencia a tensión (p.e. Uso de promotores de adherencia, pretratamientos al residuo plástico, entre otros). Asimismo, se debe validar lo hallazgos encontrados en este estudio a mediana y gran escala mediante ensayos de campo y laboratorio. Adicionalmente, se recomienda evaluar diferentes fuentes de agregados, materiales asfalticos y tipos de granulometrías.

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Diseño de sistema de diagnóstico de enfermedades auditivas asistido por inteligencia artificial (IA)

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Abstract
Audiometry, a crucial technique in hearing evaluation, has been instrumental in diagnosing hearing-related disorders. However, its usefulness has been limited due to the lack of research and innovation in this field. For this reason, we have proposed the design of a portable audiometry system, based on artificial intelligence (IA) parameters, which will provide a pre-diagnosis, with the aim of expanding access to certain vulnerable populations. This design is based on a thorough analysis of the challenges and opportunities associated with the implementation of such a system. In addition to the conceptual design phase, a detailed review of the current landscape of applications of audiometry as a diagnostic method was conducted. This approach encompassed the exploration and presentation of a comprehensive notion, as well as a strategic approach that involved an in-depth analysis of various aspects related to feasibility.

Keywords: audiometry; frequency; intensity; masking.

Design of a system for diagnosis of auditory diseases assisted by artificial intelligence (AI)

Resumen
La audiometría, una técnica crucial en la evaluación auditiva, ha sido fundamental para diagnosticar trastornos relacionados con la audición. Sin embargo, su utilidad se ha visto limitada debido a la falta de investigación e innovación en este campo. Por esta razón, se ha propuesto el diseño de un sistema de audiometría portátil, basado en parámetros de inteligencia artificial (IA), que proporcionará un prediagnóstico, con el objetivo de ampliar el acceso a ciertas poblaciones vulnerables. Este diseño se fundamenta en un análisis exhaustivo de los desafíos y oportunidades asociados con la implementación de dicho sistema. Además de la fase de diseño conceptual, se llevó a cabo una revisión detallada del panorama actual de las aplicaciones de la audiometría como método diagnóstico. Este enfoque abarcó la exploración y presentación de una noción completa, así como un planteamiento estratégico que involucró un análisis profundo de diversos aspectos relacionados con la viabilidad.

Palabras clave: audiometría; frecuencia; intensidad; enmascaramiento.

1. Introducción

La audiometría es crucial para el diagnóstico auditivo, pero enfrenta limitaciones debido a la necesidad de equipos especializados y personal capacitado, lo que resulta costoso y difícil en entornos con recursos limitados. Además, ha habido poca investigación y desarrollo en este campo en comparación con otras tecnologías médicas. Por ello, desarrollar un sistema de audiometría portátil y autónomo surge como una solución efectiva para superar estas barreras, democratizando el acceso a este importante examen auditivo. Este avance no solo amplía la disponibilidad de la audiometría, sino que también reduce significativamente las barreras económicas y logísticas asociadas con la necesidad de equipos y personal altamente especializado; también como herramienta para potenciar la calidad de vida de aquellos afectados por problemas de audición. De acuerdo con la Encuesta Nacional de Calidad de Vida realizada por el DANE, para el año 2021 en Colombia 459.784 personas se autocalifican como una persona con algún nivel de discapacidad auditiva. ante esto cabe recalcar ciertas patologías que más relación tienen en la pérdida auditiva

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como la otosclerosis que llega afectar alrededor de tres millones de personas en estados unidos [2] y el neuroma acústico que es una enfermedad progresiva que afecta a 1 de cada 100000 personas en el mundo [3]. El diseño y desarrollo de un sistema de audiometría portátil exige un enfoque multidisciplinario y meticuloso. Requiere la integración de tecnologías de detección y procesamiento de señales de audio de alta precisión, así como la implementación de algoritmos y técnicas de análisis avanzadas. Es imperativo que este sistema garantice resultados fiables y precisos, equivalentes a los obtenidos mediante equipos convencionales. Además, la portabilidad del sistema abre nuevas posibilidades en términos de alcance y aplicación. No solo se contempla su implementación en entornos clínicos, sino también su utilización en ambientes comunitarios, entornos escolares y en el campo de la telemedicina. Este avance tiene el potencial de revolucionar la forma en que se aborda el diagnóstico de trastornos auditivos, al permitir una detección temprana y un monitoreo más frecuente y accesible. Bajo esta primicia el objetivo general de este proyecto es desarrollar un sistema de audiometría portátil que sea viable y realista, con el fin de mejorar el acceso a la audiometría y la calidad de vida de las personas con problemas de audición. Para lograrlo, se plantean realizar una revisión literaria para evaluar la funcionalidad y aplicaciones de la técnica en diversos escenarios, diseñar una interfaz de usuario amigable basada en un sistema de evaluación por parámetros mediante IA, y crear un asistente basado en una API para brindar seguimiento y asesoramiento a los pacientes después de un examen. Ante esto es necesario hacer un hincapié el cuadro clínico para comprender de mejor manera ciertas patologías que se pueden diagnosticar con la audiometría, para saber el impacto que puede tener sobra la vida de las personas que padecen dichas enfermedades un diagnóstico temprano y oportuno.

