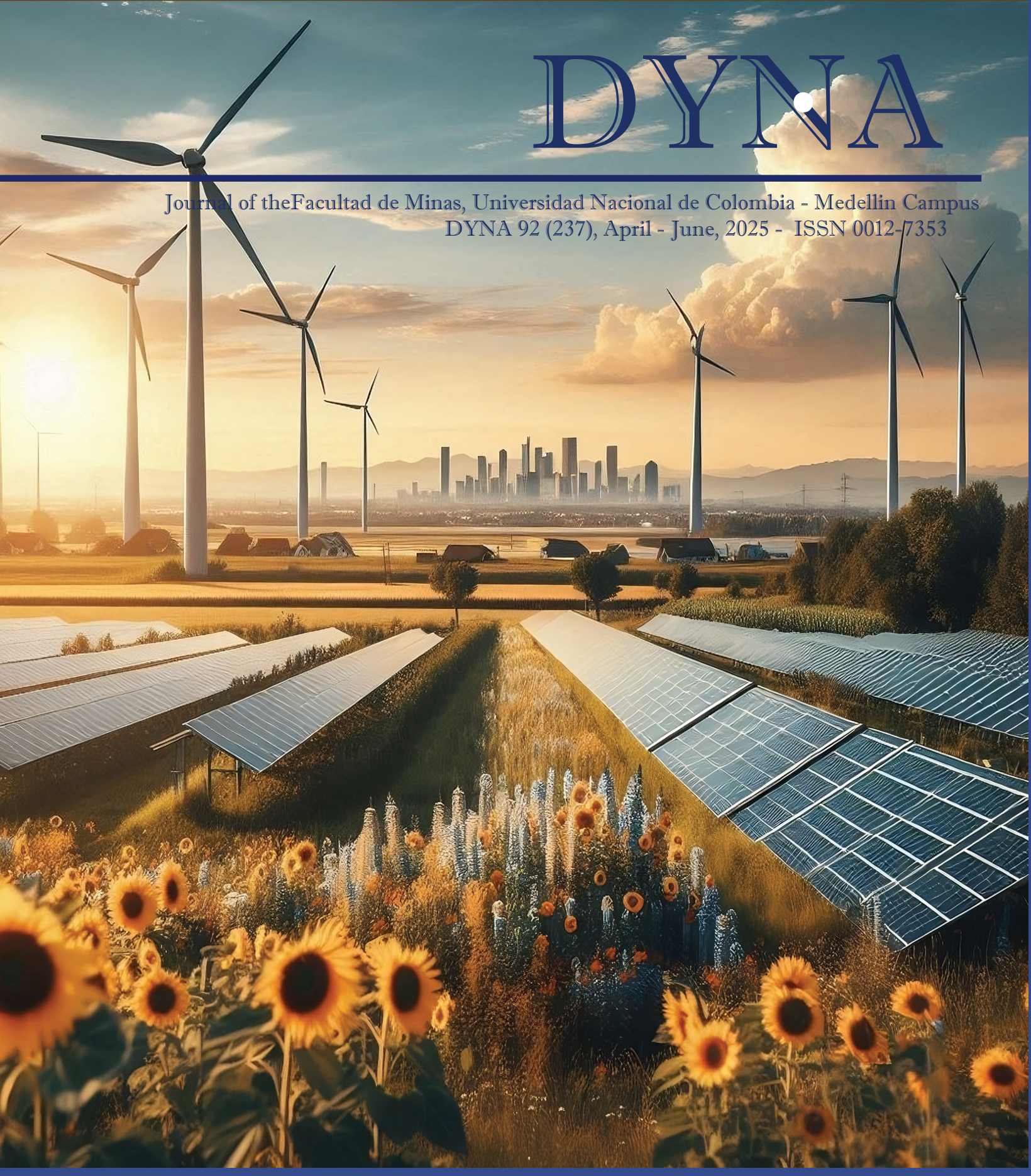

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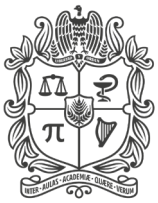

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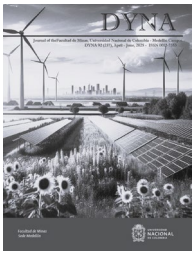

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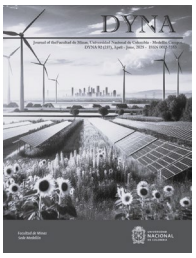

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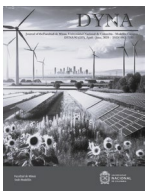

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MetS: an interactive application to identify metabolites in liquid chromatography-mass spectrometry experiments with data independent acquisition

Daniel Estevan Garcia-Niño [a], Liliana Lopez-Kleine [b] & Federico Roda-Fornaguera [c]

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Abstract
Liquid chromatography-tandem mass spectrometry (LC-MS/MS) with data-independent acquisition (DIA) enables the detection of metabolites in biological samples. However, identifying metabolites from DIA data remains challenging due to the complexity of the data. This work presents "Metabolomic Search" (MetS), a software application developed to facilitate metabolite identification in DIA experiments. The application supports filtering, correlation analysis, and similarity scoring algorithms to match DIA data to user-provided metabolite mass-to-charge ratios and fragmentation patterns. The graphical user interface is straightforward and intuitive, allowing easy data uploading, parameter configuration, and results exploration. Tests on different Solanaceae samples demonstrated successful identification of target metabolites such as scopolamine. By enabling rapid compound screening, MetS can support metabolomic based research in pharmaceutical, biotechnological, and clinical domains. The availability of this open-source tool could help address the pressing need for metabolite annotation in increasingly prevalent DIA experiments.

Keywords: application; metabolomics; metabolite identification; LC-MS/MS; data-independent acquisition.

MetS: una aplicación interactiva para identificar metabolitos en experimentos de cromatografía líquida-espectrometría de masas con adquisición independiente de datos

Resumen
La cromatografía líquida-espectrometría de masas en tándem (LC-MS/MS) con adquisición independiente de datos (DIA) permite la detección de metabolitos en muestras biológicas. Sin embargo, identificar metabolitos a partir de datos DIA sigue siendo un desafío debido a la complejidad de los datos. Este trabajo presenta "Metabolomic Search" (MetS), una aplicación de software desarrollada para facilitar la identificación de metabolitos en experimentos DIA. La aplicación admite algoritmos de filtrado, análisis de correlación y puntuación de similitud para hacer coincidir los datos de DIA con las relaciones masa-carga de metabolitos y los patrones de fragmentación proporcionados por el usuario. La interfaz gráfica de usuario es sencilla e intuitiva y permite cargar datos, configurar parámetros y explorar resultados fácilmente. Las pruebas en diferentes muestras de Solanaceae demostraron una identificación exitosa de metabolitos objetivo como la escopolamina. Al permitir la detección rápida de compuestos, MetS puede respaldar la investigación basada en metabolómica en los dominios farmacéutico, biotecnológico y clínico. La disponibilidad de esta herramienta de código abierto podría ayudar a abordar la necesidad apremiante de anotación de metabolitos en experimentos DIA cada vez más frecuentes.

Palabras clave: aplicación; metabolómica; identificación de metabolitos; LC-MS/MS; adquisición independiente de datos.

1. Introduction

At present, technological advancements allow the acquisition of high throughput molecular biology information from hundreds of samples, leading to the creation of the so-called omic sciences. Metabolomics is part of these emerging sciences and has enabled further research into the metabolism of living organisms. More specifically, metabolomics is the

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systematic identification and quantification of all metabolites in a biological sample [1]. These metabolites are molecules that participate in or result from biochemical reactions in cells. Metabolomics is applied to a variety of research fields, such as microbiology, botany, pharmacology, toxicology, functional genomics, and medicine [1]. Furthermore, its study can help discover biomarkers, elucidate physiological mechanisms, evaluate drug efficacy and toxicity, and understand the production of medicinal compounds [1].

Metabolomics employs advanced analytical techniques such as liquid chromatography (LC) in conjunction with tandem mass spectrometry (MS/MS) to separate, detect, and characterize thousands of metabolites. Liquid chromatography is a technique that allows for the separation and purification of the chemical components of a mixture (considering their physicochemical properties) through the use of a chromatographic column and two liquid phases [2]. Tandem mass spectrometry enables the determination of molecular structure, physical and chemical properties, and reaction dynamics of compounds by ionizing, fragmenting, and separating them by their mass-to-charge ratio (m/z) in two or more mass analyzers [3].

From mass spectrometry, there are two types of acquisition modes, 'Data-dependent acquisition' (DDA) and 'Data-independent acquisition' (DIA). In DDA, the most intense precursor fragments are selected to isolate and fragment them again, generating simple MS2 spectra; it has high sensitivity and selectivity but is prone to sampling bias and variability between experiments. In DIA, precursors are isolated in predefined mass windows and all precursors in each window are fragmented, generating complex MS2 spectra; it has good reproducibility and precision but requires a spectral library or advanced bioinformatics tools to identify and quantify compounds [4].

Recent reviews have highlighted the challenges in processing and interpreting data from untargeted metabolomics experiments based on mass spectrometry [5]. These reviews emphasize the need for specialized computational methods, particularly for data-independent acquisition (DIA) approaches. A comprehensive review of metabolomics-focused data mining techniques [6] discusses various analytical tools, including those designed for DIA data.

One such method, SWATH (Sequential Window Acquisition of all Theoretical Mass Spectra), has garnered attention for its DIA capabilities. Several tools have been developed to analyze SWATH data, such as OpenSWATH [7], initially created for proteomics but adaptable to metabolomics. Other software packages like XCMS [8], MS-DIAL [9], MetFrag [10], and MS-FINDER [11] have been employed for processing untargeted metabolomics data, metabolite annotation, and identification of unknown metabolites in mass spectrometry data.

A review of annotation tools for untargeted metabolomics [12] introduces MetDNA, a tool capable of processing DIA data. However, MetDNA is limited to annotation rather than identification in samples and requires previously annotated metabolites to create similarity networks.

Specific software tools have been developed to address various aspects of metabolomics data analysis. MetPathwayMap [13] organizes mass spectrometry peaks from untargeted metabolomics experiments and maps them to MetaCyc metabolic pathways. While this tool provides valuable pathway information, it relies on external software and is not explicitly designed for DIA data.

Another tool, MetMiner [14], is specifically designed for large-scale metabolomic data analysis in plants, utilizing LC-MS/MS experimental data. Although MetMiner focuses on processing, annotation, and statistical analysis of metabolomic data using plant-specific databases to improve annotation accuracy, it is not explicitly mentioned to be compatible with DIA data.

Despite these advancements, significant challenges remain in the field of metabolomics data analysis. Many of these tools are not specifically designed for DIA data, while others are restricted to specific data acquisition methods like SWATH. Some tools focus solely on annotation without providing metabolite identification in samples. These limitations significantly hinder our ability to identify and study novel compounds, highlighting the need for more versatile and comprehensive analytical tools in metabolomics research.

Within the Max Planck Tandem Group in Evolutionary Genomics of Specialized Metabolism (GEME) research group at the Universidad Nacional de Colombia in Bogotá, information was collected from LC-MS/MS experiments with DIA to identify specific classes of specialized secondary metabolites in a large set of species from the Solanaceae plant family. Currently, the collaborators of the Max Planck Institute of Molecular Plant Physiology (MPIMPP) use mainly manual inspection for identifying metabolites in DIA data. There is interest in standardizing, facilitating and optimizing this search. Especially increasing the precision and efficiency of identifications of novel compounds.

This purpose is accomplished by MetS, a computer tool that improves the process of identifying metabolites in LC-MS/MS experiments with DIA, so that it can be used by any researcher (thanks to an intuitive user interface) and is computationally efficient. The rationale that allowed the final tool to be successful is based on three main multidisciplinary aspects: 1) Comprehension of the biological problem and experiments, 2) statistical exploration to find methods to solve the problem, and finally, computer science thinking that could depict the conceptual steps in a computational tool. Given the complexity of the topic, the work was limited only to tabulated data over samples (like obtained with RefinerMS software, etc).

2. Design

The R programming language was used due to its advantages in the analysis of biological data. In addition, a user interface was created with the Shiny library that allows the application to run in any web browser, regardless of the operating system. To make the application available, a GitHub repository containing installation instructions was created: https://github.com/EstevanGN/Metabolomic-search.

The development of the application required two distinct programming paradigms. The functional paradigm was integral to the design of the Metabolomic Search (MetS)

methodology, particularly in the filtering and transformation of datasets. By implementing these operations as functions, the code became more compact, readable, and self-referential [15], allowing for flexibility in modifying different datasets without needing to restart the program. In contrast, the object-oriented paradigm was employed to take advantage of language-specific methods and to structure the user interface [16]. This combination of paradigms enhances the maintainability of the codebase and ensures that both the methodological core and the interface are easily extensible.

The structure of the application was divided into three sections: Data upload, Metabolomic search and More tools.

3. Import files

To achieve the objectives of this project, a methodology based only on tabulated data for all samples is implemented in MetS. This data set has the following configuration:

- Retention Time (RT): In chromatography, it is the time required for an analyte to migrate from the column to the detector after injection. In a sample, compounds with different physicochemical properties will arrive at different retention times. This time is generally measured in seconds or minutes.
- Intensity: In chromatography, it refers to the electrical signal generated when the ions of a sample are detected after their separation in the chromatographic column. It represents the intensity of the ion signal relative to the RT.
- m/z: In mass spectrometry, it is a measure that represents the ratio between the mass of an ion and its charge (positive or negative). The m/z value is generally presented as a decimal number, and it is used to generate a mass spectrum, which is a graphical representation of the intensity of the detected ions against their respective m/z ratios. These m/z values generate the so-called fragmentation pattern of the compounds.
- Sample: It is the identification of the organic sample that was run in the LC-MS/MS experiment with DIA in metabolomics.

The file is read in csv format and can be configured with the application parameters for correct operation and a list of 'warnings' to achieve correct loading. It is also possible to upload an additional csv file to do an automatic search on a list of compounds additional to individual searches.

4. Processing data

To identify metabolites in this type of data set, we rely on two fundamental aspects: the user knows the type of metabolite to search for, and the metabolome is similar among similar samples. That is:

- The m/z of each metabolite to be searched is known. Alternatively, the chemical formula of the metabolite can be used thanks to the added tool that calculates the m/z. The user also knows the fragmentation pattern of the molecule, when possible.
- If a metabolite exists in one sample, it will also be present in other similar samples, maintaining the fragmentation pattern given by mass spectrometry, creating a footprint in the data.

Therefore, the methodology for finding metabolites is reduced to the following steps (see Fig. 1):

1. Input:
   a. Provide an m/z.
   b. Provide a fragmentation pattern (optional). This is a theoretical fragmentation pattern found in the literature for the molecule in question. Given in m/z values.
   c. Provide an RT (optional). The RT may vary depending on the chromatogram configuration and its use represents a strong restriction on MetS. It is recommended to use it with caution only as long as the LC-MS/MS data and the metabolite input come from a practically identical experimental design.

2. Metabolomic search:
   a. With the input m/z, set a search interval, allowing variability across samples.
   b. The previous m/z interval has associated certain RT values. Generate a list with these possible RT values.
   c. For each RT in the above list, set a search interval again, allowing for variability in samples.
   d. In the RT interval, find the input m/z (previous steps ensure this). Together, the RT interval and the input m/z allow the generation of a possible fragmentation pattern for all m/z values that correlate highly (Pearson linear correlation is used given the large number of samples that are usually analyzed) across intensities in samples with the main m/z.
   e. The aforementioned possible fragmentation pattern is nothing more than a subtable of the data, presenting a similar RT and several m/z values.
   f. For each of these subtables, generate an approximation score to the input fragmentation pattern (if any), or an approximation score to the input m/z in another way.
   g. Upon completion, there will be a subtable and an approximation score for each RT.

3. Output:
   a. Best result: the subtable with the lowest approximation score.
   b. All results: a table of all possible subtables for each RT.
   c. Intensity graph: it is possible to interactively select the rows of the subtables to see the intensity of the m/z on each sample.

Each result table can be copied or downloaded in csv, xlsx, and pdf formats for further filters. Finally, this process can be visually understood in Fig. 2.

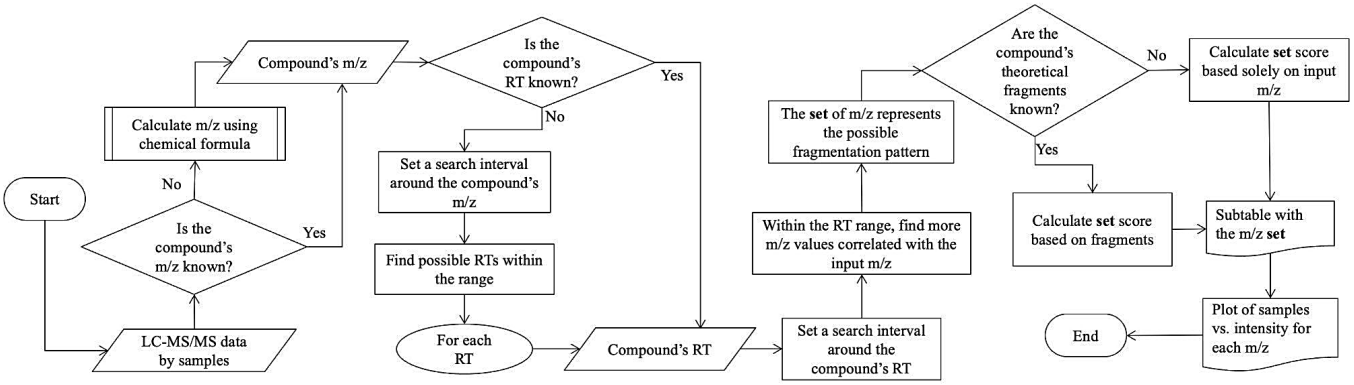

Figure 1. Flowchart for the MetS algorithm. The exact compound's RT may not be known for various reasons (LC-MS/MS experimental design was different at some stage) and a general search for the compound may be desired. For each possible RT found in the algorithm, 'Subtable with the m/z set' and 'Plot of samples vs intensity for each m/z' will be returned.
Source: Own elaboration.