1.1 Cuadro clínico (neuroma acústico)

Un neuroma acústico, o "schwannoma vestibular," es un tumor benigno y de crecimiento lento que rodea el nervio vestibular que se extiende desde el oído interno hasta el cerebro [4]. Para diagnosticarlo, se puede usar un audiograma, donde un audiólogo presenta sonidos de diversos tonos al paciente, quien indica cuándo los escucha [5]. Los factores de riesgo incluyen la neurofibromatosis tipo 2, que causa tumores benignos en los nervios de equilibrio y audición tanto en la cabeza como en otros nervios. Las complicaciones del neuroma acústico incluyen pérdida auditiva, problemas de equilibrio y tinnitus [6].

1.2 Cuadro clínico (otosclerosis)

La otosclerosis es una enfermedad del oído caracterizada por el crecimiento anormal de hueso en el oído medio. Esto puede afectar la movilidad de los huesecillos del oído (martillo, yunque y estribo), lo que a su vez puede conducir a la pérdida auditiva. Esta enfermedad puede causar una disminución gradual de la capacidad auditiva y, en algunos casos, puede provocar sordera. Los síntomas incluyen pérdida auditiva progresiva, zumbidos en los oídos (tinnitus) y, en algunos casos, mareos. La resonancia magnética puede ser un método de diagnóstico de la otosclerosis, pero al ser más complejo su tecnología, implementación y el personal que requiere para su funcionamiento suele ser con bastante diferencia más caro que otras alternativas de diagnóstico [8].

2.1.1 Análisis de diagnóstico por RM (otoesclerosis)

El estudio imagenológico es necesario cuando el cuadro clínico no es evidente y para excluir otras enfermedades que puedan parecer otosclerosis. Además, proporciona un detalle anatómico del oído útil para futuros tratamientos. Los hallazgos incluyen un foco lítico (destrucción de un área de un hueso debida a una enfermedad) en la esquina superior de la ventana oval como signo temprano de la enfermedad, que luego se extiende alrededor de las ventanas oval, en la fase crónica, aparecen zonas de calcificación. La otosclerosis fenestral obliterante es la obliteración completa de la ventana oval; Si el estudio imagenológico es negativo se debe evaluar la cadena de huesecillos para descartar lesiones congénitas o un proceso inflamatorio que explique la hipoacusia de conducción (lesiones impiden que el sonido sea conducido de manera eficaz al oído interno). Se ha demostrado que la resonancia magnética (RM) es menos sensible que la tomografía computarizada (TAC) en estos escenarios. La RM es útil para evaluar la permeabilidad de la cóclea antes de un implante coclear, aunque no es el método diagnóstico convencional. Durante el seguimiento postoperatorio, se puede usar TCMD o RM según la sospecha clínica [8]. Para personas con otosclerosis, los implantes cocleares son comunes, pero las RM pueden causar desplazamiento del dispositivo debido a los campos magnéticos intensos, lo que podría requerir cirugía para corregirlo. Por esto, el audiograma es una opción inicial factible y debe ser profundizada como técnica.

1.3 Audiograma

Un audiograma funciona como una gráfica que representa la capacidad auditiva de un individuo. En ella se muestran los niveles mínimos de sonido (umbrales) que la persona puede detectar en diferentes frecuencias. El umbral de audición marca el límite inferior de intensidad sonora que una persona puede percibir. A partir de este punto, los sonidos más suaves se vuelven inaudibles. El audiograma se crea a partir de los resultados de una prueba de tonos puros, también conocida como audiometría de tonos puros, que mide la capacidad auditiva a frecuencias específicas [11].

El audiograma se compone de dos ejes principales: el vertical y el horizontal. El eje vertical representa la intensidad del sonido, medida en decibelios (dB). Cuanto más abajo se ubique un punto en este eje, mayor será la intensidad del sonido, similar a subir el volumen de un dispositivo. En el extremo superior del eje se encuentra el decibelio cero, que representa el sonido más suave que el oído humano promedio puede detectar. el eje horizontal representa la frecuencia del sonido, medida en hercios (Hz). Esta frecuencia aumenta progresivamente a medida que se avanza hacia la derecha del eje. Las frecuencias más bajas se encuentran en el lado izquierdo del audiograma, mientras que las más altas se sitúan en el lado derecho.

1.3.1 Interpretación de resultados pacientes con afecciones auditivas

En la interpretación de una audiometría se deben considerar variables como los umbrales auditivos para medir la función auditiva del paciente, comparando umbrales de ambas vías auditivas. Las gráficas de audiometría muestran frecuencias en el eje horizontal e intensidad en el eje vertical, formando la curva audiométrica. Las hipoacusias se clasifican según su localización anatómica:

Hipoacusias de transmisión: Problemas en la transmisión del sonido desde el oído externo al interno, afectando principalmente el oído medio. En la audiometría, la vía ósea es horizontal (0-20 dB) y la vía aérea desciende más de 30 dB en tres o más frecuencias consecutivas [8].

Hipoacusias neurosensoriales: Pérdida auditiva en el oído interno o en las vías nerviosas hacia el cerebro, ya sea congénita o adquirida. En la audiometría, ambas curvas (ósea y aérea) permanecen juntas y paralelas, pero la vía ósea desciende por debajo de los 20 dB.

Para enriquecer la credibilidad y comprensión de la audiometría, es esencial explorar su trayectoria histórica y resaltar su utilidad a lo largo del tiempo. A continuación, se presentan antecedentes que ilustran la versatilidad y relevancia de esta técnica en el ámbito de la salud auditiva:

1.4 Antecedentes

En 2013, un estudio del ISSSTE evaluó la efectividad del audiograma prequirúrgico en pacientes programados para cirugía del estribo por otosclerosis. La audiometría generalmente revela hipoacusia conductiva, clave para el diagnóstico. A medida que la enfermedad avanza, se observa una creciente separación entre la vía aérea y la vía ósea, especialmente en bajas frecuencias, con un GAP aéreo-óseo que puede llegar a 50 dB. El "nicho de Carhart" es una caída en la conducción ósea a 2 kHz, indicativo de otosclerosis. La audiometría confirma hipoacusia conductiva o mixta, determina el grado de lesión coclear y la amplitud del Rinne audiométrico, influenciando la posibilidad de recuperación tras la cirugía. El tratamiento es principalmente quirúrgico y es exitoso en 75-90% de los casos, logrando un cierre de 10 dB [11].

Los resultados del estudio mostraron las siguientes curvas audiométricas prequirúrgicas: 161 tipo Bezold, 83 con nicho de Carhart, 37 tipo Lermoyes y 4 tipo Manasse. El GAP prequirúrgico fue de 34.2 dB en el oído derecho (15-60 dB) y de 23 dB en el izquierdo (15-50 dB). Hubo mejoría de la vía ósea en 13 casos (6.4%). Las características de los pacientes, la experiencia quirúrgica y los hallazgos intraoperatorios son factores clave en los resultados audiométricos. Se recomienda realizar el procedimiento de manera bilateral, ya que la audición biaural mejora la localización espacial de los sonidos y la extracción de señales en ambientes ruidosos.

VirtualEar, un sistema diseñado por la Escuela de Ingeniería de Antioquía en 2006 sobre la plataforma LabVIEW 7.1, realiza evaluaciones de la capacidad auditiva. Para ello, emplea una prueba de audiometría aérea con enmascaramiento, la cual permite detectar la audición cruzada. Esta prueba utiliza tonos puros en frecuencias audibles (de 125 Hz a 8000 Hz) y una intensidad de presión sonora variable que va desde 0 dB hasta 110 dB,el enmascaramiento envía ruido blanco al oído opuesto del evaluado. Los umbrales de presión sonora mínima son detectados por VirtualEar permiten la creación y el almacenamiento de información en tablas, gráficos y reportes, así como la gestión de los archivos de cada paciente y la impresión de los resultados [12].

El sistema de control y funcionamiento del audiómetro VirtualEar permite que el operario del equipo vea las variables de frecuencia e intensidad de cualquier sonido que se emita durante la prueba.

En 2017, la Sociedad Gallega de Otorrinolaringología (SCORL) presentó un estudio sobre casos de sordera neurosensorial en niños con anemia hemolítica. A través de audiometrías, se reveló sordera neurosensorial bilateral en cada paciente. Un caso específico de un niño de 4 años mostró una "curva en forma de barco" en su audiograma. Los potenciales evocados auditivos del tronco cerebral (PEATC) demostraron una onda V de hasta 60 dB en el oído derecho y hasta 80 dB en el izquierdo. El paciente fue rehabilitado con audífonos convencionales en ambos oídos, lo que mejoró su desarrollo del lenguaje y comportamiento [13].

Tabla 1
Ventaja y desventajas de la audiometría

Ventajas	Desventajas
Una de las principales ventajas de digitalizar una audiometría es el ahorro de costes, utilizando las soluciones TIC, ya que resulta ser una solución más productiva, económica y segura.	Al no tratarse de una prueba auditiva peligrosa, no se conocen riesgos que puedan afectar directamente a la salud del oído del paciente
Someterse a revisiones auditivas, es que éstas ayudan a Detectar la Pérdida Auditiva. Al ser capaz de diagnosticarse de manera precoz, se puede frenar su avance a tiempo y mantener una pérdida de audición leve sin que llegue a ser pronunciada.	Posible es un mal diagnóstico, por eso se recomienda acudir siempre a un especialista en la salud auditiva para que delimite con garantías los resultados de dichas pruebas
Permiten hacer un Seguimiento más exhaustivo de la Capacidad Auditiva de cada persona. A partir de los 50 años, inevitablemente ésta comienza a mermar	Al ser un dispositivo de bajo riesgo el mantenimiento suele ser poco frecuente por lo que la variación del porcentaje de error en cada prueba puede variar
La obtención de datos consolidados en Formato digital, fácilmente transmisibles a otros dispositivos y conectados a internet, que permite poder consultarlos cuando se desee	Es susceptible a interferencias del exterior por lo que debe realizarse bajo ciertos estándares clínicos
Mejoran la eficiencia y productividad del personal sanitario. Por esta razón, es recomendable que el especialista trabaje con un dispositivo que permita la realización	Al no tratarse de una prueba más invasiva o que permita al operador indagar más a fondo en el sistema auditivo es una primera opción para el diagnóstico de enfermedades auditivas, pero tampoco la definitiva

Fuente: Autoría propia

Después de llevar a cabo una revisión exhaustiva del estado actual de la audiometría, se procedió a realizar una evaluación detallada, revisando tanto sus ventajas como sus limitaciones. A continuación, se presenta un resumen de estos aspectos, como se observa en la Tabla 1.

2. Métodos

Para implementar una red neuronal, es esencial contar con una base de datos para su entrenamiento. Dado que no se disponía de una base de datos de audiometría, se diseñó un código en Matlab para simular una utilizando patrones de distintos tipos de hipoacusia proporcionados por el acta de otorrinolaringología gallega [8].