5. Results

Thanks to the collective work carried out in the GEME group, MetS could be tested with LC-MS/MS data in Solanaceae samples and metabolites already known from this plant family. In Fig. 3, we see the result of finding the chemical compound 'scopolamine' in leaf samples from multiple species from the Solanaceae family. The configuration was as follows:

- Search only with m/z value.
- m/z of scopolamine: 304.15.
- m/z interval of search: 0.01.
- Fragments: 138.09 and 156.10.
- Correlation: 0.95.
- RT interval of search: 0.01.

The best result of the search is a subtable with seven m/z values at an approximate RT of 4.97. Within this subtable is the fragmentation pattern for scopolamine in rows 2, 3, and 6. Again in Fig. 3, the intensity graph for each sample in the selected fragmentation pattern is shown (rows 2, 3, and 6). Therefore, the method allows identifying metabolites with a certain level of error given by the variability of the samples, the intervals of the parameters, and the chosen correlation level.

6. Discussion

With the MetS application we have narrowed down the search due to the search mechanism and its options in comparison to other pipelines to analyze DIA data. Moreover, it is important to note that other methodologies proposed earlier [17-19] use complementary information, which is not exclusive to the LC-MS/MS experiment with DIA in metabolomics.

In [17], the authors developed a workflow named DaDIA, which combines DIA analysis of biological samples with DDA analysis of quality control samples. The DIA analysis provides high coverage of metabolic features and MS/MS spectra, and the DDA analysis generates high-quality MS/MS spectra to enhance the confidence of metabolite annotation. The authors also created an R package, DaDIA.R, to automate data processing and metabolite annotation from DaDIA data. The DaDIA workflow was applied to a study that compared metabolic alteration in the plasma of leukemia patients before and after chemotherapy. The results demonstrated that the DaDIA workflow can detect and annotate approximately four times more significantly altered metabolites than the conventional DDA workflow.

In [18], DDA and DIA data were compared in metabolomics. For the analysis of DIA-type data, the MS-DIAL software was used, which allows spectral deconvolution and similarity comparison with a reference spectral library. The quality of the MS/MS spectra obtained by the dot product method was evaluated, which measures the degree of match between the evaluated spectra and the reference ones. It was observed that the dot products obtained with the DIA method were generally lower than those obtained with the DDA method, due to the greater complexity and lower purity of the DIA spectra. However, the DIA method allowed obtaining structural information from all the detected compounds, which facilitates the identification of unknown metabolites.

Specialized software has been created to extract information from DIA in the same MS/MS experiment with different energy settings as in [19], where DIA-type data were analyzed using a workflow called MetaboMSDIA, which uses the R programming language and several open-source packages to extract, align, and annotate MS2 spectra in different acquisition channels with different collision energies. The workflow allows identifying metabolites by searching for their MS2 spectra in public or private databases, or by searching for characteristic fragmentation patterns of metabolite families.

There are approaches that do not use DDA data as support and instead base their search on statistical or machine learning techniques. Some examples are MetaboAnnotator, CANOPUS, NPClassifier, and MS2DeepScore [20]. GNPS is another tool that uses molecular networks to annotate compounds in both DIA and DDA [21]. The functionality of these tools is based, almost exclusively, on the structural comparison of fragmentation patterns with metabolite databases.

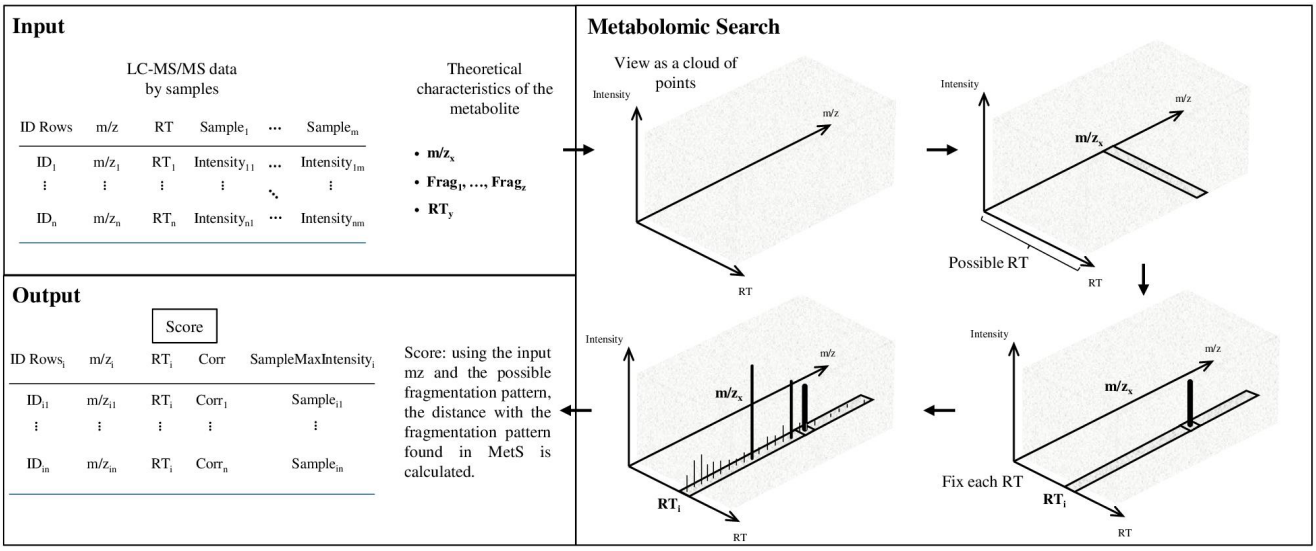

Figure 2. Internal methodology for the MetS algorithm. The input should contain the data from the scientific experiment and the characteristics of the metabolite to be found. LC-MS/MS data can be viewed as a three-dimensional point cloud. The m/z of the input is used to find possible RTs within a fixed interval. For each RT, the recommended fragmentation pattern is constructed, taking into account only the data that correlates with the m/z of the input. Each RT returns a table referring to the fragmentation pattern and a proximity score to the characteristics of the metabolite. This process can be extended to a list of compounds.
Source: Own elaboration.

Thus, all the software proposed to date use comparisons with complementary information, such as supporting DDA data or metabolite databases, to produce results. However, the complexity of the chemical structure of metabolites and the way they fragment [22] prevent these tools from having a real application in DIA type data. It is here, where MetS offers a novel solution by proposing possible fragmentation patterns, controlled by statistical theory, for each of the chemical compounds to be identified.

Bioinformatics tools are increasingly important in modern biology, challenges related to usability, implementation, and user education remain [23]. Moreover, accessibility and usability of bioinformatics software tools is crucial for research [24]. Softwares like MetS overcome the principal challenges of installability and long-term availability assuring reproducibility of scientific findings due to its free and easy access and because it is the result of a collaborative and interdisciplinary effort.

7. Conclusions and recommendations

The application exclusively relies on information gathered through DIA and data analysis techniques, eliminating the necessity for supplementary experimental designs. This distinctive approach offers a novel utility and significance unparalleled by other methods addressing similar issues. MetS, due to its open-access code and construction paradigms allows ongoing development and enhancement. The user interface is intuitive for researchers and can handle user errors. The algorithm relies solely on filters, searches, and correlations, allowing for polynomial time computational complexity. This application works for all LC-MS/MS experiments with DIA type data and can be used by researchers from different areas of knowledge. Tests with metabolomic data from the Solanaceae plant family were successful, as the application found compounds characteristic of this family of plants, and demonstrated that MetS is robust against typographical errors.

This is a user friendly software that can be used by researchers from different areas. However, it is highly recommended to conduct research in collaboration with chemists or technicians specializing in LC-MS/MS machinery. This interdisciplinary approach can foster a more comprehensive understanding and facilitate the development of more robust solutions. The application could be further enhanced to perform not only the identification of metabolites but also their annotation, leveraging the power of artificial intelligence. This would provide a more detailed analysis and could potentially uncover new insights in the metabolomic data. In addition, incorporating an error calculation feature into the application could provide a measure of certainty regarding the results allowing researchers to gauge the reliability of the findings and make informed decisions about their research.

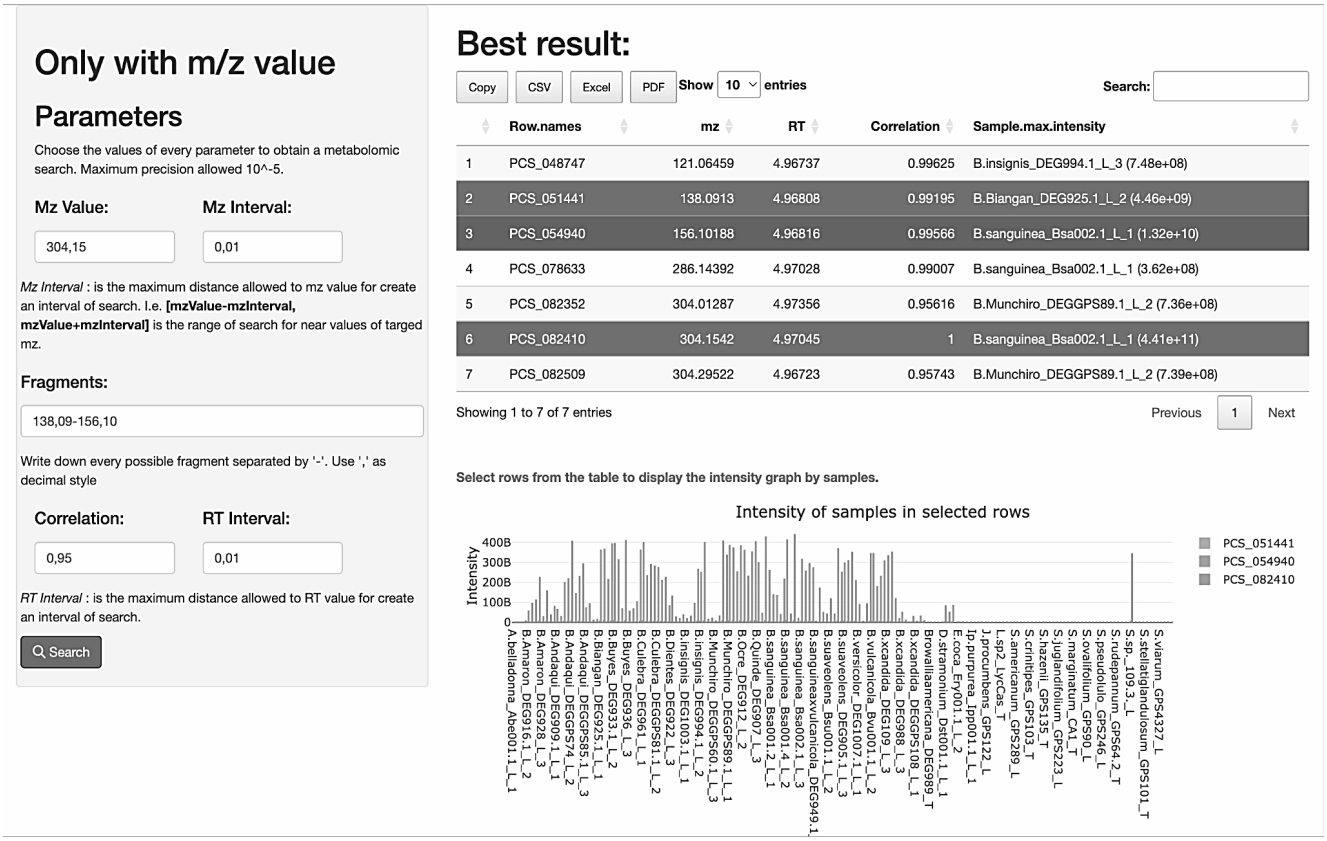

Figure 3. MetS results from LC-MS/MS experiment in Solanaceae samples searching for the metabolite scopolamine.
Source: Own elaboration.

8. Funding

Agreement 566 of 2014 between Universidad Nacional de Colombia (https://unal.edu.co/) and Colciencias (Now Minciencias https://minciencias.gov.co/).

References

[1] Yang, Q. et al., Metabolomics biotechnology, applications, and future trends: a systematic review. RSC Adv., 9(64), pp. 37245–37257, 2019. DOI: https://doi.org/10.1039/C9RA06697G

[2] Coskun, O., Separation Tecniques: Chromatography. North Clin Istanbul, 2016. DOI: https://doi.org/10.14744/nci.2016.32757

[3] Amorim-Madeira, P.J., and Helena, M., Applications of tandem mass spectrometry: from structural analysis to fundamental studies. Tandem Mass Spectrometry - Applications and Principles, J. Prasain, Ed., InTech, 2012. DOI: https://doi.org/10.5772/31736

[4] Li, J., Smith, L.S., and Zhu, H.-J., Data-independent acquisition (DIA): an emerging proteomics technology for analysis of drug-metabolizing enzymes and transporters. Drug Discovery Today: Technologies, 39, pp. 49–56, Dec. 2021. https://doi.org/10.1016/j.ddtec.2021.06.006

[5] Perez De Souza L. & Fernie, A. R., Computational methods for processing and interpreting mass spectrometry-based metabolomics. Essays in Biochemistry, 68(1), pp. 5–13, 2024. DOI: https://doi.org/10.1042/EBC20230019

[6] Shen, S., Zhan, C., Yang, C., Fernie, A.R., and Luo, J., Metabolomics-centered mining of plant metabolic diversity and function: past decade and future perspectives. Molecular Plant, 16(1), pp. 43–63, 2023. DOI: https://doi.org/10.1016/j.molp.2022.09.007

[7] Röst H.L. et al., OpenSWATH enables automated, targeted analysis of data-independent acquisition MS data. Nat Biotechnol, 32(3), pp. 219–223, 2014. DOI: https://doi.org/10.1038/nbt.2841

[8] Mahieu, N.G., Genenbacher, J.L., and Patti, G.J., A roadmap for the XCMS family of software solutions in metabolomics. Current Opinion in Chemical Biology, 30, pp. 87–93, 2016. DOI: https://doi.org/10.1016/j.cbpa.2015.11.009

[9] Tsugawa, H. et al., MS-DIAL: data-independent MS/MS deconvolution for comprehensive metabolome analysis. Nat Methods, 12(6), pp. 523–526, 2015. DOI: https://doi.org/10.1038/nmeth.3393

[10] Ruttkies, C., Neumann, S., and Posch, S., Improving MetFrag with statistical learning of fragment annotations. BMC Bioinformatics, 20(1), art. 376, 2019. DOI: https://doi.org/10.1186/s12859-019-2954-7

[11] Lai, Z. et al. Identifying metabolites by integrating metabolome databases with mass spectrometry cheminformatics. Nat Methods, 15(1), pp. 53–56, 2018. DOI: https://doi.org/10.1038/nmeth.4512

[12] Cai, Y., Zhou, Z., and Zhu, Z.-J., Advanced analytical and informatic strategies for metabolite annotation in untargeted metabolomics. TrAC Trends in Analytical Chemistry, 158, art. 116903, 2023. DOI: https://doi.org/10.1016/j.trac.2022.116903

[13] Moghe, G., and Strickler, S., metaPathwayMap: a tool to predict metabolic pathway neighborhoods from structural classes of untargeted metabolomics peaks. bioRxiv. Art. 48433, 2022. DOI: https://doi.org/10.1101/2022.03.15.484337

[14] Wang, X. et al. MetMiner: a user-friendly pipeline for large-scale plant metabolomics data analysis. JIPB, art. 13774, 2024. DOI: https://doi.org/10.1111/jipb.13774

[15] Abajirov, D., Does functional programming improve software quality?: an empirical analysis of open-source projects on GitHub. Universität Stuttgart. 2021, DOI: https://doi.org/10.18419/OPUS-11582

[16] Chambers, J.M., Object-Oriented Programming, Functional Programming and R. Statist. Sci., 29(2), 2014. DOI: https://doi.org/10.1214/13-STS452
[17] Guo, J., Yu, H., Xing, S., and Huan, T., Addressing big data challenges in mass spectrometry-based metabolomics. Chem. Commun., 58(72), pp. 9979–9990, 2022. DOI: https://doi.org/10.1039/D2CC03598G
[18] Barbier Saint Hilaire, P. et al. Comparative evaluation of data dependent and data independent acquisition workflows implemented on an orbitrap fusion for untargeted metabolomics. Metabolites, 10(4), art. 158, 2020. DOI: https://doi.org/10.3390/metabo10040158
[19] Ledesma-Escobar, C.A., Priego-Capote, F., and Calderón-Santiago, M., MetaboMSDIA: a tool for implementing data-independent acquisition in metabolomic-based mass spectrometry analysis. Analytica Chimica Acta, 1266, art. 341308, 2023. DOI: https://doi.org/10.1016/j.aca.2023.341308
[20] Ebbels, T.M.D. et al. Recent advances in mass spectrometry-based computational metabolomics. Current Opinion in Chemical Biology, 74, art. 102288, 2023. DOI: https://doi.org/10.1016/j.cbpa.2023.102288
[21] Wang, M. et al. Sharing and community curation of mass spectrometry data with Global Natural Products Social Molecular Networking. Nat Biotechnol, 34(8), pp. 828–837, 2016. https://doi.org/10.1038/nbt.3597
[22] Collins, S.L., Koo, I., Peters, J.M., Smith, P.B., and Patterson, A.D., Current challenges and recent developments in mass spectrometry–based metabolomics. Annual Rev. Anal. Chem., 14(1), pp. 467–487, 2021. DOI: https://doi.org/10.1146/annurev-anchem-091620-015205
[23] Ahmad. Software tools in Bioinformatics: a survey on the importance and Issues faced in implementation. Global Engineers and Technologists Review, 3, pp. 6–10, 2013
[24] Mangul, S. et al. Challenges and recommendations to improve the installability and archival stability of omics computational tools. PLoS Biol, 17(6), art. e3000333, 2019. DOI: https://doi.org/10.1371/journal.pbio.3000333

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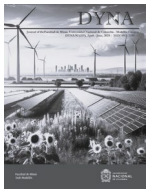

UNIVERSIDAD NACIONAL DE COLOMBIA

Emerging trends in Retail analytics: a bibliometric analysis of the last decade

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Abstract
Retail analytics has become a transformative force, leveraging data-driven insights to optimize operations, personalize customer experiences, forecast demand, and enhance supply chain efficiency. This study provides a comprehensive bibliometric analysis of 563 documents indexed in Scopus, profiling the evolution of retail analytics over the past ten years. Key findings include 131 emerging topics clustered into 13 core trends. The analysis highlights the growing application of artificial intelligence, machine learning, and big data to drive decision-making, improve profitability, and enhance competitiveness in the retail industry. This paper addresses critical questions of "what," "where," "when," and "who" in retail analytics research, identifying areas of innovation and future growth, especially in predictive analytics, customer insights, and business operations optimization.

Keywords: Retail analytics; Artificial Intelligence; machine learning; research profile; tech mining; text analysis.

Tendencias emergentes en la analítica del Retail: un análisis bibliométrico de la última década

Resumen
La analítica del retail se ha convertido en una fuerza transformadora que aprovecha los conocimientos basados en datos para optimizar las operaciones, personalizar las experiencias de los clientes, pronosticar la demanda y mejorar la eficiencia de la cadena de suministro. Este estudio proporciona un análisis bibliométrico exhaustivo de 563 documentos indexados en Scopus, que perfilan la evolución de la analítica del comercio minorista en los últimos diez años. Los hallazgos clave incluyen 131 temas emergentes agrupados en 13 tendencias centrales. El análisis destaca la creciente aplicación de la inteligencia artificial, el aprendizaje automático y el big data para impulsar la toma de decisiones, mejorar la rentabilidad y mejorar la competitividad en la industria minorista. Este documento aborda preguntas críticas de "qué", "dónde", "cuándo" y "quién" en la investigación de la analítica del comercio minorista, identificando áreas de innovación y crecimiento futuro, especialmente en análisis predictivos, conocimientos del cliente y optimización de las operaciones comerciales.

Palabras clave: Retail analytics; Inteligencia Artificial; aprendizaje de máquinas; perfil investigativo; minería de tecnología; análisis de texto.

1 Introduction

Retail Analytics (RA) is broadly defined as applying data-driven techniques to optimize various facets of retail operations, including consumer behavior insights, inventory management, and sales forecasting. By analyzing vast datasets, RA enables retailers to make informed decisions that enhance performance and customer experience. The discipline integrates advanced technologies such as Machine Learning (ML), big data analytics, and predictive modeling to uncover consumer purchasing patterns and improve operational efficiency [1,2]. It has evolved to address complex challenges, such as intermittent demand and sparse sales data, through sophisticated models that enhance predictive accuracy [3].

One of the critical strengths of RA is its ability to merge online and offline consumer behaviors, providing a comprehensive view that traditional methods often miss [4]. This holistic view allows retailers to optimize pricing strategies, forecast demand more accurately, and personalize

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customer experiences, all while improving store segmentation and management [5,6]. Integrating data analytics with store operations has become critical in achieving competitive advantages as the retail landscape shifts towards increased digitization, especially in brick-and-mortar stores [7,8]. Innovations like mobile location data and intelligent shelf systems enable real-time insights into customer preferences and shopping behaviors, enhancing operational decisions and customer satisfaction [7,9].

Moreover, RA plays a strategic role in aligning supply chain operations with retail objectives. Analyzing large data sets helps businesses anticipate market trends, improve product placement, and refine inventory control strategies. The fusion of RA with supply chain management provides retailers with the tools necessary to adapt to fluctuating market conditions, thus reinforcing its indispensable role in gaining a competitive edge [10,11]. As the field continues to evolve, it is becoming increasingly crucial for driving superior performance and maintaining market relevance in today's highly competitive retail environment [8].

This article aims to provide researchers and practitioners with a profile of the most relevant literature on RA. This paper seeks to understand the body of literature on RA and characterize significant topics and key researchers to provide a clear picture of the field. This work answers four research questions:

What are the emergent topics in the literature?

- Where is the work done?
- Who is doing the work?
- When?

The answers to these questions provide usable intelligence, which researchers and practitioners can use to make strategic decisions.

The rest of this paper is organized as follows: Section 2 discusses the methodology used. Section 3 presents the results. Section 4 discusses the findings. Finally, Section 5 presents the conclusions.

2 Materials and Methods

2.1 Study Design

Scopus was chosen as the bibliographic database because of its extensive coverage and relevance to the RA research topics. Its vast collection of peer-reviewed literature ensures access to high-quality, multidisciplinary resources. The search strategy is designed to capture published documents on RA that are indexed in Scopus, maximizing the breadth and depth of relevant material for this study.

The design of the search string used in Scopus followed an iterative process. Initially, a search was conducted for documents containing “retail analytics” in the title or author keywords without any time restriction. A manual analysis of the titles, author keywords, and index keywords from each retrieved document was performed to identify additional terms and refine the Scopus search operators. Each time a new term or variation of the search operators was identified, it was incorporated into the search string, and the search and analysis processes were repeated. This process continued until no new terms were found. The final search string is presented in Fig. 1.

```
TITLE( "retail analytics" )
OR TITLE( retail PRE/2 analytics)
OR TITLE( retail AND "data science" )
OR TITLE( retail AND insight )
OR TITLE( retail AND "big data" )
OR TITLE( retail AND insight )
OR TITLE( retail AND "predictive analytics" )
OR TITLE( retail AND "consumer analytics" )
OR TITLE( retail AND "artificial intelligence" )
OR TITLE( retail AND "machine learning" )
OR TITLE( inventory PRE/2 analytics )
OR AUTHKEY( "retail analytics" )
OR AUTHKEY ( retail PRE/2 analytics)
OR AUTHKEY ( retail AND "data science" )
OR AUTHKEY ( retail AND insight )
OR AUTHKEY ( retail AND "big data" )
OR AUTHKEY ( retail AND insight )
OR AUTHKEY ( retail AND "predictive analytics" )
OR AUTHKEY ( retail AND "consumer analytics" )
OR AUTHKEY ( retail AND "artificial intelligence" )
OR AUTHKEY ( retail AND "machine learning" )
OR AUTHKEY ( inventory PRE/2 analytics )
```

Figure 1. Search String
Source: The authors.

Inclusion and exclusion criteria were established to ensure the relevance and quality of the selected documents. The inclusion criteria encompassed peer-reviewed articles, conference papers, and book chapters. Exclusion criteria eliminated any articles that fell outside the scope of RA.

The search string presented in Fig. 1 was applied on Scopus on August 2, 2024, retrieving 635 documents. A time restriction was used during the screening phase to focus the analysis on the last ten years, excluding 46 papers published before 2014. The titles and abstracts of the remaining 582 papers published since 2014 were reviewed during the eligibility phase. As a result, 26 papers were excluded for being irrelevant to RA. The final database consists of 563 documents.

2.2 Data Treatment

In line with widely accepted practices in the literature, bibliographic data from Scopus was downloaded in CSV format for further analysis. The dataset included document titles, abstracts, author and index keywords, author affiliations, source titles, and bibliographies. To ensure the data was accurate and consistent, a combination of computational methods and manual adjustments was applied to the dataset, including:

- Converting text to uppercase.
- Changing British spelling to American.
- Eliminating extra spaces within strings.
- Standardizing hyphenated terms.

During the data treatment phase, different text analysis techniques were applied to improve the dataset for the analysis. The most essential applied process was the extraction of noun phrases from titles and abstracts. A new column titled “descriptors” was added to enable more in-depth analysis, consolidating noun phrases, author keywords, and index keywords. This “descriptors” column played a

crucial role in identifying the emergent themes within the literature.

Next, a cleaning process was applied to the "descriptors" column. This process aimed to identify and unify "conceptual synonyms," representing the same idea or concept. This phase was particularly challenging due to the large volume of terms that needed to be analyzed and standardized. By consolidating these conceptual synonyms, the analysis became more cohesive and accurate, allowing for more precise identification of emergent topics and ideas within the literature.

2.3 Data Analysis

Key bibliometric performance indicators have been computed and presented for the curated database of selected documents. These indicators, which assess the impact and influence of the publications, are based on the methodologies outlined by Aria & Cuccurullo [12] and Donthu et al. [13].

The detection of emerging topics, presented in Section 3.9, is closely linked to the concept of emergence, as discussed in the literature on innovation in science and technology [14], [15]. This study applies this concept to identify RA topics that are objectively gaining attention in current research. Emergence is defined by four key elements: novelty, persistence, community, and growth. Ten years is typically analyzed to detect emerging themes. The first three years serve as the base period, while the following seven years comprise the active period, with the last three years representing the recent period. The parameters used in this analysis are as follows:

- Novelty: A topic that could have been more present or received more attention during the base period. The descriptor appears in less than 15% of the records from the base period.
- Persistence: The topic has been studied over multiple periods and holds some significance. The descriptor appears in at least seven documents and spans three or more periods (not necessarily consecutive).
- Community: Two or more independent research groups address the topic, indicating its importance to the academic community. As a criterion, two or more organizations must independently study the subject.
- Growth: There is increasing interest in the topic within the academic community. As a criterion, the growth in research during the recent period must be at least double that of the base period.

Once emerging descriptors are identified, the Louvain clustering algorithm is applied to extract the corresponding themes. The values of these parameters are based on the works of Garner et al. [15] and Porter et al. [14].

3 Results

This section presents the basic bibliometric indicators of the analyzed dataset on RA.

3.1 Publication Trend

Over the past decade, there has been a notable increase in interest in RA, as evidenced by the steady rise in the number of publications per year. Fig. 2 plots the number of documents published by year. In 2014, there were only seven publications on the topic, but by 2023, this number had escalated to 107. The data demonstrates a consistent upward trajectory, with an annual growth rate of 49.0%. The number of documents surged from 17 in 2017 to 102 in 2022, reflecting RA's growing importance and relevance in academic and practical domains. The data for 2024 is partial, and this year is not included in the plot.

3.2 Leading Scopus Subject Areas

This section presents an analysis based on the subject areas provided by Scopus. These subject areas are assigned to the document sources and not individually to the papers. Subject areas can indicate the disciplines involved in the research about RA. The 563 papers used in this research are associated with 20 subject areas (Scopus has a total of 27), and five subject areas are associated with 47 or more documents. The leading subject areas are:

- Business, management, and accounting with 155 documents.
- Computer Science with 146 documents.
- Engineering with 96 documents.
- Decision Sciences with 67 documents.
- Mathematics with 47 documents.

3.3 Cited References

The 563 documents selected for this analysis cite 20,017 documents (12,591 of them in Scopus). The most cited sources include the Journal of Retailing and Consumer Services (301 documents), the Journal of Business Research (249 documents), Expert Systems with Applications (184 documents), Management Science (160 documents), and the Journal of Retailing (145 documents).

It is interesting to note that other documents in the same database reference 117 papers from within the database, and 15 of these papers are cited by at least 5. The most locally cited papers include the works of Huber and Stuckenschmidt [16], Pillai et al. [17], and Weber and Schütte [18]. Using machine learning methods, The work of Huber and

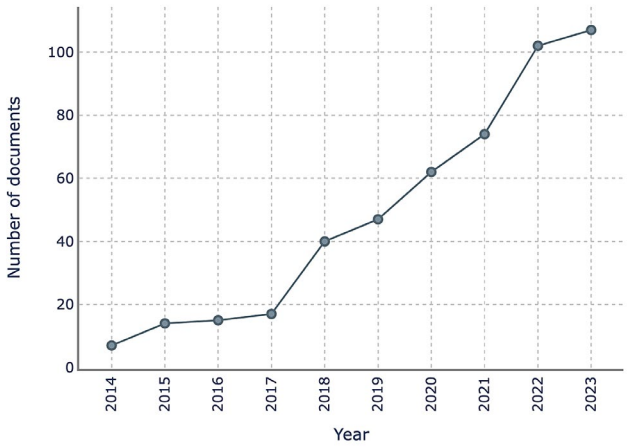

Figure 2. Number of documents published by year.
Source: The authors.

Stuckenschmidt [16] addresses demand forecasting challenges on special calendar days for a bakery chain. This paper demonstrates that classification approaches outperform regression-based methods in accuracy and suitability for large-scale retail demand forecasting scenarios.

Pillai et al. [17] explore the antecedents of consumer intention to shop at AI-powered automated retail stores, integrating the Technology Readiness and Acceptance Model with AI-specific constructs like perceived enjoyment, customization, and interactivity. Based on a survey of 1250 consumers, this research reveals that innovativeness, optimism, perceived ease of use, and perceived usefulness significantly predict shopping intention, while insecurity negatively affects perceived usefulness.

The study by Weber and Schütte [18] explores the current application of AI in the retail industry, focusing on value-added core tasks. Through scientific database searches and an empirical analysis of the ten largest international retail companies, it is found that AI adoption varies widely. While AI is highly developed in areas like marketing and replenishment, where forecasting is crucial, market adoption ranges from extensive integration to little or no usage. This research is one of the first to analyze AI's impact across core retail processes.

3.4 Similarity among Scopus subject areas

Fig. 3 presents a cross-correlation map of the subject areas in Scopus crossed with the cited journals. This map offers a perspective of how the publications are interrelated regarding the subject areas. The numbers following the subject area name represent the number of documents and citations. The links between nodes represent similarity. The size of the nodes is proportional to the number of records. The map shows a well-connected research area, with a unique isolated node corresponding to the "Economics, Econometrics, and Finance" subject area.

3.5 Leading Countries

The inspection of the dataset reveals that the documents are authored in institutions located in 79 countries. The leading countries are India (with 125 papers), the United States (78), China (59), and the United Kingdom (56). The rest of the countries have 36 published documents or less.

3.6 Leading Institutions

Another perspective on the dataset can be gained by analyzing the authors' affiliations. The dataset includes 883 different institutions. The leading contributors are Maynooth University (Ireland), with eight papers, followed by the University of Applied Sciences Upper Austria (Austria) and Amity University (India), each with six papers. Additionally, the University of Duisburg-Essen (Germany), University of Bristol (UK), Dublin City University (Ireland), Massachusetts Institute of Technology (USA), and University of Moratuwa (Sri Lanka) each contributed five papers.

3.7 Leading Publication Sources

The 563 documents in this dataset were published across 395 different sources. The top sources are the Journal of Retailing and Consumer Services (18 papers), Lecture Notes in Networks and Systems (14 papers), Lecture Notes in Computer Science (10 papers), the International Journal of Retail and Distribution Management (9 papers), ACM International Conference Proceeding Series (9 papers), and Advances in Intelligent Systems and Computing (8 papers). All other sources have published five or fewer documents.

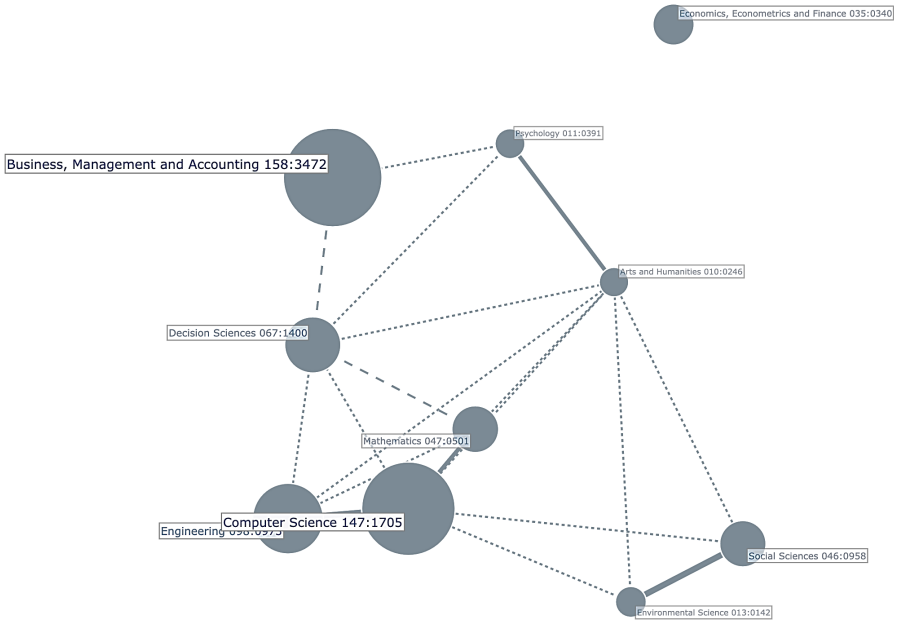

Figure 3. Correlation map of Scopus Subject Areas crossed with cited journals.
Source: The authors.

3.1 Most Cited Documents

Table 1 presents the papers with the ten highest global and ten highest local citations. It includes citation indicators for 16 papers. The two rank columns show the position of each paper when considering all the documents analyzed in the study. Notably, four papers [17,19-21] appear globally and locally cited.

Gawankar et al. [19] investigate how big data-driven retail supply chains in the Indian Retail 4.0 context influence supply chain and organizational performance. Through a survey of 380 respondents from Indian retail organizations, the research highlights the importance of governance structure and provides insights for planning big data analytics investments.

Bertacchini et al. [20] present a robotic shopping assistant with a cognitive architecture to study human-robot interaction in smart retail settings. Using machine learning systems and social robotics, the robotic assistant interacts socially with customers, influencing shopping behavior by recognizing emotional states and providing human-like companionship. Thus, it enhances customer acceptance of advanced technologies.

Hofmann and Rutschmann [22] examine the role of big data analytics in enhancing demand forecasting accuracy within retail supply chains. The study develops a conceptual framework combining scientific literature and industry knowledge, illustrating how integrating different data sources in demand forecasting can guide meaningful big data analytics initiatives. It emphasizes the need for data scientists and appropriate technological foundations.

Sung et al. [23] investigate consumer responses to an AI-embedded mixed reality exhibit in a retail/entertainment complex. Findings reveal that the quality of AI, such as speech recognition and machine learning, enhances mixed reality immersion, leading to increased consumer engagement and purchase intentions. The study highlights the potential of interactive AI and mixed reality technologies to open new avenues for consumer engagement.

Table 1.
Most Cited Documents in Retail Analytics.