- **Parámetros Generales:** Se establecen el número total de pacientes (num_pacientes) y una lista de frecuencias auditivas en Hz (frecuencias).
- **Inicialización de la Matriz de Datos:** Se crea una matriz base_de_datos para almacenar los datos de los audiogramas, inicializada con ceros y con dimensiones (num_pacientes, longitud de frecuencias).
- **Inicialización de la Matriz de Estado de Audición:** Se crea una matriz de celdas estado_audicion para almacenar el estado de audición de cada paciente.
- **Simulación de Audiogramas para Cada Paciente**: Se utiliza un bucle for para iterar sobre cada paciente, generando aleatoriamente diferentes tipos de hipoacusia y ajustando los umbrales auditivos en función de estos tipos. Los umbrales se almacenan en base_de_datos y el estado de audición en estado_audicion.
- **Creación de una Tabla de Datos:** Se convierten los nombres de las frecuencias auditivas en una matriz de caracteres y se crea una tabla de datos (tabla_datos) utilizando la matriz de audiogramas y la matriz de estado de audición, agregando una columna adicional para el estado de audición.
- **Guardado de la Tabla en un Archivo Excel**: Se guarda la tabla de datos en un archivo Excel con el nombre especificado en la variable nombre_archivo.

Luego de ya tener la base de datos por medio del código anteriormente expuesto, es necesario el diseño de un modelo de red neuronal utilizando TensorFlow y Keras esto en el lenguaje de programación Python, para clasificar tipos de audición basados en datos de audiogramas simulados.

- **Importación de Bibliotecas:** Se importan las bibliotecas necesarias como NumPy, Pandas, TensorFlow y otras relacionadas.
- **Carga de Datos:** Se carga un conjunto de datos desde un archivo Excel llamado 'audiogramas_simulados_con_tipos_corregido.xlsx' utilizando pd.read_excel() de Pandas.
- **Diseño del Modelo con Keras:**Se añade una capa densa con 10 neuronas y activación 'relu', que espera una entrada de tamaño 6 (el número de características de los datos).La capa de salida tiene 3 neuronas con activación 'softmax', correspondiente a las tres clases de tipos de audición.
- **Compilación del Modelo:** Se compila el modelo especificando la función de pérdida categorical_crossentropy, el optimizador adam y la métrica accuracy.
- **Entrenamiento del Modelo:** Se entrena el modelo con el método fit(), especificando el conjunto de entrenamiento, número de épocas, tamaño del lote, y datos de validación. Se muestra una barra de progreso durante el entrenamiento (verbose=1).
- **Guardado del Modelo:** Una vez entrenado, el modelo se guarda en un archivo 'modelo_audiometria_multiclase2.h5' utilizando el método save() de Keras. Este archivo contiene la arquitectura del modelo, los pesos y configuraciones de entrenamiento.

Este código realiza varias tareas relacionadas con la predicción del tipo de audiometría de un usuario y la generación de recomendaciones personalizadas para mejorar la salud auditiva. Aquí está la explicación detallada del código:

- **Carga del Modelo Entrenado:** Utiliza la función load_model() de Keras para cargar un modelo de clasificación de audiometría preentrenado desde un archivo .h5.
- **Definición de Nuevos Datos de Audiometría:** Crea un DataFrame de Pandas con valores de frecuencia auditiva arbitrarios para un nuevo conjunto de datos de audiometría.
- **Predicción del Tipo de Audiometría:** Utiliza el modelo cargado para predecir el tipo de audiometría basado en los nuevos datos, calculando las probabilidades de cada clase y determinando la clase predicha con np.argmax().
- **Asignación de Nombres a las Clases Predichas:** Asigna un nombre descriptivo a la clase predicha para proporcionar una etiqueta legible del tipo de audiometría.
- **Configuración de la Clave de API de OpenAI:** Establece la clave de API de OpenAI para utilizar los servicios de generación de texto (GPT-4).
- **Definición del Prompt para Generación de Texto:** Crea un prompt con la información del tipo de audiometría predicha para generar recomendaciones personalizadas con GPT-4.
- **Solicitud de Generación de Texto a GPT-4:** Utiliza la función openai. Completion.create() para solicitar a GPT-4 que genere recomendaciones basadas en el prompt definido, especificando el motor (gpt-3.5-turbo) y ajustando el número máximo de tokens.

Tras alcanzar este punto, se ha desarrollado una interfaz gráfica en Python como se puede ver en la Fig. 1, usando la biblioteca Tkinter para facilitar la generación de tonos para audiometrías. Esta interfaz permite ajustar las frecuencias de los tonos según las necesidades del profesional, proporcionando una plataforma intuitiva para seleccionar y ajustar diferentes frecuencias de manera rápida y fácil. Además de generar tonos de diferentes frecuencias, la interfaz puede controlar el volumen de los tonos, la duración de cada prueba auditiva y presentar los resultados de manera clara y concisa.

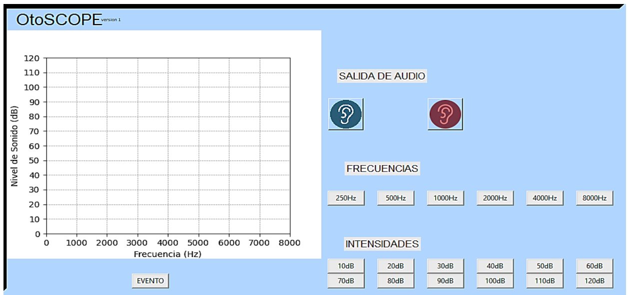

Figura 1. Interfaz de usuario
Fuente. Autoría propia


Figura 2. Adaptador RCA A BNC
Fuente. Autoría propia

Para evaluar la funcionalidad de la interfaz en la generación de tonos en diversas frecuencias, se empleó un osciloscopio TEKTRONIX tbs1102b-edu como se evidencia en la Fig. 3, para visualizar las señales resultantes. Además, se utilizó un adaptador RCA a BNC como se puede observar en la Fig. 2, para garantizar una señal más limpia, evitando la necesidad de utilizar un dispositivo embebido adicional

También se dispuso de realizar un análisis de armónicos, Los armónicos de una señal son componentes frecuenciales que tienen una relación entera con la frecuencia fundamental de esa señal. Cuando una onda no es puramente sinusoidal, sino que tiene formas de onda más complejas, como cuadradas o triangulares, se generan armónicos. Estos armónicos constituyen múltiplos enteros de la frecuencia fundamental. Por ejemplo, si la frecuencia base es 100 Hz, los armónicos serán a 200 Hz (2º armónico), 300 Hz (3º armónico), 400 Hz (4º armónico), y así sucesivamente. Los armónicos pueden ser importantes en diversas aplicaciones, como en la música, la electrónica de potencia y la comunicación, entre otros campos. En música, los armónicos dan forma al timbre de un sonido, mientras que, en electrónica de potencia, pueden causar distorsiones no deseadas en la forma de onda de una señal eléctrica. Para esto se usó el osciloscopio TEKTRONIX tbs1102b-edu, que es capaz de realizar la FFT con cualquier señal.

Posterior a esto se evaluará la capacidad de la IA para predecir el tipo de acucia que tiene el paciente, en tres escenarios como se evidencia Tabla 2 y Tabla 3.

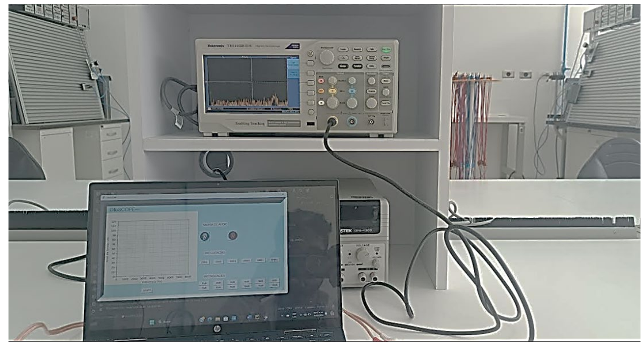
Figura 3. Osciloscopio TEKTRONIX tbs1102b-edu 99B
Fuente. Autoría propia

Tabla 2.
Valores oído izquierdo.

Normoacusia	Hipoacusia de leve transmisión	Hipoacusia moderada neurosensorial
250Hz(10dB)	250Hz(27dB)	250Hz(40dB)
500Hz(15dB)	500Hz(29dB)	500Hz(45dB)
1000Hz(16dB)	1000Hz(30dB)	1000Hz(50dB)
2000Hz(17dB)	2000Hz(37dB)	2000Hz(55dB)
4000Hz(21dB)	4000Hz(22dB)	4000Hz(60dB)
8000Hz(22dB)	8000Hz(28dB)	8000Hz(65dB)

Fuente: Autoría propia.

Tabla 3.
Valores oído derecho.

Normoacusia	Hipoacusia de leve transmisión	Hipoacusia moderada neurosensorial
250Hz(14dB)	250Hz(22dB)	250Hz(22dB)
500Hz(18dB)	500Hz(27dB)	500Hz(34dB)
1000Hz(19dB)	1000Hz(32dB)	1000Hz(37dB)
2000Hz(22dB)	2000Hz(35dB)	2000Hz(42dB)
4000Hz(22dB)	4000Hz(26dB)	4000Hz(55dB)
8000Hz(24dB)	8000Hz(22dB)	8000Hz(70dB)

Fuente: Autoría propia.

Para el caso de la API se copiará únicamente la respuesta dada para cada escenario ya que al ser tan larga no se logra visualizar en la interfaz.