Title	Authors	Document Type	Rank Global Citations	Global Citations	Rank Local Citations	Local Citations
Shopping intention at AI-powered automated retail stores (AIPARS)	Pillai et al. [17]	Article	1	201	2	13
A study on investments in the big data-driven supply chain, performance measures Stuckenschmidt [*142*] and organizational performance in Indian retail 4.0 context	Gawankar et al. [19]	Article	2	130	7	6
Shopping with a robotic companion	Bertacchini et al. [20]	Article	3	127	4	9
Big data analytics and demand forecasting in supply chains: a conceptual analysis	Hofmann and Rutschmann [22]	Article	4	111	16	4
Consumer engagement via interactive artificial intelligence and mixed reality	Sung et al. [23]	Article	5	103	52	1
Drivers and impact of big data analytic adoption in the retail industry: A quantitative investigation applying structural equation modeling	Lutfi et al. [24]	Article	6	95	27	3
Retail business analytics: Customer visit segmentation using market basket data	Griva et al. [25]	Article	7	91	11	5
Agent-Based Modeling of Retail Electrical Energy Markets with Demand Response	Dehghanpour et al. [26]	Article	8	91	117	0
Indian shopper motivation to use artificial intelligence: Generating Vroom's expectancy theory of motivation using grounded theory approach	Chopra [21]	Article	9	87	5	8
Retail sales forecasting with meta-learning	Ma and Fildes [27]	Article	10	86	12	5
Daily retail demand forecasting using machine learning with emphasis on calendric special days	Huber and Stuckenschmidt [16]	Article	11	80	1	16
State-of-the-art and adoption of artificial intelligence in retailing	Weber and Schütte [18]	Article	18	70	3	12
Revolution of Retail Industry: From Perspective of Retail 1.0 to 4.0	Har et al. [28]	Article	32	49	8	6
Artificial intelligence in retail: applications and value creation logics	Cao [29]		40	43	6	8
Low-cost embedded system for increasing retail environment intelligence	Pierdicca et al. [30]		49	37	9	6
Incorporating big data within retail organizations: A case study approach	Aversa et al. [31]	Article	58	31	10	6

Source: The authors.

The work of Lutfi et al. [24] explores the drivers and impact of big data analytics (BDA) adoption in the retail industry in Jordan, utilizing the technology-organization-environment framework and resource-based view theory. Findings indicate that factors like relative advantage, organizational readiness, and top management support significantly influence BDA adoption, which, in turn, positively impacts firm performance.

Griva et al. [25] propose a business analytics approach based on market basket data for customer visit segmentation. The study identifies shopping missions behind visits and suggests a semi-supervised feature selection approach to enhance data mining results. The approach is demonstrated in a real case with a significant European FMCG retailer, supporting decisions on marketing campaigns, store layout redesign, and product recommendations.

Dehghanpour et al. [26] study the behavior of a retail electrical energy market with demand response from air conditioning loads through a hierarchical multi-agent framework using a machine learning approach. The model optimizes retail prices and consumption patterns, maintaining consumer data privacy. Simulation results show reduced overall power consumption costs and maximized retailer profit, with implications for managing peak loads under high penetration of photovoltaic power.

Chopra [21] explores the motivation of young Indian consumers to use AI tools like chatbots and voice assistants in shopping. Using a grounded theory approach, the study generates Vroom's expectancy theory and finds that motivation to use AI tools is driven by factors like ease of use, tool competence, and satisfaction. The findings have substantial implications for retailers in developing countries.

Ma and Fildes [27] introduce a meta-learning framework for retail sales forecasting. The framework uses deep convolutional neural networks to learn feature representations from raw sales time series data. It combines base forecasting methods and shows superior performance compared to state-of-the-art benchmarks. The study suggests building a pool of base forecasters for optimal combination forecasts, though challenges remain with feature interpretability.

3.1 Exploring Emerging Topics

3.1.1 Emerging Topics

As previously discussed, descriptors (a combination of noun phrases, author, and index keywords) were prepared for analysis using text analysis techniques. By applying the concept of technology emergence indicators, 131 descriptors demonstrating a notable acceleration in research attention were identified. Table 2 shows the 40 most frequent emergent descriptors, which include a mix of terms related to consumers, AI, ML, and retail issues. Some general terms, such as “management” and “insights,” are also included, though they are less informative in context.

Table 3 presents four dimensions of analysis (journals, countries, organizations, and authors) related to the emergent topics. This table was generated using only the database documents containing the emergent topics. It lists the ten most frequent and cited items within each dimension.

Table 2.
Highly emerging terms.

Emergent Term	Records	Emergent Term	Records
Artificial Intelligence	350	Data Analytics	31
Retail Industry	111	Random Forest	31
Prediction	78	Customer Experience	29
Retail Organizations	75	Insights	28
Retail Sector	70	Analytics	26
Learning Systems	53	Decision Trees	26
Electronic Commerce	50	Internet of Things	25
Decision Making	49	Classification	25
Consumer Behavior	44	Retail Location	22
Supply Chain	37	Covid 19	21
Neural Network	36	Management	21
Predictive Analytics	36	Customer Satisfaction	21
Learning	35	Demand Forecasting	21
Deep Learning	34	Supply Chain Mgmt	20
Customers	34	Digital Transformation	19
Retail Sales	33	Information Systems	19
Commerce	33	Data Science	19
Customer Behavior	33	Social Media	18
On-line Retailers	32	Competition	18
Data Mining	32	Sales Forecasts	18

Source: The authors.

3.1.2 Clustering the Emerging Topics

The emergent descriptors were clustered into themes using a recursive version of the Louvain algorithm. The key objective of this process was to identify emergent themes for further analysis. Table 4 presents the 12 themes identified. They are analyzed in the next section. The themes of “retail sales prediction,” “AI-driven consumer insights,” and “consumer behavior and price dynamics” dominate the table.

4 Discussion

4.1 Retail Sales Prediction

The emergent cluster uses predictive analytics, particularly time series forecasting, to enhance retail sales strategies. Predictive models, built on historical sales data, external factors like weather, and promotional events, enable retailers to make informed decisions about inventory management, supply chain operations, and sales promotions [22,32-34]. Accurate forecasting is essential for optimizing stock levels, mitigating demand uncertainty, and aligning product availability with expected sales, reducing risks of overstocking or stockouts [35-39]. Studies highlight that integrating advanced machine learning techniques improves sales pattern identification and seasonality forecasting, supporting strategic decisions and maximizing the effectiveness of sales promotions [39-43]. Furthermore, these models help retailers navigate fluctuating market conditions, improving long-term viability, customer satisfaction, and competitive positioning through better inventory and promotional strategies [35,44-46]. Thus, predictive analytics is pivotal in driving retail performance by minimizing uncertainty and enhancing decision-making [38,45].

Table 3.
Dimensions for analysis of emerging topics.

Journals	Rank Occurrences	Occurrences	Rank Citations	Citations
Journal of Retailing and Consumer Services	1	18	1	632
Lecture Notes in Networks and Systems	2	14	56	25
Lecture Notes in Computer Science	3	10	16	79
ACM International Conference Proceeding Series	4	9	42	37
International Journal of Retail and Distribution Management	5	8	3	232
Advances in Intelligent Systems and Computing	6	8	74	18
Sustainability (Switzerland)	7	5	12	95
Lecture Notes in Electrical Engineering	8	5	92	12
International Journal of Production Research	9	4	2	246
Procedia Computer Science	10	4	13	93
Annals of Operations Research	19	3	9	116
International Journal of Information Management	29	2	4	182
European Journal of Operational Research	30	2	5	162
Computers in Human Behavior	31	2	6	148
International Journal of Logistics Management	32	2	7	131
International Journal of Physical Distribution and Logistics Management	33	2	8	118
Expert Systems with Applications	34	2	10	99
Countries				
India	1	124	2	1131
United States	2	69	1	1190
China	3	56	5	429
United Kingdom	4	51	3	1020
Germany	5	35	4	497
Italy	6	20	6	412
Canada	7	20	8	188
Russia	8	18	25	63
Brazil	9	14	7	215
Ireland	10	13	9	188
Hong Kong	21	7	10	177
Organizations				
Maynooth Univ. (IRL)	1	8	9	129
Univ. of Appl. Sciences Upper Austria (AUT)	2	6	5	158
Amity Univ. (IND)	3	6	36	76
Univ. of Bristol (GBR)	4	5	14	107
Dublin City Univ. (IRL)	5	5	37	76
Massachusetts Inst. of Technol. (USA)	6	5	58	55
Univ. of Moratuwa (LKA)	7	5	204	14
Univ. of Duisburg-Essen (DEU)	8	4	20	100
Univ. of Tennessee (USA)	9	4	33	81
Univ. of Bologna (ITA)	10	4	59	55
Swansea Univ. (GBR)	37	2	1	242
Montana State Univ. (USA)	38	2	4	194
Univ. of Mannheim (DEU)	39	2	6	156
Pune Inst. of Bus. Manag. (IND)	116	1	2	201
Sri Balaji Univ. (IND)	117	1	3	201
California State Univ. (USA)	118	1	7	130
Nac. Inst. of Ind. Eng. (NITIE) (IND)	119	1	8	130
Università della Calabria (ITA)	120	1	10	127
Authors				
Razmochaeva N.V.	1	7	117	46
Bezbradica M.	2	5	57	76
Cirqueira D.	3	5	58	76
Helfert M.	4	5	59	76
Klionskiy D.M.	5	5	240	21
Griva A.	6	4	12	122
Frontoni E.	7	4	17	103
Pantano E.	8	4	20	103
Frazzon E.M.	9	3	15	106
Pereira M.M.	10	3	16	106
Huber J.	33	2	4	156
Stuckenschmidt H.	34	2	5	156
Dwivedi Y.K.	137	1	1	201
Pillai R.	138	1	2	201
Sivathanu B.	139	1	3	201
Gawankar S.A.	140	1	6	130
Gunasekaran A.	141	1	7	130
Kamble S.	142	1	8	130
Bertacchini F.	143	1	9	127
Bilotta E.	144	1	10	127

Source: The authors.

Table 4.
Emergent topics clusters.

Cluster Name	Num Terms	Percentage	Main Terms
Retail Sales prediction	9	12.5	Prediction; Retail Sales; Sales Forecasts; Sales Data; Time Series; Retail Trade; Strategic Decisions; Sales Promotions; Sales Prediction
AI-Driven Customer Insights	9	12.5	Artificial Intelligence; Retail Industry; Retail Organizations; Customer Satisfaction; Artificial Intelligence Technology; Computer Vision; Experience; Information Technology; Business Performance
Consumer Behavior and Price Dynamics	8	11.1	Consumer Behavior; Insights; Retail Operators; Data Sets; Consumption Behaviors; Customer Engagement; Price Dynamics; Pricing
ML for Predictive Modeling	7	9.7	Random Forest; Decision Trees; Retail Location; Logistic Regression; Predictive Models; Support Vector Machine; Boosting
AI-driven Retail Performance	7	9.7	Learning Systems; Neural Network; Deep Learning; Convolutional Neural Networks; Radio Frequency Identification; Performance Metrics; Supervised Learning
Data-Driven Social and Consumer Dynamics	6	8.3	Social Media; Consumer; Retail Banks; Finance; Robots; Retail Data
Customer-Centric Data-Driven Strategies	6	8.3	Customers; Data Mining; Customer Relationship Management; Business Analytics; Electronic Commerce Websites; Mobile Devices
Consumer-Centric Experience	5	6.9	Customer Experience; Management; Customer Service; Customer Data; Consumer Data
Predictive Customer Behavior Systems	5	6.9	Customer Behavior; Information System; Recommender Systems; Transaction Data; Customer Demands
Predictive Customer Behavior Systems	4	5.6	Decision Making; Decision Support Systems; Decisions; Efficiency
Human-Centered Business Process Strategy	3	4.2	Strategy; Business Processes; Human Resource Managers
Fashion Analytics	3	4.2	Data Science; Data Analysis; Fashion

Source: The authors.

4.1.1 AI-Driven Customer Insights

The second emergent cluster emphasizes the transformative role of AI in enhancing customer satisfaction and optimizing business performance in the retail industry through various advanced technologies, including computer vision, machine learning, and data-driven insights [47-49]. AI enables personalized shopping experiences by automating decision-making processes and providing tailored recommendations, fostering stronger consumer-brand relationships [48-50]. This technology significantly improves operational efficiency, particularly in areas like inventory management, customer engagement, and product displays, which positively affect profitability and customer retention [51,52]. However, the ethical challenges AI poses, such as privacy concerns and trust, highlight the need for Corporate Digital Responsibility (CDR) to ensure that AI is used responsibly and ethically [53]. While AI improves business performance, it must do so within an ethical framework that addresses performance risks and fosters trust between consumers and AI-driven systems [53,54]. Overall, AI's integration into retail is critical for maintaining a competitive edge, enhancing both the customer experience and operational outcomes, but it requires balancing technological advancements with ethical considerations [49,55,56].

4.2 Consumer Behavior and Price Dynamics

This cluster integrates insights into consumer behavior, pricing dynamics, and customer engagement, highlighting the growing importance of data-driven strategies in the retail sector. Retail operators leverage large data sets and real-time data to analyze consumption patterns and adjust pricing strategies, enhancing profitability and customer satisfaction [57-59]. The integration of ML and AI further enables retailers to predict consumer behavior, optimizing pricing decisions and engagement strategies [60]. Studies emphasize how inflation and external economic stressors, like the COVID-19 pandemic, impact consumer price sensitivity and reshape consumption behaviors, underscoring the need for adaptable pricing mechanisms [61,62]. By aligning pricing strategies with consumer engagement and behavioral insights, retailers can remain competitive, ensuring customer satisfaction and operational efficiency [63-65]. Empirical research, such as studies on Dutch consumers during the pandemic, illustrates how shifts in price elasticity for essential and non-essential goods drive pricing adjustments, further supporting the role of real-time data in strategic decision-making [62].

4.3 ML for Predictive Modeling

This emergent cluster centers on integrating predictive modeling techniques, particularly machine learning algorithms like Random Forests, Decision Trees, and Support Vector Machines, to enhance decision-making processes in retail analytics. These models are pivotal for predicting customer behavior, optimizing retail locations, and managing customer churn, improving operational efficiency and sales forecasting [35,66,67]. These models provide critical insights into demand fluctuations and uncertainties by analyzing promotional pricing, retail location, and customer behavior [33,35]. Ensemble methods, including boosting and logistic regression, further refine predictive accuracy, capture non-linear relationships, and enhance performance in applications like fraud detection and inventory management [36,68].

Incorporating geographic information systems (GIS) into predictive models allows for practical spatial analysis, helping retailers identify key variables influencing store success [69]. Overall, this thematic focus highlights the transformative role of machine learning in retail, enabling businesses to leverage data-driven insights for strategic planning, resource allocation, and improved customer experiences [70-72].

4.4 AI for Retail Optimization and Operation

The cluster emphasizes the integration of advanced learning systems, particularly neural networks and deep learning techniques like convolutional neural networks (CNNs), to enhance operational efficiency and decision-making in retail environments. This thematic area explores the application of supervised learning models, focusing on optimizing tasks such as demand forecasting, inventory management, and customer behavior analysis. For instance, Radio Frequency Identification (RFID) systems with CNNs improve real-time inventory accuracy and customer tracking, enhancing responsiveness and strategic decision-making [73], [74]. Additionally, deep learning systems process real-time data to analyze consumer traffic and emotional responses, providing insights crucial for optimizing store design and marketing strategies [75,76]. The convergence of these advanced machine-learning techniques supports the development of predictive models that enhance retail operations' reliability and performance metrics and quantify the efficiency and effective learning systems in retail applications [77,78].

Moreover, the convergence of these intelligent systems drives innovations in customer behavior prediction, inventory management, and resource allocation, demonstrating a transformative shift toward more intelligent retail operations [75,79]. By continually adapting to retail demands, AI-driven learning systems facilitate enhanced decision-making and operational precision, pushing the boundaries of traditional retail through innovative technological advancements [80-82]. Thus, this thematic cluster represents a critical intersection of machine learning techniques and retail performance metrics, fostering data-driven insights and predictive capabilities essential for modern retail success.

4.5 Data-Driven Social and Consumer Dynamics

The seventh thematic cluster emphasizes the integration of AI, social media, consumer behavior, and robotics within the retail finance sector. Social media serves as a crucial consumer data source, enabling retailers and banks to understand preferences, enhance engagement strategies, and deliver personalized experiences based on consumer behavior [83]. AI technologies, including autonomous decision-making systems and chatbots, facilitate improved interactions, shaping consumer trust and influencing purchasing decisions [56]. The deployment of robotic automation in retail processes further enhances efficiency by analyzing large consumer datasets and automating tasks, thus optimizing customer interactions and financial transactions [84,85]. Integrating retail data with advanced automation reflects a significant shift towards personalized service delivery and operational effectiveness. This suggests that the convergence of consumer insights from social media and robotics is redefining the retail-finance relationship [6,86]. However, challenges related to the accuracy, security, and psychological impacts of AI and automation remain, particularly in finance, necessitating careful management of consumer trust and reliability issues [70,87]. This cluster illustrates the growing reliance on technology-driven strategies to enhance retail bank performance and consumer retention [88,89].

4.6 Customer-Centric Data-Driven Strategies

The eighth thematic cluster emphasizes the integration of data mining and business analytics with Customer Relationship Management (CRM) systems to enhance customer engagement, mainly through electronic commerce websites and mobile devices [51]. Businesses can develop personalized marketing strategies and optimize customer journeys by leveraging customer data from diverse sources. This integration allows anticipating customer preferences and improving acquisition, retention, and overall customer satisfaction [90]. Supported by predictive analytics, CRM systems facilitate real-time insights that enhance engagement strategies and foster brand loyalty [74]. Additionally, mobile devices are essential platforms for continuous customer interaction, enabling businesses to tailor experiences based on real-time data collection [85]. The development of predictive models further aids in creating dynamic feedback loops, driving personalized offerings, and strengthening customer relationships [91]. This cluster highlights the significant role of technology in managing customer relationships and optimizing marketing performance through data-driven insights and advanced analytics in an increasingly digital marketplace [63,86].

4.7 Consumer-Centric Experience

The cluster emphasizes the strategic integration of customer and consumer data to enhance customer experience and optimize service management. It highlights the evolving role of data-driven decision-making, where businesses leverage vast datasets to forecast consumer behavior and personalize interactions, significantly improving customer satisfaction and retention [1,48,60]. Companies can analyze customer behavior using ML and AI to craft tailored recommendations and refine service strategies for online and brick-and-mortar environments [92,93]. This cluster underscores the necessity of balancing personalization with operational efficiency in service delivery as firms strive to adapt to shifting customer expectations through advanced analytics [94-96]. Additionally, the relationship between customer data management and service optimization is evident, revealing how retailers can create meaningful interactions and foster loyalty by anticipating customer needs and preferences [97,98]. The focus on leveraging consumer insights for informed decision-making reflects a broader trend toward innovative service models that meet the demands of hypercompetitive markets, positioning customer data as a cornerstone of effective business strategies [99,100].