3. Resultados

3.1 Resultados frecuencias y voltajes

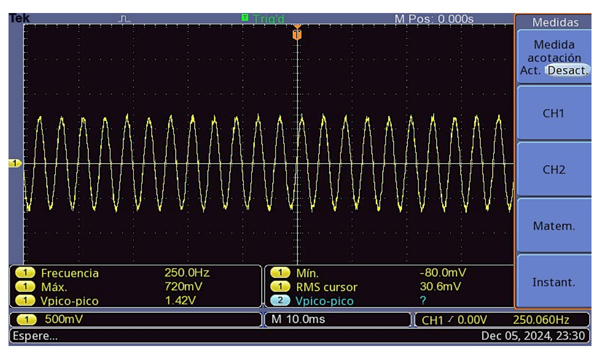

Figura 4. Adquisición de datos 250 Hz
Fuente. Autoría propia

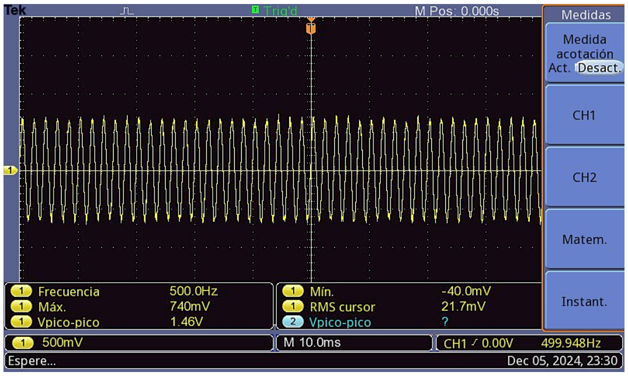

Figura 5. Adquisición de datos 500 Hz
Fuente. Autoría propia

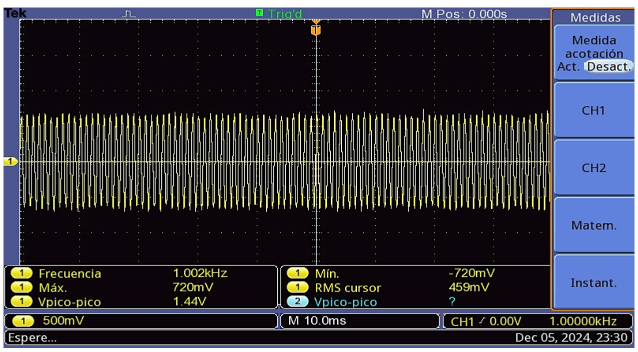

Figura 6. Adquisición de datos 1000 Hz
Fuente. Autoría propia

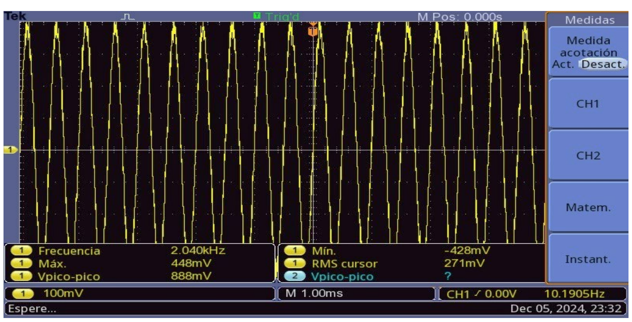

Figura 7. Adquisición de datos 2000 Hz
Fuente. Autoría propia

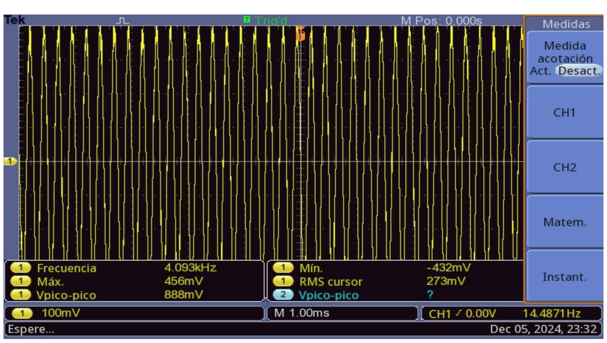

Figura 8. Adquisición de datos 4000 Hz
Fuente. Autoría propia

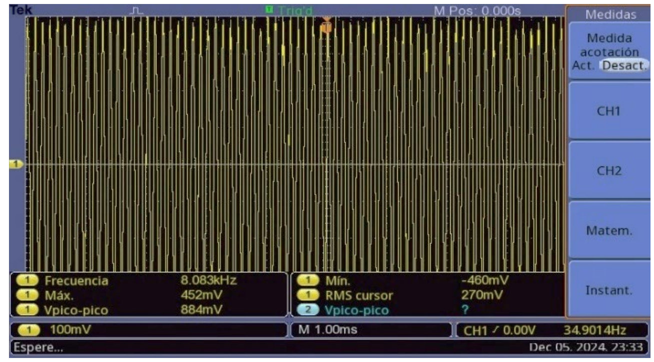

Figura 9. Adquisición de datos 8000 Hz
Fuente. Autoría propia

3.2 Resultados armónicos

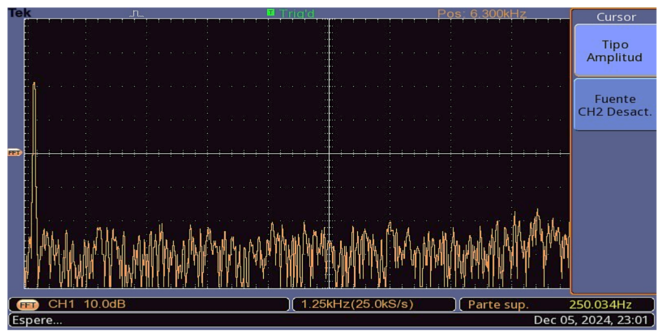

Figura 10. Armónico 250 Hz
Fuente. Autoría propia

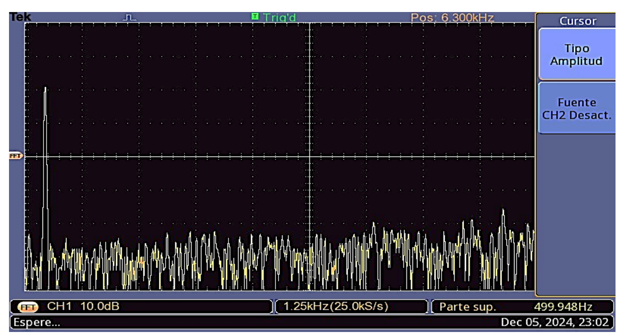

Figura 11. Armónico 500 Hz
Fuente. Autoría propia

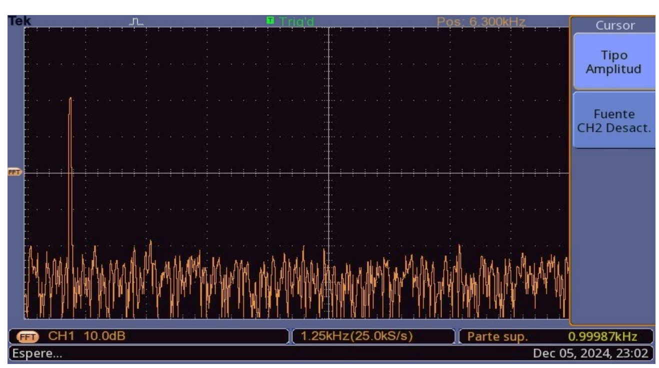

Figura 12. armónico 1000 Hz
Fuente. Autoría propia

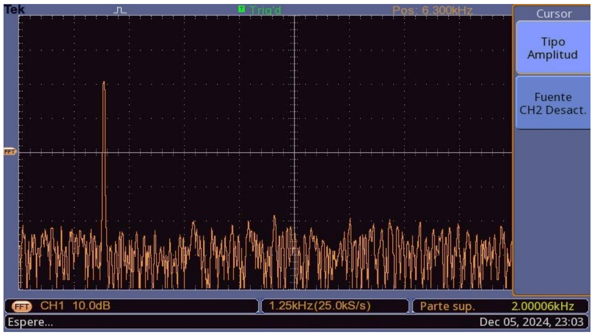

Figura 13. armónico 2000 Hz
Fuente. Autoría propia

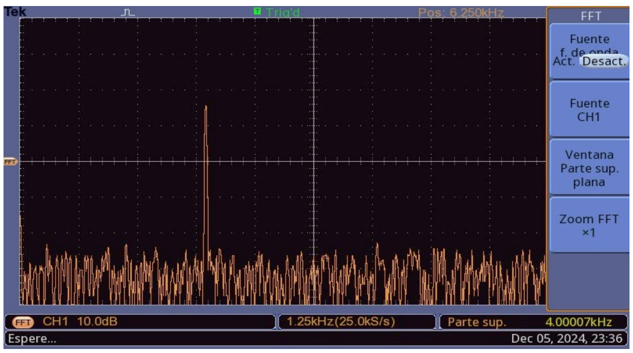

Figura 14. armónico 4000 Hz
Fuente. Autoría propia

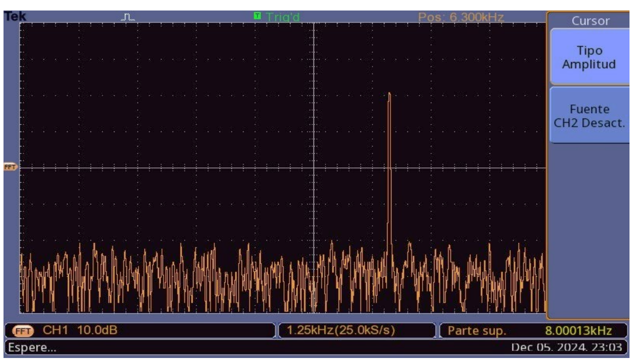

Figura 15. Armónico 8000 Hz
Fuente. Autoría propia

3.3 Resultados diagnostico IA

```
1/1 [==============================] - 0s 83ms/step
Probabilidades de clases: [[9.9999964e-01 4.0277865e-07 3.7065142e-24]]
Clases predichas: [1] normacusia
```

Figura 16. Escenario 1 normoacusia
Fuente. Autoría propia

```
1/1 [==============================] - 0s 75ms/step
Probabilidades de clases: [[3.8720050e-20 1.0000000e+00 5.5434214e-08]]
Clases predichas: [2] Hipoacusia Leve de Transmisión
```

Figura 17 Escenario 2 hipoacusia de leve transmisión
Fuente. Autoría propia

```
1/1 [==============================] - 0s 147ms/step
Probabilidades de clases: [[0.0000000e+00 1.2241879e-04 9.9987757e-01]]
Clases predichas: [3] Hipoacusia Moderada Neurosensorial
```

Figura 18. Escenario 3 hipoacusia moderada neurosensorial
Fuente. Autoría propia

3.4 Resultados API

3.4.1 escenario 1 normacusia

Recommendations APPI=¡Hola! Si has recibido el diagnóstico de normacusia, significa que tu audición se encuentra dentro de los límites normales. ¡Felicidades! Es importante continuar cuidando tu audición para mantenerla en óptimas condiciones a lo largo del tiempo. Aquí tienes algunas recomendaciones para ayudarte a preservar tu salud auditiva:

Protege tus oídos del ruido excesivo: Aunque tu audición esté en buen estado, es importante proteger tus oídos del ruido fuerte y prolongado. Usa protectores auditivos en situaciones ruidosas, como conciertos, eventos deportivos o al trabajar con maquinaria ruidosa.

Mantén un volumen seguro: Al escuchar música con auriculares o en sistemas de sonido, ajusta el volumen a un nivel seguro. Evita escuchar música a un volumen muy alto durante períodos prolongados, ya que esto puede causar daño auditivo con el tiempo.