4.8 Predictive Customer Behavior Systems

This cluster emphasizes the critical intersection of customer behavior, information systems, and recommender systems, focusing on leveraging transaction data to predict and respond to customer demands. This integration facilitates the development of advanced recommender systems that analyze past behaviors and real-time interactions to deliver personalized recommendations, enhancing customer satisfaction and optimizing retail strategies [101,102]. The relationship among customer behavior, transaction data, and information systems underscores the importance of accurate data-driven insights for strategic decision-making in rapidly changing retail environments [103,104]. Moreover, these systems address immediate purchasing decisions and refine long-term customer relationship management strategies by forecasting customer needs and aligning product offerings with evolving preferences [105-107]. As businesses increasingly depend on sophisticated predictive models, the utilization of transaction data becomes pivotal in enhancing operational efficiency and maintaining a competitive advantage, ultimately reflecting a significant shift toward customer-centric retail strategies [108-110], [111]. This cluster thus highlights the necessity for robust information systems that can process vast amounts of data to provide actionable insights, ensuring that retailers can effectively respond to dynamic customer demands [101].

4.9 Human-Centered Business Process Strategy

The cluster focuses on the intersection of strategic decision-making, human resource management (HRM), and the optimization of business processes within the context of RA. Central to this cluster is the role of human resource managers in shaping business strategies that drive organizational efficiency and adaptability. As crucial actors in strategic planning, HR managers align workforce capabilities with business objectives, ensuring that human capital is effectively utilized and a driver of process innovation and competitive advantage [112]. This cluster reflects the growing importance of integrating human resources with broader business processes in retail analytics to respond to dynamic market demands and technological advancements [113]. The relationship among these elements highlights a critical view of HRM as not merely administrative but a strategic partner in fostering innovation, improving business performance, and supporting organizational agility, mainly by deploying tailored business processes that maximize workforce potential [114].

4.10 Human-Centered Business Process Strategy

The eleventh thematic cluster delves into the intersection of data science and the fashion industry, highlighting how advanced data analysis, ML and AI revolutionize decision-making processes in fashion supply chains. This cluster emphasizes the utilization of predictive analytics to gain insights into consumer behavior, forecast demand, and optimize inventory management, addressing the complexities of fluctuating customer preferences and product availability. ML facilitates enhanced customer profiling and strategic retail operations, allowing brands to personalize fashion experiences and improve operational efficiency [34,115].

Furthermore, integrating data science into fashion retail promotes sustainability and profitability by streamlining supply chains and reducing waste [116]. Despite the current limitations in research, the potential for data-driven methodologies to transform decision-making is significant, as they help fashion stakeholders—from customers to supply chain managers—navigate the combinatorial explosion inherent in online fashion retail [105]. This cluster underscores the critical balance between technological advancements and the human aesthetic aspects of fashion, raising questions about the role of creativity in a data-centric industry [117]. Ultimately, it positions fashion analytics as a vital area for innovation, fostering consumer loyalty and maximizing sales.

4.11 Fashion Analytics

The last cluster emphasizes the intersection of data science, ML, and fashion retail, where predictive analytics, classification algorithms, and AI play a crucial role in enhancing decision-making processes across customer behavior forecasting, inventory management, and supply chain optimization [98,114,118]. These techniques are vital in predicting customer churn, improving loyalty, and addressing the assortment problem, which involves distributing products across regions with diverse preferences [119]. Data science tools, particularly AI-driven decision support systems, help fashion retailers adapt to dynamic customer needs and market fluctuations by providing personalized experiences and product recommendations [105]. Integrating AI and machine learning is also critical in tackling industry challenges like sustainability, waste reduction, and trend prediction [116]. Despite the transformative potential of these tools, the limited research on customer models highlights a gap in fully leveraging AI's capabilities in fashion retail supply chains [105]. As fashion retailers increasingly adopt data-driven innovation, balancing advanced analytics with cost-effectiveness while ensuring high customer satisfaction remains a central concern [115], positioning data science as a critical driver of competitive advantage in the sector [34,114].

5 Conclusions

RA has emerged as a transformative force, utilizing data-driven insights to enhance various aspects of the retail industry, including operational optimization, personalized customer experiences, demand forecasting, and supply chain efficiency. This bibliometric study, which analyzed 563 documents indexed in Scopus, offers a comprehensive view of the evolution of retail analytics over the past decade. Key findings reveal 131 emerging topics, organized into 13 core trends, including Retail Sales Prediction, AI-Driven Customer Insights, and AI and Machine Learning applications across diverse retail challenges. Additionally, the study provides a detailed examination of publication trends, highlighting leading countries, organizations, authors,

and journals in the field. These insights map the current landscape of retail analytics research and point to future directions for innovation and development within the industry.

References

[1] Arefin , S. et al., Retail Industry Analytics: unraveling consumer behavior through RFM segmentation and machine learning, in 2024 IEEE International Conference on Electro Information Technology (eIT), IEEE, 2024, pp. 545–551.

[2] Verma, N., and Singh, J., A comprehensive review from sequential association computing to Hadoop-MapReduce parallel computing in a retail scenario, Journal of Management Analytics, 4(4), pp. 359–392, 2017. DOI: https://doi.org/10.1080/23270012.2017.1373261.

[3] Pitkin, J., Manolopoulou, I., and Ross, G., Bayesian hierarchical modelling of sparse count processes in retail analytics, Annals of Applied Statistics, 18(2), pp. 946–965, 2024. DOI: https://doi.org/10.1214/23-AOAS1811.

[4] Schultz, D., and Block, M.P., Fusing complex big data sets to understand consumer's online relationships that create In-Store retail bonding: an abstract, in developments in Marketing Science: Proceedings of the Academy of Marketing Science, 2019, 169 P. DOI: https://doi.org/10.1007/978-3-030-02568-7_48.

[5] Pitkin, J., Ross, G., and Manolopoulou, I., Dirichlet process mixtures of order statistics with applications to retail analytics, Journal of the Royal Statistical Society. Series C: Applied Statistics, 68(1), pp. 3–28, 2019. DOI: https://doi.org/10.1111/rssc.12296.

[6] Bilgic, E., Cakir, O., Kantardzic, M., Duan, Y., and Cao, G., Retail analytics: store segmentation using Rule-Based Purchasing behavior analysis, International Review of Retail, Distribution and Consumer Research, 31(4), pp. 457–480, 2021. DOI: https://doi.org/10.1080/09593969.2021.1915847.

[7] Aversa, J., Azmy, A., and Hernandez, T., Untapping the potential of mobile location data: the opportunities and challenges for retail analytics, Journal of Retailing and Consumer Services, 81, art. 103993, 2024.

[8] Becker, J., Müller, K., Cordes, A.-K., Hartmann, P., and Von Lojewski, L., Development of a conceptual framework for machine learning applications in brick-and-mortar stores, presented at the Proceedings of the 15th International Conference on Business Information Systems 2020 Developments, Opportunities and Challenges of Digitization, WIRTSCHAFTSINFORMATIK 2020, 2020. DOI: https://doi.org/10.30844/wi_2020_c2.

[9] Jose, J.A.C. et al., Smart shelf system for customer behavior tracking in supermarkets, Sensors, 24(2), 2024. DOI: https://doi.org/10.3390/s24020367.

[10] Subramani, K., Building a strategic framework for retail supply chain analytics, in Handbook of Research on Strategic Supply Chain Management in the Retail Industry, 2016, pp. 216–232. DOI: https://doi.org/10.4018/978-1-4666-9894-9.ch012.

[11] Gregorczuk, H., Retail analytics: smart-stores saving bricks- and-mortar retail or a privacy problem?. Law, Technology and Humans, 4(1), pp. 63–78, 2022. DOI: https://doi.org/10.5204/lthj.2088.

[12] Aria, M., and Cuccurullo, C., Bibliometrix: an R-tool for comprehensive science mapping analysis, Journal of Informetrics, 11(4), pp. 959–975, 2017. DOI: https://doi.org/10.1016/j.joi.2017.08.007.

[13] Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., and Lim, W.M., How to conduct a bibliometric analysis: an overview and guidelines, Journal of Business Research, 133, pp. 285–296, 2021. DOI: https://doi.org/10.1016/j.jbusres.2021.04.070.

[14] Porter, A.L., Garner, J., Carley, S.F., and Newman, N.C., Emergence scoring to identify frontier R&D topics and key players, Technological Forecasting and Social Change, 146, pp. 628–643, 2019. DOI: https://doi.org/10.1016/j.techfore.2018.04.016.

[15] Garner, J., Carley, S., Porter, A.L., and Newman, N.C., Technological emergence indicators using emergence scoring, in 2017 Portland international conference on management of engineering and technology (PICMET), IEEE, 2017, pp. 1–12.

[16] Huber, J., and Stuckenschmidt, H., Daily retail demand forecasting using machine learning with emphasis on calendric special days, International Journal of Forecasting, 36(4), pp. 1420–1438, 2020. DOI: https://doi.org/10.1016/j.ijforecast.2020.02.005.

[17] Pillai, R., Sivathanu, B., and Dwivedi, Y.K., Shopping intention at AI-powered automated retail stores (AIPARS), Journal of Retailing and Consumer Services, 57, art. 102207, 2020. DOI: https://doi.org/10.1016/j.jretconser.2020.102207.

[18] Weber, F.D., and Schütte, R., State-of-the-art and adoption of artificial intelligence in retailing, Digital Policy, Regulation and Governance, 21(3), pp. 264–279, 2019. DOI: https://doi.org/10.1108/DPRG-09-2018-0050.

[19] Gawankar, S.A., Gunasekaran, A., and Kamble, S., A study on investments in the big data-driven supply chain, performance measures and organisational performance in Indian retail 4.0 context, International Journal of Production Research, 58(5), pp. 1574–1593, 2020. DOI: https://doi.org/10.1080/00207543.2019.1668070.

[20] Bertacchini, F., Bilotta, E., and Pantano, P., Shopping with a robotic companion, Computers in Human Behavior, 77, pp. 382–395, 2017. DOI: https://doi.org/10.1016/j.chb.2017.02.064.

[21] Chopra, K., Indian shopper motivation to use artificial intelligence: generating Vroom's expectancy theory of motivation using grounded theory approach, International Journal of Retail and Distribution Management, 47(3), pp. 331–347, 2019. DOI: https://doi.org/10.1108/IJRDM-11-2018-0251.

[22] Hofmann, E., and Rutschmann, E., Big data analytics and demand forecasting in supply chains: a conceptual analysis, International Journal of Logistics Management, 29(2), pp. 739–766, 2018. DOI: https://doi.org/10.1108/IJLM-04-2017-0088.

[23] Sung, E.C., Bae, S., Han, D.-I.D., and Kwon, O., Consumer engagement via interactive artificial intelligence and mixed reality, International Journal of Information Management, 60, 2021. DOI: https://doi.org/10.1016/j.ijinfomgt.2021.102382.

[24] Lutfi, A. et al., Drivers and impact of big data analytic adoption in the retail industry: a quantitative investigation applying structural equation modeling, Journal of Retailing and Consumer Services, 70, art. 103129, 2023. DOI: https://doi.org/10.1016/j.jretconser.2022.103129.

[25] Griva, A., Bardaki, C., Pramatari, K., and Papakiriakopoulos, D., Retail business analytics: customer visit segmentation using market basket data, Expert Systems with Applications, 100, pp. 1–16, 2018. DOI: https://doi.org/10.1016/j.eswa.2018.01.029.

[26] Dehghanpour, K., Hashem-Nehrir, M., Sheppard, J.W., and Kelly, N.C., Agent-based modeling of retail electrical energy markets with demand response, IEEE Transactions on Smart Grid, 9(4), pp. 3465–3475, 2018. DOI: https://doi.org/10.1109/TSG.2016.2631453.

[27] Ma, S., and Fildes, R., Retail sales forecasting with meta-learning, European Journal of Operational Research, 288(1), pp. 111–128, 2021. DOI: https://doi.org/10.1016/j.ejor.2020.05.038.

[28] Har, L.L., Rashid, U.K., Chuan, L.T., Sen, S.C., and Xia, L.Y., Revolution of retail industry: from perspective of Retail 1.0 to 4.0, presented at the Procedia Computer Science, 2022, pp. 1615–1625. DOI: https://doi.org/10.1016/j.procs.2022.01.362.

[29] Cao, L., Artificial intelligence in retail: applications and value creation logics, International Journal of Retail and Distribution Management, 49(7), pp. 958–976, 2021. DOI: https://doi.org/10.1108/IJRDM-09-2020-0350.

[30] Pierdicca, R., Liciotti, D., Contigiani, M., Frontoni, E., Mancini, A., and Zingaretti, P., Low cost embedded system for increasing retail environment intelligence, presented at the 2015 IEEE International Conference on Multimedia and Expo Workshops, ICMEW 2015, 2015. DOI: https://doi.org/10.1109/ICMEW.2015.7169771.

[31] Aversa, J., Hernandez, T., and Doherty, S., Incorporating big data within retail organizations: a case study approach, Journal of Retailing and Consumer Services, 60, 2021. DOI: https://doi.org/10.1016/j.jretconser.2021.102447.

[32] Bharadwaj, A.A., and Gunasekaran, M., Analysis of demand forecasting trends using hybrid regression model in comparison with seasonal autoregressive integrated moving average with eXogenous factors model, in 2024 Ninth International Conference on Science Technology Engineering and Mathematics (ICONSTEM), IEEE, 2024, pp. 1–6.

[33] Alekhyasri, N.N., Prasad, G.B., Pardhasaradhi, T., Reddy, A.P.V., and Bhargavi, M., Predictive analysis for retail: sales forecasting at Walmart, in 2024 3rd International Conference on Applied Artificial Intelligence and Computing (ICAAIC), IEEE, 2024, pp. 1018–1022.

[34] Espinoza-Vega, A., and Roa, H.N., Boosting customer retention in pharmaceutical retail: a predictive approach based on machine learning models, in Science and Information Conference, Springer, 2024, pp. 97–117.

[35] Phumchusri, N., and Phupaichitkun, N., Sales prediction hybrid models for retails using promotional pricing strategy as a key demand driver, Journal of Revenue and Pricing Management, 2024. DOI: https://doi.org/10.1057/s41272-024-00477-7.

[36] Javed, S., and Akhtar, R., Data driven approaches for demand forecasting in supply chain for business decisions, presented at the 2024 5th International Conference on Advancements in Computational Sciences, ICACS 2024, 2024. DOI: https://doi.org/10.1109/ICACS60934.2024.10473234.

[37] Tran, B.R., Sellin' in the rain: weather, climate, and retail sales, Management Science, 69(12), pp. 7423–7447, 2023. DOI: https://doi.org/10.1287/mnsc.2023.4799.

[38] Ratre, S., and Jayaraj, J., Sales prediction using ARIMA, Facebook's prophet and XGBoost model of machine learning, presented at the Lecture Notes in Electrical Engineering, 2023, pp. 101–111. DOI: https://doi.org/10.1007/978-981-19-5868-7_9.

[39] Upadhyay, H., Shekhar, S., Vidyarthi, A., Prakash, R., and Gowri, R., Sales prediction in the Retail industry using machine learning: a case study of BigMart, presented at the IEEE International Conference on Electrical, Electronics, Communication and Computers, ELEXCOM 2023, 2023. DOI: https://doi.org/10.1109/ELEXCOM58812.2023.10370313.

[40] Suimon, Y., Tanabe, H., and Izumi, K., Using weather-based machine learning approach to estimate retail sales and interpret weather factors, presented at the Proceedings - 2023 14th IIAI International Congress on Advanced Applied Informatics, IIAI-AAI 2023, 2023, pp. 725–727. DOI: https://doi.org/10.1109/IIAI-AAI59060.2023.00151.

[41] Suresh, B.S., and Suresh, M., A Comprehensive analysis of retail sales forecasting using machine learning and deep learning methods, presented at the 2023 International Conference on Data Science and Network Security, ICDSNS 2023, 2023. DOI: https://doi.org/10.1109/ICDSNS58469.2023.10245887.

[42] Kheawpeam, N., and Sinthupinyo, S., Demand forecasting using machine learning to manage product inventory for multi-channel retailing store, presented at the 2023 IEEE International Conference on Omni-Layer Intelligent Systems, COINS 2023, 2023. DOI: https://doi.org/10.1109/COINS57856.2023.10189241.

[43] Shi, R., and Zhang, C., A study of sales forecasting in multinational retail companies: a feature extraction-machine learning-classification based forecasting framework, presented at the 2023 IEEE International Conference on Sensors, Electronics and Computer Engineering, ICSECE 2023, 2023, pp. 401–405. DOI: https://doi.org/10.1109/ICSECE58870.2023.10263406.

[44] Ocaña, L.L., Ruiz, D.P., and Fiallos, B.V., Optimizing retail business strategies with advanced analytics and improved business intelligence techniques, Journal of Intelligent Systems and Internet of Things, 11(1), pp. 75–83, 2024. DOI: https://doi.org/10.54216/JISIoT.110108.

[45] Feldman, J., Zhang, D.J., Liu, X., and Zhang, N., Customer Choice Models vs. Machine Learning: finding optimal product displays on Alibaba, Operations Research, 70(1), pp. 309–328, 2022. DOI: https://doi.org/10.1287/opre.2021.2158.

[46] Punia, S., and Shankar, S., Predictive analytics for demand forecasting: a deep learning-based decision support system, Knowledge-Based Systems, 258, 2022. DOI: https://doi.org/10.1016/j.knosys.2022.109956.

[47] ElSayad, G., and Mamdouh, H., Are young adult consumers ready to be intelligent shoppers? The importance of perceived trust and the usefulness of AI-powered retail platforms in shaping purchase intention, Young Consumers, 2024.

[48] Duwadi, S., and Cautinho, C., ChatGPT based recommendation system for retail shops, presented at the Procedia Computer Science, 2024, pp. 253–260. DOI: https://doi.org/10.1016/j.procs.2024.05.103.

[49] Yang, Y., and Lan, T., Boosting sports card sales: leveraging visual display and machine learning in online Retail, Journal of Retailing and Consumer Services, 81, art. 103991, 2024.

[50] Ho, S.P.S., and Chow, M.Y.C., The role of artificial intelligence in consumers' brand preference for retail banks in Hong Kong, Journal of Financial Services Marketing, 2023. DOI: https://doi.org/10.1057/s41264-022-00207-3.

[51] Reddy, N.S., and Khanna, P., The role of artificial intelligence in reimaging the customer experience in Retail Sector – NVIVO analysis for customer journey mapping, International Journal of Intelligent Systems and Applications in Engineering, 12(4s), pp. 566–585, 2024.

[52] Aljaž, T., Enhancing retail operations: integrating artificial intelligence into the theory of constraints thinking process to solve shelf issue, Elektrotehniski Vestnik/Electrotechnical Review, 91(1–2), pp. 53–58, 2024.

[53] Scarpi, D., and Pantano, E., 'With great power comes great responsibility': exploring the role of Corporate Digital Responsibility (CDR) for Artificial Intelligence Responsibility in Retail Service Automation (AIRRSA), Organizational Dynamics, 53(2), 2024. DOI: https://doi.org/10.1016/j.orgdyn.2024.101030.

[54] Blut, M., Wünderlich, N.V., and Brock, C., Facilitating retail customers' use of AI-based virtual assistants: a meta-analysis, Journal of Retailing, 100(2), pp. 293–315, 2024. DOI: https://doi.org/10.1016/j.jretai.2024.04.001.

[55] Bai, B., and Wu, G., The role of big data in the formation of supply chain platform for new forms of online retail, Chinese Management Studies, 18(4), pp. 1047–1064, 2024. DOI: https://doi.org/10.1108/CMS-09-2022-0336.

[56] Sharma, S., Islam, N., Singh, G., and Dhir, A., Why do retail customers adopt Artificial Intelligence (AI) based autonomous decision-making systems? IEEE Transactions on Engineering Management, 71, pp. 1846–1861, 2024. DOI: https://doi.org/10.1109/TEM.2022.3157976.

[57] Yamuna, G., Dhinakaran, D.P., Vijai, C., Kingsly, P.J., Devi, S.R., and others, Machine learning-based price optimization for dynamic pricing on online retail, in 2024 Ninth International Conference on Science Technology Engineering and Mathematics (ICONSTEM), IEEE, 2024, pp. 1–5.

[58] Karpushkin, G., Predicting consumer behavior based on big data of user-generated online content in retail marketing, Global Journal of Flexible Systems Management, 25(1), pp. 163–178, 2024. DOI: https://doi.org/10.1007/s40171-024-00372-5.

[59] Klepo, M. and Novoselnik, B., Product demand forecasting for shelf space allocation in retail via machine learning, in 2024 47th MIPRO ICT and Electronics Convention (MIPRO), IEEE, 2024, pp. 146–151.

[60] Alawadh, M., and Barnawi, A., A consumer behavior analysis framework toward improving market performance indicators: Saudi's retail sector as a case study, Journal of Theoretical and Applied Electronic Commerce Research, 19(1), pp. 152–171, 2024. DOI: https://doi.org/10.3390/jtaer19010009.

[61] Muñoz-Villamizar, A., Piatti, M., Mejía-Argueta, C., Pirabe, L.F., Namdar, J., and Gomez, J.F., Navigating retail inflation in Brazil: a machine learning and web scraping approach to the basic food basket, Journal of Retailing and Consumer Services, 79, 2024. DOI: https://doi.org/10.1016/j.jretconser.2024.103875.

[62] Chen H., and Lim, A., Were consumers less price sensitive to life necessities during the COVID-19 Pandemic? an empirical study on dutch consumers, presented at the Lecture Notes in Networks and Systems, 2023, pp. 79–100. DOI: https://doi.org/10.1007/978-3-031-16075-2_6.

[63] Raman, R., and Mookherjee, U.K., Revolutionizing retail: empowering personalized shopping with advanced algorithms, presented at the Proceedings of 2023 IEEE Technology and Engineering Management Conference - Asia Pacific, TEMSCON-ASPAC 2023, 2023. DOI: https://doi.org/10.1109/TEMSCON-ASPAC59527.2023.10531538.

[64] Srivastava, S., Tripathi, K.M., Sharma, K., Agarwal, R., Wable, U., and Gaikwad, P., Retail transformation through Big Data in inventory control and consumer analytics, presented at the 3rd IEEE International Conference on ICT in Business Industry and Government, ICTBIG 2023, 2023. DOI: https://doi.org/10.1109/ICTBIG59752.2023.10456076.

[65] Mehla, A., and Raman, R., The rise of smart retail: enhancing operations with cutting-edge algorithms, presented at the 2023 Global Conference on Information Technologies and Communications, GCITC 2023, 2023. DOI: https://doi.org/10.1109/GCITC60406.2023.10426006.

[66] Lu, J., Zheng, X., Nervino, E., Li, Y., Xu, Z., and Xu, Y., Retail store location screening: a machine learning-based approach, Journal of Retailing and Consumer Services, 77, 2024. DOI: https://doi.org/10.1016/j.jretconser.2023.103620.

[67] Harish, A.S., and Malathy, C., Evaluative study of cluster based customer churn prediction against conventional RFM based churn model, presented at the 2023 2nd International Conference on Electrical, Electronics, Information and Communication Technologies, ICEEICT 2023, 2023. DOI: https://doi.org/10.1109/ICEEICT56924.2023.10156962.

[68] Knuth, T., and Ahrholdt, D.C., Consumer fraud in online shopping: detecting risk indicators through data mining, International Journal of

Electronic Commerce, 26(3), pp. 388–411, 2022. DOI: https://doi.org/10.1080/10864415.2022.2076199.

[69] You, Y., and Zhang, J., Analysis of new retail location based on GIS spatial analysis—Take Starbucks and Luckin Coffee for example, presented at the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, 2022, pp. 79–84. DOI: https://doi.org/10.5194/isprs-archives-XLVIII-3-W2-2022-79-2022.

[70] Gattermann-Itschert, T., and Thonemann, U.W., Proactive customer retention management in a non-contractual B2B setting based on churn prediction with random forests, Industrial Marketing Management, 107, pp. 134–147, 2022. DOI: https://doi.org/10.1016/j.indmarman.2022.09.023.

[71] De Almeida, F.M., Martins, A.M., Nunes, M.A., and Bezerra, L.C.T., Retail sales forecasting for a Brazilian supermarket chain: An empirical assessment, presented at the Proceedings - 2022 IEEE 24th Conference on Business Informatics, CBI 2022, 2022, pp. 60–69. DOI: https://doi.org/10.1109/CBI54897.2022.00014.

[72] Dahake, P.S., Bagaregari, P., and Dahake, N.S., Shaping the future of retail: a comprehensive review of predictive analytics models for consumer behavior, in Entrepreneurship and Creativity in the Metaverse, 2024, pp. 143–160. DOI: https://doi.org/10.4018/979-8-3693-1734-1.ch011.

[73] Neroni, M., Rizzi, A., Romagnoli, G., and Rosa, M., RFID software-based shielding: Implementation of further approaches under varying surrounding conditions, International Journal of RF Technologies: Research and Applications, 12(2), pp. 127–143, 2022. DOI: https://doi.org/10.3233/RFT-220320.

[74] Girimurugan, B., Gokul, K., Sasank, M.S.S., Pokuri, V, Kurra, N.K., and Reddy, V.D., Leveraging artificial intelligence and machine learning for advanced customer relationship management in the retail industry, presented at the 2024 2nd International Conference on Disruptive Technologies, ICDT 2024, 2024, pp. 51–55. DOI: https://doi.org/10.1109/ICDT61202.2024.10488981.

[75] Joby, G., Cordeiro, H., Anantpurkar, M., and Tripathy, A.K., CCRNET Customer Conversion Rate Network, presented at the 2022 IEEE 3rd Global Conference for Advancement in Technology, GCAT 2022, 2022. DOI: https://doi.org/10.1109/GCAT55367.2022.9972152.

[76] Caliskan, A., Ozdemir, V., Bayturk, E., Oztork, O.M., Kefeli, O.D., and Uzengi, A., Real time retail analytics with computer vision, presented at the Proceedings - 2022 Innovations in Intelligent Systems and Applications Conference, ASYU 2022, 2022. DOI: https://doi.org/10.1109/ASYU56188.2022.9925538.

[77] Murindanyi, S., Wycliff-Mugalu, B., Nakatumba-Nabende, J., and Marvin, G., Interpretable machine learning for predicting customer churn in retail banking, presented at the 7th International Conference on Trends in Electronics and Informatics, ICOEI 2023 - Proceedings, 2023, pp. 967–974. DOI: https://doi.org/10.1109/ICOEI56765.2023.10125859.

[78] Yakymchuk, B., and Liashenko, O., Forecasting of new grocery store opening success using machine learning algorithms, presented at the Proceedings - International Conference on Advanced Computer Information Technologies, ACIT, 2022, pp. 203–206. DOI: https://doi.org/10.1109/ACIT54803.2022.9913157.

[79] Dias, J., Godinho, P., and Torres, P., Machine learning for customer churn prediction in retail banking, presented at the Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 2020, pp. 576–589. DOI: https://doi.org/10.1007/978-3-030-58808-3_42.

[80] 2nd International Workshop on Recent Advances in Digital Security: Biometrics and Forensics, BioFor 2019, 1st International Workshop on Pattern Recognition for Cultural Heritage, PatReCH 2019, 1st International Workshop eHealth in the Big Data and Deep Learning Era, e-BADLE 2019, International Workshop on Deep Understanding Shopper Behaviors and Interactions in Intelligent Retail Environments, DEEPRETAIL 2019 and Industrial session held at the 20th International Conference on Image Analysis and Processing, ICIAP 2019, Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 11808 LNCS, 2019, [Online]. Available at: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85072870782&partnerID=40&md5=a3845613a40ad49106629d08bb76087c

[81] Ibrahim, N.F., and Wang, X., Mining social network content of online retail brands: a machine learning approach, presented at the Proceedings of the 11th European Conference on Information Systems Management, ECISM 2017, 2017, pp. 129–138. [Online]. Available at: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85039840879&partnerID=40&md5=6e536bca97462b904c98f5be59b832b1

[82] Cheema, A.S., Harnessing supremacy of big data in retail sector via hadoop, presented at the Communications in Computer and Information Science, 2018, pp. 111–123. DOI: https://doi.org/10.1007/978-981-13-0755-3_9.

[83] Griva, A., 'I can get no e-satisfaction'. What analytics say? Evidence using satisfaction data from e-commerce, Journal of Retailing and Consumer Services, 66, 2022. DOI: https://doi.org/10.1016/j.jretconser.2022.102954.

[84] Wu, E., and Maslov, D., Raspberry Pi retail applications: transform your business with a low-cost single-board computer. in Raspberry Pi Retail Applications: Transform Your Business with a Low-Cost Single-Board Computer. 2022, 246 P. DOI: https://doi.org/10.1007/978-1-4842-7951-9.

[85] Santos, V., and Bacalhau, L.M., Digital transformation of the retail point of sale in the artificial intelligence era, in Management and Marketing for Improved Retail Competitiveness and Performance, 2023, pp. 200–216. DOI: https://doi.org/10.4018/978-1-6684-8574-3.ch010.

[86] Paranavithana, I.R., Rupasinghe, T.D., and Prior, D.D., A machine-learnt approach to market segmentation and purchase prediction Using Point-Of-Sale (POS) Data, presented at the Lecture Notes in Electrical Engineering, 2023, pp. 49–61. DOI: https://doi.org/10.1007/978-981-19-3579-4_4.

[87] Mittal, A., Chaturvedi, D.D., Chaturvedi, S., and Singh, P.K., Impact of negative aspects of artificial intelligence on customer purchase intention: an empirical study of online retail customers towards AIEnabled E-Retail Platforms, in Demystifying the Dark Side of AI in Business, 2024, pp. 159–173. DOI: https://doi.org/10.4018/979-8-3693-0724-3.ch010.

[88] Kumar, M.R., Venkatesh, J., and Rahman A.M.J.M.Z., Data mining and machine learning in retail business: developing efficiencies for better customer retention, Journal of Ambient Intelligence and Humanized Computing, 2021. DOI: https://doi.org/10.1007/s12652-020-02711-7.

[89] Chen, Y., Using machine learning to compare the information needs and interactions of Facebook: taking six retail brands as an example, Information (Switzerland), 12(12), art. 120526, 2021. DOI: https://doi.org/10.3390/info12120526.

[90] Pulari, S.R., Murugesh, T.S., Vasudevan, S.K., and Ramakrishnan, A.B., Reinforcement learning for demand forecasting and customized services, in cognitive analytics and reinforcement learning: theories, Techniques and Applications, 2024, pp. 123–134. DOI: https://doi.org/10.1002/9781394214068.ch6.

[91] Behera, R.K., Bala, P.K., Rana, N.P., Algharabat, R.S., and Kumar, K., Transforming customer engagement with artificial intelligence E-marketing: an E-retailer perspective in the era of retail 4.0, Marketing Intelligence and Planning, 2024. DOI: https://doi.org/10.1108/MIP-04-2023-0145.

[92] Zimmermann, R. et al., Enhancing brick-and-mortar store shopping experience with an augmented reality shopping assistant application using personalized recommendations and explainable artificial intelligence, Journal of Research in Interactive Marketing, 17(2), pp. 273–298, 2023. DOI: https://doi.org/10.1108/JRIM-09-2021-0237.

[93] Loukili, M., Messaoudi, F., and Ghazi, M.E., Personalizing product recommendations using collaborative filtering in online retail: a machine learning approach, presented at the 2023 International Conference on Information Technology: Cybersecurity Challenges for Sustainable Cities, ICIT 2023 - Proceeding, 2023, pp. 19–24. DOI: https://doi.org/10.1109/ICIT58056.2023.10226042.

[94] Atunwa, M., Ush, S.Z., Shatha, G.R., and Jamila, M., Utilizing ensemble approach for predictive customer clustering analysis with unsupervised cluster labeling, presented at the Proceedings - International Conference on Developments in eSystems Engineering, DeSE, 2023, pp. 258–263. DOI: https://doi.org/10.1109/DeSE60595.2023.10469368.

[95] Agbemadon, K.B., Couturier, R., and Laiymani, D., Churn detection using machine learning in the retail industry, presented at the 2022 2nd International Conference on Computer, Control and Robotics, ICCCR 2022, 2022, pp. 172–178. DOI: https://doi.org/10.1109/ICCCR54399.2022.9790213.

[96] Rodríguez-Pardo, C., Patricio, M.A., Berlanga, A., and Molina, J.M., Machine learning for smart tourism and retail, in Handbook of Research on Big Data Clustering and Machine Learning, 2019, pp. 311–333. DOI: https://doi.org/10.4018/978-1-7998-0106-1.ch014.

[97] Adke, V., Bakhshi, P., and Askari, M., Impact of disruptive technologies on customer experience management in ASEAN: a review, presented at the

2022 IEEE International Conference on Computing, ICOCO 2022, 2022, pp. 364–368. DOI: https://doi.org/10.1109/ICOCO56118.2022.10031882.

[98] Pondel, M., and Pondel, J., Machine learning solutions in retail eCommerce to increase marketing efficiency, presented at the IFIP Advances in Information and Communication Technology, 2021, pp. 91–105. DOI: https://doi.org/10.1007/978-3-030-85001-2_8.

[99] Mora, D. et al., Who wants to use an augmented reality shopping assistant application? presented at the CHIRA 2020 - Proceedings of the 4th International Conference on Computer-Human Interaction Research and Applications, 2020, pp. 309–318. [Online]. Available at: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85108113079&partnerID=40&md5=ea001aed1627c64c9e3b52cb71f9ad6b

[100] Zeba, F., and Shaheen, M., Consumer insights through retail analytics, in Artificial Intelligence and Machine Learning in Business Management: Concepts, Challenges, and Case Studies, 2021, pp. 15–28. DOI: https://doi.org/10.1201/9781003125129-2.

[101] Topçu, B., Göksu, D., Aşkın, N., Yıldırım, M.C., Aktaş, T., and U. Menteş, B., Improving replenishment for retail: utilizing planogram information, in Intelligent Systems Conference, Springer, 2024, pp. 132–152.

[102] Nasseri, M., Falatouri, T., Brandtner, P., and Darbanian, F., Applying machine learning in retail demand prediction—A comparison of tree-based ensembles and long short-term memory-based deep learning, Applied Sciences (Switzerland), 13(19), 2023. DOI: https://doi.org/10.3390/app131911112.

[103] Kulkarni, P.M., Gokhale, P., and Dandannavar, P.S., Big Data challenges in retail sector: perspective from data envelopment analysis, presented at the EAI/Springer Innovations in Communication and Computing, 2023, pp. 89–97. DOI: https://doi.org/10.1007/978-3-031-28324-6_8.

[104] Yakymchuk, B., and Liashenko, O., Modeling the resource planning system for grocery retail using machine learning, presented at the Communications in Computer and Information Science, 2023, pp. 288–299. DOI: https://doi.org/10.1007/978-3-031-48325-7_22.

[105] Pereira, A.M. et al., Customer models for artificial intelligence-based decision support in fashion online retail supply chains, Decision Support Systems, 158, 2022. DOI: https://doi.org/10.1016/j.dss.2022.113795.

[106] Sruthi, K., and Prabhu, S., Influence of consumer decisions by recommendar system in fashion e-commerce website, presented at the 2022 International Conference on Decision Aid Sciences and Applications, DASA 2022, 2022, pp. 421–424. DOI: https://doi.org/10.1109/DASA54658.2022.9765312.

[107] Shaukat, K., Luo, S., Abbas, N., Mahboob Alam, T., Ehtesham Tahir, M., and Hameed, I.A., An analysis of blessed friday sale at a retail store using classification models, presented at the ACM International Conference Proceeding Series, 2021, pp. 193–198. DOI: https://doi.org/10.1145/3451471.3451502.

[108] Narayana, C.V., Likhitha, C.L., Bademiya, S., and Kusumanjali, K., Machine Learning techniques to predict the price of used cars: predictive analytics in retail business, presented at the Proceedings of the 2nd International Conference on Electronics and Sustainable Communication Systems, ICESC 2021, 2021, pp. 1680–1687. DOI: https://doi.org/10.1109/ICESC51422.2021.9532845.

[109] Al-Omoush, R., Fraihat, S., Al-Naymat, G., and Awad, M., Design and implementation of business intelligence framework for a global online retail business, presented at the 2022 International Conference on Emerging Trends in Computing and Engineering Applications, ETCEA 2022 - Proceedings, 2022. DOI: https://doi.org/10.1109/ETCEA57049.2022.10009688.