Hazte chequeos auditivos regulares: Aunque tu audición esté bien en este momento, es importante hacerse chequeos auditivos periódicos. Esto ayuda a detectar cualquier cambio en tu audición de manera temprana y tomar medidas preventivas si es necesario.

3.4.2 escenario 2 hipoacusia de leve transmisión

Recommendations APPI= ¡Hola!, dados los datos del audiograma proporcionados, esta pérdida auditiva parece ser de leve a moderada en las frecuencias de 250 Hz a 4000 Hz, con una pérdida auditiva moderada en la frecuencia de 8000 Hz.Una recomendación inicial sería que este paciente consulte a un otorrinolaringólogo o a un audiólogo para un diagnóstico completo y una evaluación más detallada de su audición. Dependiendo de los resultados de esa evaluación y de los factores individuales del paciente, se podrían explorar opciones de tratamiento como audífonos, terapia auditiva, o intervenciones médicas si es necesario. En resumen, la recomendación sería buscar atención médica especializada para una evaluación completa y un plan de tratamiento personalizado.

3.4.3 escenario 3 hipoacusia neurosensorial

Recommendations APPI=¡Hola! Si has sido diagnosticado con hipoacusia neurosensorial, es importante tomar medidas para proteger tu audición restante y mejorar tu calidad de vida. Aquí tienes algunas recomendaciones para ayudarte a enfrentar los desafíos asociados con esta condición:

- Consulta a un especialista en audición: Es fundamental consultar a un otorrinolaringólogo o a un audiólogo para obtener un diagnóstico preciso y recibir información sobre los tratamientos disponibles.

- Considera el uso de dispositivos auditivos: Los dispositivos auditivos, como los audífonos o los implantes cocleares, pueden mejorar significativamente la calidad de vida y la capacidad auditiva dependiendo del grado de pérdida auditiva. Un audiólogo puede ayudarte a encontrar el dispositivo más adecuado para tus necesidades.
- Aprende técnicas de comunicación: Amplía tus opciones de comunicación para superar las barreras en entornos desafiantes. Explora alternativas como el lenguaje de señas, la lectura de labios o aplicaciones de transcripción en tiempo real, que te permitirán mantener una comunicación fluida incluso en lugares ruidosos o con dificultades auditivas.
- Evita la exposición a ruidos fuertes: La hipoacusia neurosensorial puede hacer que seas más susceptible a los daños por ruido. Por lo tanto, es importante evitar la exposición a ruidos fuertes y utilizar protectores auditivos en situaciones ruidosas para proteger la audición restante.

4. Discusion y conclusiones

Teniendo los resultados anteriores es necesario recalcar como en el apartado de generación de tonos, la interfaz logro generar cada uno de los 6 tonos con gran precisión como se logra observar en las Figs. 4-9, ya que las frecuencias son las que se esperaban en un inicio. Se encontró que las frecuencias utilizadas en la interfaz estaban en general en línea con los estándares reconocidos. En el estudio de los armónicos es necesario recalcar que la señal original es una onda sinusoidal, se identificaron los picos en el espectro de frecuencia correspondientes a los tonos fundamentales y sus armónicos en las frecuencias de interés, la aplicación de la FFT en el análisis de señales de audiometría permitió identificar con precisión los tonos fundamentales y sus armónicos en las frecuencias evaluadas. Los resultados obtenidos proporcionan información valiosa sobre la composición espectral de los tonos audibles en cada frecuencia como se evidencia en las Figs. 10-15, lo que puede ser relevante para la evaluación y diagnóstico de la audición en pacientes. Este enfoque analítico podría ser útil en la calibración y ajuste de audiómetros, así como en la investigación de trastornos auditivos y la evaluación de la eficacia de tratamientos auditivos.

Basándonos en las predicciones proporcionadas por el modelo de IA en los tres escenarios evaluados, el modelo de IA muestra una alta precisión como se logra observar en la Fig. 16 para normoacusia,en la Fig. 17 para hipoacusia de leve transmisión, y en la Fig. 18 para hipoacusia moderada neurosensorial. Sin embargo, es necesario mejorar su entrenamiento y realizar pruebas exhaustivas para validar su utilidad clínica. La robustez del modelo depende de su capacidad para generar predicciones precisas y consistentes en diversas condiciones. Los resultados son prometedores, pero es esencial seguir refinándolo mediante entrenamiento y validación continuos. Para garantizar su fiabilidad en aplicaciones clínicas, se requiere una evaluación exhaustiva en diferentes situaciones clínicas y con diversos conjuntos de datos. Además, es fundamental considerar la interpretación y aplicación ética de las predicciones del modelo en la práctica médica y su incorporación a la toma de decisiones clínicas.

Las recomendaciones proporcionadas por la API demostraron un nivel notable de precisión y utilidad en el contexto evaluado. Sin embargo, es fundamental tener en cuenta ciertos aspectos adicionales que influyen en su implementación efectiva. Es relevante recordar que el acceso y uso de una API conllevan un costo asociado, ya sea en términos de licencias de software, tarifas de suscripción o consumo de recursos computacionales. Por lo tanto, aquellos que consideren integrar esta API en sus sistemas o aplicaciones deben evaluar cuidadosamente cuántos tokens desean generar para obtener respuestas de la misma. Esta consideración financiera es crucial para garantizar una implementación sostenible y rentable a largo plazo. Al proporcionar recomendaciones preventivas, la API no solo contribuye a mejorar la conciencia y la educación auditiva, sino que también puede ayudar a reducir la incidencia de enfermedades auditivas.

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