[110] Javaid, K. et al., Explainable artificial intelligence solution for online retail, Computers, Materials and Continua, 71(2), pp. 4425–4442, 2022. DOI: https://doi.org/10.32604/cmc.2022.022984.

[111] Khatri, B., and Rungi, M., Regression-based business decision support: application in online retail, presented at the IEEE International Conference on Industrial Engineering and Engineering Management, 2022, pp. 1505–1509. DOI: https://doi.org/10.1109/IEEM55944.2022.9989568.

[112] Chaudhary, M., Gaur, L., and Chakrabarti, A., Detecting the employee satisfaction in retail: a latent dirichlet allocation and machine learning approach, presented at the Proceedings - 2022 3rd International Conference on Computation, Automation and Knowledge Management, ICCAKM 2022, 2022. DOI: https://doi.org/10.1109/ICCAKM54721.2022.9990186.

[113] Thyagharajan, K.K., Lalitha, S.D., Madhavi, N.B., Seal, S., Nithya Jenev, J., and Senthilnathan, B., Random forest-based retail management to improve the recognition rates of employees, presented at the 2023 IEEE International Conference on Research Methodologies in Knowledge Management, Artificial Intelligence and Telecommunication Engineering, RMKMATE 2023, 2023. DOI: https://doi.org/10.1109/RMKMATE59243.2023.10369487.

[114] Sousa, C., Manuela Gonçalves, A., and da Costa Freitas, A., Categories's Churn: a machine learning approach in retail, in International Conference on Computational Science and Its Applications, Springer, 2024, pp. 319–336.

[115] Gopal, P.R.C., Rana, N.P., Krishna, T.V., and Ramkumar, M., Impact of big data analytics on supply chain performance: an analysis of influencing factors, Annals of Operations Research, 333(2–3), pp. 769–797, 2024. DOI: https://doi.org/10.1007/s10479-022-04749-6.

[116] Silva, E.S., Hassani, H., and Madsen, D.Ø., Big Data in fashion: transforming the retail sector, Journal of Business Strategy, 41(4), pp. 21–27, 2020. DOI: https://doi.org/10.1108/JBS-04-2019-0062.

[117] Goti, A., Querejeta-Lomas, L., Almeida, A., de la Puerta, J.G., and López-de-Ipiña, D., Artificial intelligence in business-to-customer fashion retail: a literature review, Mathematics, 11(13), 2023. DOI: https://doi.org/10.3390/math11132943.

[118] Fares, N., Lebbar, M., and Sbihi, N., A customer profiling' machine learning approach, for in-store sales in fast fashion, presented at the Advances in Intelligent Systems and Computing, 2019, pp. 586–591. DOI: https://doi.org/10.1007/978-3-030-11928-7_53.

[119] Fares, N., Lebbar, M., Sbihi, N., and El Boukhari El Mamoun, A., Data mining dynamic hybrid model for logistic supplying chain: Assortment setting in fast fashion retail, presented at the Advances in Intelligent Systems and Computing, 2019, pp. 578–585. DOI: https://doi.org/10.1007/978-3-030-11928-7_52.

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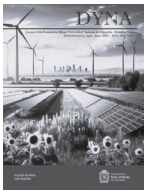

UNIVERSIDAD NACIONAL DE COLOMBIA

A new thin-film solar cell prototype based on Na-doped $BiFeO_3$

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Abstract
The development of thin film photovoltaic devices based on third and fourth generation materials has attracted the attention of the scientific community worldwide, finding the need to experiment among different assemblies and structurally modified materials to find the best efficiency of converting solar energy into electrical energy. Therefore, in this work, the efficiency of three prototypes of thin-film photovoltaic perovskite solar cells (PSCs) constructed using three sodium-doped samples of $BiFeO_3$ as absorber layers has been evaluated. The assembly was carried out based on an *n-i-p* architecture obtaining thin-films with glass/ITO/CdS/perovskite/Au/Mo/glass general configuration. The study has led to the conclusion that the efficiency of the assembled photovoltaic devices increases with the insertion of sodium and that the proposed configuration is functional for the construction of thin-film perovskite solar cells (PSCs).

Keywords: Perovskite; ferroelectricity; voltage-current; *p*-type doping; efficiency.

Un nuevo prototipo de célula solar de capa fina basada en $BiFeO_3$ dopado con Na

Resumen
El desarrollo de dispositivos fotovoltaicos de película delgada basados en materiales de tercera y cuarta generación ha atraído la atención de la comunidad científica mundial, encontrando la necesidad de experimentar entre diferentes ensamblajes y materiales estructuralmente modificados para encontrar la mejor eficiencia de conversión de energía solar en energía eléctrica. Por ello, en este trabajo se ha evaluado la eficiencia de tres prototipos de células solares fotovoltaicas de capa delgada de perovskita (PSCs) construidas utilizando tres muestras dopadas con sodio de $BiFeO_3$ como capa absorbente. Los ensamblajes se realizaron en base a una arquitectura *n-i-p* obteniéndose películas delgadas con configuración general vidrio/ITO/CdS/perovskita/Au/Mo/vidrio. El estudio ha permitido concluir que la eficiencia de los dispositivos fotovoltaicos ensamblados aumenta con la inserción de sodio y que la configuración propuesta es funcional para la construcción de células solares de capa delgada de perovskita (PSCs).

Palabras clave: Perovskita; ferroelectricidad; tensión-corriente; dopaje tipo *p*; eficiencia.

1 Introduction

In recent decades, the design of photovoltaic devices has attracted the attention of many researchers around the world, as the development of new configurations and cell types has grown exponentially, with promising results for better utilization of solar energy sources and their conversion into electrical energy [1]. In order to find a more efficient device, numerous studies have been developed exploring different prototypes, such as the thin-film solar cell, which is still being experimented with [2]. The most developed thin-film solar cells have used three main materials as the absorber layer: amorphous silicon (α-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS) [3]. However, some limitations have been found for each of these systems, such as photon scattering and its rapid degradation when interacting with light (Staebler-Wronski effect) in α-Si based cells [4,5], the high cost of manufacturing CdTe devices given that tellurium (Te) is a scarce element in nature and that Cd is a primary element of high toxicity [3,6]. On the other hand, indium (In) used in CIGS thin-films, is also a scarce element in nature,

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and compounds such as H_2Se, are a source of highly toxic selenium (Se), so its use should be limited [3,7].

To overcome the limitations of traditional cells, recent work has investigated a variety of materials for use in third- and fourth-generation devices [8,9]. Among these are perovskites of ABX_3 structure, which readily absorb light and carry charge when illuminated by a light source. Due to their high dielectric constants, high absorption coefficient [10], low bond excitation energy [11], ferroelectric properties [12,13] and other chemical and physical properties, perovskites are promising materials for the design of photovoltaic and optoelectronic devices [9].

The conventional architecture of a perovskite solar cell (PSC) is either planar *n-i-p* (FTO/ETL/perovskite/HTL/metal) or planar *p-i-n* (FTO/HTL/perovskite/ETL/metal). In both cases, particles from the HTL or ETL layers can be added to the active layer (mesoporous structures): FTO is the photoanode layer (glass or ITO, a transparent conductive composite), HTL corresponds to the hole carrier layer (p-type layer usually based on NiO, Cu_xO, MoO_X, etc.). The *i*-layer is a perovskite or absorber material with ABX_3 structure, ETL is the electron transport layer (n-type layer usually based on TiO_2, ZnO, SnO_2, CdS, etc.) and the last layer is a conductive metal or back electrode such as Au, Ag or Al [8,9,14–19]. This type of cell works when the photons irradiated by a source interact with the perovskite layer, which absorbs the energy, allowing the generation of excitons that separate into electrons and holes, creating a potential difference that moves towards the electrodes of the diode-type system, thus converting solar energy into electrical energy [8,9,12,14].

The efficiency of PSCs depends on several variables related to the architecture and the physical, chemical and electrical properties of the materials in the different layers. Their electrical, optical and magnetic properties such as bandgap, conductivity and resistance phenomena are determined by the structure, composition and morphology of the material. $BiFeO_3$ (BFO) is one of the perovskites whose structure can be modified by p-type and *n*-type cation doping in order to improve its electrical and optoelectronic behavior for use as an absorber layer. Some doping includes the insertion of alkaline earth, transition and rare earth cations at the A and B positions [20–34]. The *p*-type doping of BFO with Na atoms has been explored and found to decrease the optical bandgap values and increase the electrical conductivity, making this type of material promising for the design of PSCs [27,35].

In the present study, three photovoltaic devices with glass/ITO/CdS/perovskite/Au/Mo/glass architecture (*n-i-p* configuration; where *i* and *p* are only from perovskite) were assembled, alternating three BFO samples doped with 0 %, 8 % and 10 % sodium in the A position. To evaluate the efficiency of the new solar cells constructed by modifying the conventional PSC architecture, they were designed using undoped BFO or BFO samples doped with different sodium ratios (abbreviated NaBFO) as the absorber layer. The cells were electrically characterized to determine the influence of the structural and morphological properties of each perovskite sample on the conversion efficiency of the devices.

This study presents a novel approach by introducing Na doping, which has not been systematically investigated in BiFeO-based solar cells. The research shows that Na incorporation significantly enhances carrier mobility and reduces recombination losses, resulting in improved photovoltaic performance. This work fills a critical gap in the field of photovoltaics by establishing a direct correlation between Na doping concentration and efficiency improvements, providing a new way to optimize $BiFeO_3$ based materials in development of PSCs.

1.1 Key Contributions

The key contributions of this study are as follows:

i. First systematic study of Na doping in $BiFeO_3$ thin-film solar cells with this general configuration, demonstrating its impact on efficiency enhancement.
ii. Improved photovoltaic performance, showing a significant increase in open-circuit voltage (Voc) and short-circuit current (Jsc) compared to undoped $BiFeO_3$.
iii. Fabrication of a prototype solar cell, to demonstrate the feasibility of Na-doped $BiFeO_3$ for practical applications.

2 Materials and Methods

The cells assembled in this work were fabricated based on the architecture described in Fig. 1; (glass/ITO/CdS/perovskite/Au/Mo/glass) with an interlayer contact area of 80 mm^2 (10 mm x 8 mm). A photovoltaic flat glass plate manufactured by Yilin Glass Manufacturing Co., Ltd. with a thickness of 2 mm, visible light reflectance of 7.30 %, visible light transmittance of 91.60 % without anti-reflective (AR) coating, ultraviolet (UV) transmittance of 86.80 % and total solar heat gain coefficient of 93.20 % was used as the top substrate. The deposition of the ITO (top contact), Au (back contact) and Mo layers were performed by sputtering technique in a Three-head DC/RF sputtering magnetron, model CY-MSP300S-RFDC, CYKY brand, assisted by argon plasma. Each layer was deposited at a power of 70 W, with a pressure of $1.3x10^{-3}$ Pa for 20 min at room temperature, obtaining 270 nm thick layers from sputtering targets with 99.99 % purity purchased from Plasmaterials.

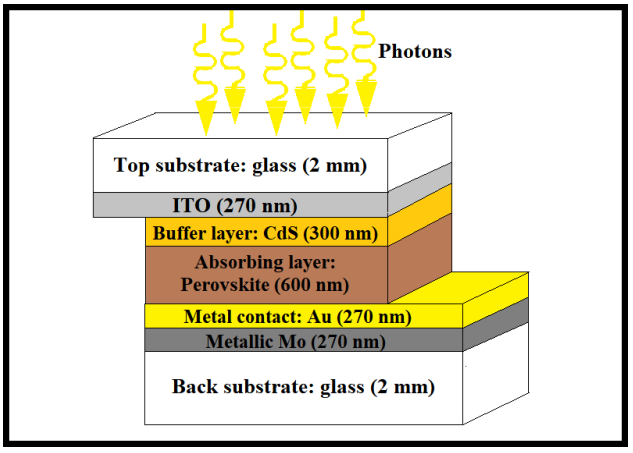

Figure 1. Architecture of the solar cells assembled in this work.
Source: the authors

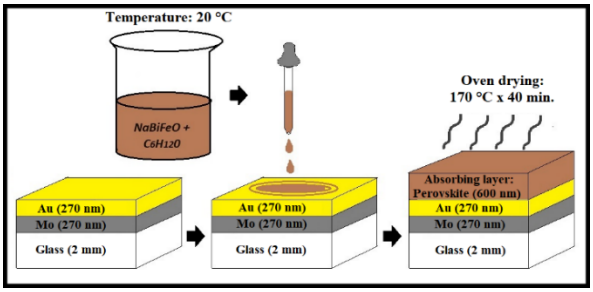

Figure 2. Deposition by drop casting technique for the buffer layer and the selected NaBFO adsorbent layer.
Source: the authors

The buffer and adsorbent layers were deposited using the drop-casting technique of A. Kumar *et al.* [36], as shown in Fig. 2. The buffer layer was deposited suspending CdS powders (98 % pure, Thermo Scientific Chemicals) in cyclohexanol (99 % pure, Thermo Scientific Chemicals), the heterogeneous mixture was drop-cast onto the ITO layer at room temperature and the liquid was evaporated at 170 °C for 40 minutes to control the coffee ring effect (CRE) [37]. Three layers were deposited by the same method until a homogeneous deposit of 300 nm thickness was obtained.

In this study, the drop-casting technique was selected for the deposition of the buffer layer on the Na-doped $BiFeO_3$ thin films due to specific material considerations. Since the Na-doped $BiFeO_3$ was synthesized in bulk form, alternative deposition methods such as thermal evaporation were not suitable, as they could induce structural changes, leading to secondary phase formation and potential loss of Na doping. In addition, spin coating was considered inappropriate due to the large grain size of the synthesized material, which would result in uneven film distribution. Furthermore, both undoped and Na-doped $BiFeO_3$ exhibit intrinsic magnetic properties that could interact with the electromagnetic fields present in certain deposition systems, potentially affecting film uniformity and composition. Therefore, drop-casting was chosen as the most suitable method to ensure homogeneous film formation while maintaining the integrity of the doped $BiFeO_3$ structure.

Thus, a 600 nm absorber layer was deposited using one of the three previously synthesized doped BFO samples with different concentrations of sodium, allowing three different cells to be assembled. Each sample used and its structural, morphological and electrical properties are detailed in Table 1 and are the result of previous characterizations performed by the authors of this work [35]. Finally, a lower substrate of glass was placed as a back support of the cell with the same characteristics as the upper substrate and the low resistance contacts were soldered.

The electrical characterization of the deposited cells was performed using a Thorlabs MCWHL5 photodiode of 470 nm at 6500 K and 840 mW, coupled to a GAMRY 1010 potentiostat-galvanostat interface. The electrical response was measured with Keithley 2450 SourceMeter® equipment by the voltage-current method (I vs. V) generating the electrical signals from the incidence of the 470 nm light beam with a maximum irradiance of 24.8 μW/mm^2 at a distance of 30 mm over the cross-sectional area of the cell of 80 mm^2 area, which produced an effective irradiance of 24.6 μW/mm^2 calculated by Lambert's law [38].

Table 1.
Summary of all variables and measurements of the NaBFO samples package deposited as active layer in this work (Ʊ = S).

Sample	Na doped (%)	Purity (%)
NaBFO-00	0	100
NaBFO-08	8	69.34
NaBFO-10	10	63.95
Sample	**Main phase**	**Impurity phase**
NaBFO-00	$BiFeO_3$	-----
NaBFO-08	$Na_{0.08}Bi_{0.92}FeO_{3-\delta}$	$Bi_2Fe_4O_9$
NaBFO-10	$Na_{0.10}Bi_{0.90}FeO_{3-\delta}$	$Bi_2Fe_4O_9$
Sample	**Microdeformations main phase**	**Oxygen Vacancies main phase = δ**
NaBFO-00	2.10 x 10^{-4}	----
NaBFO-08	5.17 x 10^{-4}	8.40 x 10^{-2}
NaBFO-10	9.54 x 10^{-4}	10.50 x 10^{-2}
Sample	**Mean particle diameter (μm)**	**Indirect optical bandgap (eV)**
NaBFO-00	11.26	2.77
NaBFO-08	13.57	2.15
NaBFO-10	9.72	2.12
Sample	**Conductivity (S m^{-1})**	**Warburg diffusion element (Ʊ s$^{1/2}$)**
NaBFO-00	1.15 x 10^{-5}	2.28 x 10^{-8}
NaBFO-08	4.75 x 10^{-5}	8.38 x 10^{-7}
NaBFO-10	1.36 x 10^{-4}	8.01 x 10^{-6}

Source: the authors

The GAMRY 1010 potentiostat-galvanostat interface has a reported accuracy of ±1.0 mV (2 %) for voltage measurements and ±3 pA (3 %) for current readings, while the Keithley 2450 SourceMeter® instrument has percent basic accuracy at 6½-digit resolution for voltage and current. Both instruments were calibrated to the manufacturer's specifications using certified reference cells and standard resistance benchmarks to ensure data reliability.

To ensure reliability, all electrical measurements were performed in triplicate for each sample. The reported voltage and current values represent the average of the three independent measurements. Since no significant oscillations or variations were observed in the data, error measures were not included in the graphical presentation. The consistency of the measurements indicates the reproducibility of the results and confirms the stability of the Na-doped $BiFeO_3$ thin films under tested conditions.

The I-V measurements reported by the instruments allowed the determination of the listed parameters and the calculating of the cell efficiency (η_{eff}) using eq. (1) [14]:

- ✓ Maximum current (I_{MAX}) and voltage (V_{MAX}).
- ✓ Maximum power (P_{MAX}).
- ✓ Open circuit voltage (V_{OC}).
- ✓ Short circuit current (I_{SC}).

$$\eta_{eff} = \frac{V_{OC} * I_{SC} * FF}{I_{sun} * A_L} \quad (1)$$

Where FF is the fill factor – eq. (2), I_{sun} indicates the luminous intensity applied on the cell and A_L is the area of the cell radiated [39].

$$FF = \frac{V_{MAX} * I_{MAX}}{V_{OC} * I_{SC}} \quad (2)$$

3 Results and Discussion

Fig. 3 shows the I-V curve obtained for the thin-film cell with NaBFO-00 absorber layer without Na doping. The electrical parameters obtained from the curve and the instrument are given in Table 2. The behavior of the diode-type system is typical of a semiconductor, whose behavior is attributed to the absorber layer (synthesized BFO) and the cell configuration (glass/ITO/CdS/NaBFO-00/Au/Mo/glass).

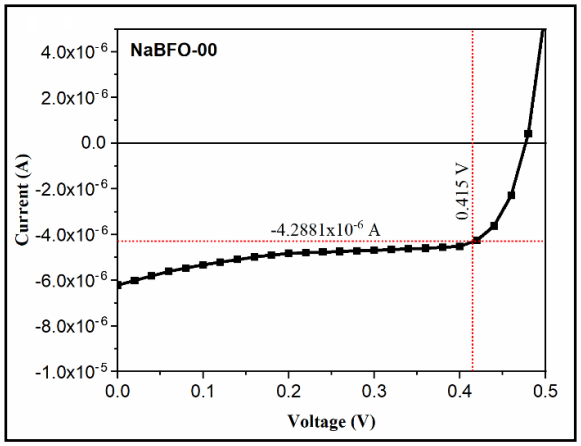

Figure 3. I-V curve for the cell with NaBFO-00 absorber layer.
Source: the authors

Table 2.
Electrical parameters of the cell with NaBFO-00 absorber layer.

Parameter		Magnitude	Units
Open circuit voltage	V_{oc}	476.10	mV
Short circuit current	I_{sc}	6.17 x 10^{-3}	mA
Maximum power	P_{max}	1.78	µW
Voltage at maximum power point	V_m	415.00	mV
Current at maximum power point	I_m	4.29 x 10^{-3}	mA

Source: the authors

Fig. 4 shows the I-V curve obtained for the thin-film cell with NaBFO-08 absorber layer, 8 % sodium doped material (configuration: glass/ITO/CdS/NaBFO-08/Au/Mo/glass). The electrical parameters resulting from the curve and also provided by the equipment are shown in Table 3.

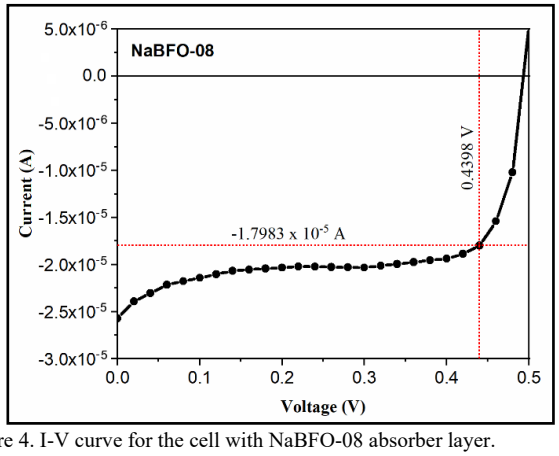

Figure 4. I-V curve for the cell with NaBFO-08 absorber layer.
Source: the authors

Table 3.
Electrical parameters of the cell with NaBFO-08 absorber layer.

Parameter		Magnitude	Units
Open circuit voltage	V_{oc}	492.80	mV
Short circuit current	I_{sc}	2.57 x 10^{-2}	mA
Maximum power	P_{max}	7.91	µW
Voltage at maximum power point	V_m	439.80	mV
Current at maximum power point	I_m	1.80 x 10^{-2}	mA

Source: the authors

Fig. 5 shows the I-V curve obtained for the thin-film cell with NaBFO-10 absorber layer, 10 % sodium doped material (configuration: glass/ITO/CdS/NaBFO-10/Au/Mo/glass). The electrical parameters resulting from the curve and also provided by the instrument are shown in Table 4.

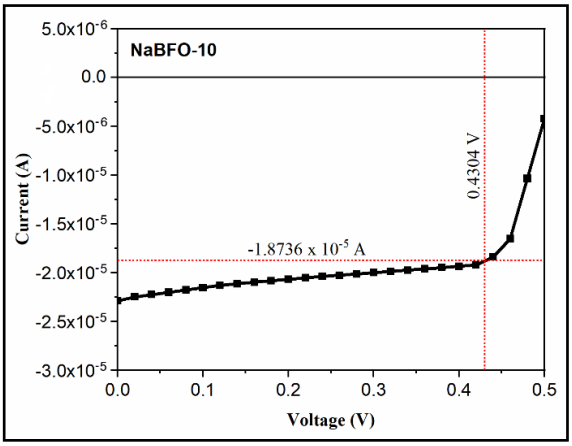

Figure 5. I-V curve for the cell with NaBFO-10 absorber layer.
Source: the authors

Table 4.
Electrical parameters of the cell with NaBFO-10 absorber layer.

Parameter		Magnitude	Units
Open circuit voltage	V_{oc}	510.50	mV
Short circuit current	I_{sc}	2.28 x 10^{-2}	mA
Maximum power	P_{max}	8.06	µW
Voltage at maximum power point	V_m	430.40	mV
Current at maximum power point	I_m	1.87 x 10^{-2}	mA

Source: the authors

The measured parameters recorded in Table 2 to Table 4 were mathematically conducted by means of eq. (1) and eq. (2), and the efficiency value for each assembled cell was obtained (Table 5).

Table 5.
Electrical measurements of irradiated cells.

Absorbent layer material	V_{oc} (mV)	I_{sc} (mA)	P_{max} (µW)	FF (%)
NaBFO-00	476.10	6.17 x 10^{-3}	1.78	0.61
NaBFO-08	492.80	2.57 x 10^{-2}	7.91	0.62
NaBFO-10	510.50	2.28 x 10^{-2}	8.06	0.69

Absorbent layer material	I_{sun} (µW/mm^2)	A_L (mm^2)	η (%)
NaBFO-00	24.60	80	9.04 x 10^{-2}
NaBFO-08	24.60	80	0.40
NaBFO-10	24.60	80	0.41

Source: the authors

Table 6.
Efficiency of undoped BFO solar cells reported in the literature.

Author	Cell structure	I_{sun} (mW/cm^2)	η (%)	Ref.
O. Ceballos-Sánchez et al.	glass/ITO/CdS/BFO-Thin/PbS/Ag	100	7.65 x 10^{-3}	[40]
Z. Xie et al.	flexible-mica/$SrRuO_3$/BFO/Au	455	3.1 x 10^{-2}	[41]
Z. Fan, K. Yao, and J. Wang	Si/SiO_2/Ti/Pt/BFO/ZnO/FTO	22.3	0.33	[42]
S. Chatterjee, A. Bera, and A. J. Pal	glass/ITO/NiO/BFO/ZnO/Al	100	9.8 x 10^{-2}	[32]
H. Sattarian, T. Tohidi, and Sh. Rahmatallahpur	glass/ITO/CdS/PbS/Al	90	1.31	[43]

Source: the authors

According to the values obtained for the efficiency of each cell and recorded in Table 5, an increase in the solar conversion efficiency is observed with the doping of the doped BFOs used as absorber layer; therefore, the stoichiometric increase of Na^+ ions, caused the decrease of the electrochemical resistance of the material and improved the electrical conductivity in proportion to the increase of oxygen vacancies and the structural defects generated in the main phase by the presence of the larger host cation as recorded in Table 1. On the other hand, the resistive effect of the material associated with the purity, size and boundary of the sintered grains increased, resulting in a lower electron flow reflected in an increase of only 0.01 % in efficiency between the cell with 8 % and 10 % Na doping.

The efficiency values obtained for the cell (glass/ITO/CdS/NaBFO-00/Au/Mo/glass) with a NaBFO-00 or BFO absorber layer without Na doping are within the average range of the values obtained by other authors as shown in Table 6.

The difference between the reported values and those obtained for the undoped BFO cell assembled in this work are attributed to the structural defects together with the morphological properties of the synthesized BFO, the measurement conditions and the constructive form of the cell, finding an efficiency very similar to that obtained by S. Chatterjee, A. Bera, and A. J. Pal, with values of 9.8 x 10^{-2} % for the glass/ITO/NiO/BFO/ZnO/Al assembly [32]. The glass/ITO/CdS/NaBFO-00/Au/Mo/glass thin-film structure favored the efficiency with respect to other designs reported in the literature, since the molybdenum and gold layers received the unabsorbed photons and refracted them to the absorber layer, favoring a higher interaction between the *p*-type material and the photons per unit area irradiated [44,45]. On the other hand, the transparent conductive oxide (ITO) and the gold metal contact favored the flow of electrons in the circuit since its function as electrodes induced low electrical resistance. In addition, the contact area between the electrodes and the *p-n* junction was established as the same size, improving the conduction of the cell. Likewise, the thickness ratio of the *p-n* layers had an impact on the final efficiency of the cell, since the potential difference in the diode depends on this parameter, similarly the thickness had a 2:1 ratio of BFO:CdS, which guaranteed the best efficiency in the measurement conditions [46].

Given the same design conditions between the cells with Na-doped BFO absorber layer and the cell with undoped BFO, the differences in efficiency are attributed to the structural and morphological variables compared in Table 1 for the synthesized materials, finding a direct relationship between the increase in efficiency and the sodium ratio. The increase of sodium induced a lack of charges in the system and the formation of a doped stable phase, in which oxygen vacancies were formed and its equilibrium is described by the Kröger-Vink notation recorded in eq. (3) and eq. (4), showing repercussions in the vacancies concentration in the synthesized systems. Despite this, the measurements in the cell show a better behavior in the more doped material, which means that a higher density of vacancies prevailed in this system, producing an increase in the conductivity that generates efficient potential differences, favoring the recombination processes; reason why an efficiency of 0.40 was obtained for the cell with the BFO doped with 8 % Na and 0.41 for the cell doped with 10 % Na [47].

$$Na_2O \rightarrow 2(Na_{Bi})^{"} + O_O^X + 4h^{\cdot} \quad (3)$$

$$Fe^{2+} + \frac{1}{3}V_{O}^{\cdot\cdot} + \frac{1}{3}h^{\cdot} \rightarrow Fe^{3+} + V_{O}^{\cdot\cdot} \quad (4)$$

Where *NaBi* corresponds to the substitution of a sodium atom (Na) by a bismuth atom (Bi), O_O^X is the released oxygen that could enter the structure or be released to the environment as $O_{2(g)}$, *h* refers to the hole-type charge carriers, V_O are the oxygen vacancies [35].

On the other hand, the reduction of the optical bandgap of the Na-doped BFO was the variable that most determined the efficiency, since the energy required to move electrons from the valence band to the conduction band was significantly lower. Aspects such as particle size and reduced purity induced resistive phenomena in the cells, so that the difference in the efficiency measure between the systems constructed with sodium-doped absorber layers is minimal, since the presence of a secondary phase with higher bandgap values limited the number of electrons available in the conduction layer, as well as the resistance generated by the grain boundary associated to materials, limiting the recombination processes.

The efficiencies measured for NaBFO-08 and NaBFO-10 respectively, are consistent with the increase in efficiency reported by other authors when $BiFeO_3$ is doped with cations such as Al, Cr, Cu, Ti, La, Pr, Nd, and Gd [21,22,31,48]. Thus, it is concluded that, given the conditions under which the cells were synthesized and manufactured; doping the BFO with 10% sodium increases its efficiency by approximately 0.32%, which corresponds to 3.53 times the efficiency of the undoped BFO cell.

Under the measurement conditions, there is a dispersion between the light waves reflected by the molybdenum, gold and perovskite layers, and the same waves emitted by the light source, but despite these light interaction phenomena, the measurement was standardized at a distance of 30 mm,

since at this distance no dispersive variations were observed in the trends shown in Fig. 5. In addition, the indirect bandgap values of the perovskite samples used as the absorber layer in this study ranged from 2.12 to 2.77 eV, so that according to the empirical relationship proposed by J. K. Singh, S. K. Mandal and G. Banerjee [49], an increase in refractive index (*n*) values between 2 and 3 units can be estimated, which contributed to the reflection losses and led to a decrease in light absorption by the Na-doped BFO samples [50]. Likewise, it is possible to improve the fabrication process by depositing all the layers preferably by the sputtering method, which, will allow a precise control of the morphological homogeneity in each layer of the cell.

The observed increase in efficiency due to Na doping can also be attributed to changes in the electronic bands structure of the $BiFeO_3$. While no previous theoretical studies have explicitly reported the band structure, defect density, or carrier concentration for Na-doped $BiFeO_3$, the experimental results provide indirect evidence for these effects. The reduction in the optical bandgap observed in Table 1 suggests a narrowing of the energy difference between the valence and conduction bands, which facilitates carrier excitation and improves photovoltaic performance. In addition, the improvement in device efficiency implies an increase in defect density, which in turn could contribute to a higher carrier concentration by introducing shallow donor cations. These effects are consistent with previous reports on aliovalent doping in perovskite oxides, where the introduction of cations leads to electronic structure modifications and defect engineering. Future theoretical studies, such as density functional theory (DFT) calculations, may provide further insight into the precise role of Na in tuning the electronic properties of $BiFeO_3$. However, extended stability assessments, such as prolonged exposure to humidity, temperature fluctuations, and continuous light illumination, are required to fully evaluate a complete behavior mechanism of these materials. Possible challenges include Na diffusion, phase segregation, or interfacial degradation that could affect long-term performance, as well as the study of accelerated aging tests in-situ with spectroscopic techniques would provide deeper insights into the stability of Na-doped $BiFeO_3$ solar cells.

Finally, this work allowed for the calculation of the efficiency of light conversion into electrical energy of three perovskite cells, in which samples doped with 0 %, 8 % and 10 % sodium were used as the active layer. It was observed that the efficiency increases with the insertion of the host cation and that the differences are a consequence of the purity, morphology and structures of the phases present in the material, so that perovskites of the $Na_{(x)}Bi_{(1-x)}.FeO_{3-\delta}$ type are an alternative to consider for the study of second and third generation photovoltaic devices. In addition, it was possible to verify that the cell architecture is functional and has efficiencies similar to those found by other researchers for $BiFeO_3$-based cells.

4 Conclusions

The efficiency of thin-film cells assembled with Na-doped BFO samples as the absorber layer, allowed for the conclusion that the insertion of the host cation improves the electrical and optoelectronic properties of the BFO for its use in design of solar cells. An increase of 0.32 % in efficiency was found when the BFO was doped with 10 % sodium which allowed obtaining a cell with an approximate efficiency of 0.41 % for the glass/ITO/CdS/NaBFO-10/Au/Mo/glass assembly, so that the sample with 63.95 % of the $Na_{0.10}Bi_{0.90}FeO_{2.895}$ phase is the sample used in this work with better structural properties for the construction of PSCs. Therefore, the hypothesis formulated in this work is accepted and it is confirmed that the structural modification of BFO with Na atoms improves the efficiency of perovskite-based thin-film absorber layer photovoltaic devices.

The *n-i-p* configuration (where *i* and *p* are formed only by perovskite) proposed in this work was functional, comparing the measured values with those reported by other authors using similar architectures *p-i-n* and *n-i-p* type along different layers. For future work, it is recommended to explore alternative thin-film solar cell structures, where the *p-i-n* junction is standardized to favor the recombination processes and to control the interaction between the irradiated light and the reflected light due to reflective phenomena in the cell.

References

[1] Lee, T.D., and Ebong, A.U., A review of thin film solar cell technologies and challenges. Renewable and Sustainable Energy Reviews, 70, pp. 1286–1297, 2017. DOI: https://doi.org/10.1016/j.rser.2016.12.028.

[2] Zeman, M., and Schropp, R.E.I., 1.17 - Thin-Film Silicon PV Technology. Comprehensive Renewable Energy, A. Sayigh, Ed., Oxford: Elsevier, 2012, pp. 389–398. DOI: https://doi.org/10.1016/B978-0-08-087872-0.00119-0.

[3] Efaz, E.T. et al., A review of primary technologies of thin-film solar cells. Engineering Research Express, 3(3), art. 032001, 2021. DOI: https://doi.org/10.1088/2631-8695/ac2353.

[4] Tanimoto, H., Arai, H., Mizubayashi, H., Yamanaka, M. and Sakata, I., Light-induced hydrogen evolution from hydrogenated amorphous silicon: Hydrogen diffusion by formation of bond centered hydrogen. J Appl Phys, 115(7), art. 073503, 2014. DOI: https://doi.org/10.1063/1.4865166.

[5] Schüttauf, J.W. et al., Amorphous silicon–germanium for triple and quadruple junction thin-film silicon based solar cells. Solar Energy Materials and Solar Cells, 133, pp. 163–169, 2015. DOI: https://doi.org/10.1016/j.solmat.2014.11.006.

[6] Candelise, C., Winskel, M. and Gross, R., Implications for CdTe and CIGS technologies production costs of indium and tellurium scarcity. Progress in Photovoltaics: Research and Applications, 20(6, pp. 816–831, 2012. DOI: https://doi.org/10.1002/pip.2216.

[7] Fthenakis, V.M. and Moskowitz, P.D., Thin-film Photovoltaic Cells: Health and Environmental Issues in their Manufacture Use and Disposal. Progress in Photovoltaics: Research and Applications, 3(5, pp. 295–306, 1995. DOI: https://doi.org/10.1002/pip.4670030504.

[8] Khalid, S., Sultan, M., Ahmed, E. and Ahmed, W., Chapter 1 - Third-generation solar cells. Emerging Nanotechnologies for Renewable Energy, Elsevier, 2021, pp. 3–35. DOI: https://doi.org/10.1016/B978-0-12-821346-9.00019-5.

[9] Rehman, F. et al., Fourth-generation solar cells: a review. Energy Advances, 2(9), pp. 1239–1262, 2023. DOI: https://doi.org/10.1039/D3YA00179B.

[10] Faridi, A.W. et al., Synthesis and Characterization of High-Efficiency Halide Perovskite Nanomaterials for Light-Absorbing Applications. Ind Eng Chem Res, 62(11, pp. 4494–4502, 2023, DOI: https://doi.org/10.1021/acs.iecr.2c00416.

[11] Bello, S., Urwick, A., Bastianini, F., Nedoma, A.J. and Dunbar, A., An introduction to perovskites for solar cells and their characterisation. Energy Reports, 8, pp. 89–106, 2022. DOI: https://doi.org/10.1016/j.egyr.2022.08.205.

[12] Li, H. et al., Photoferroelectric perovskite solar cells: Principles, advances and insights. Nano Today, 37, p. 101062, 2021. DOI: https://doi.org/10.1016/j.nantod.2020.101062.

[13] Röhm, H., Leonhard, T., Schulz, A.D., Wagner, S., Hoffmann, M.J. and Colsmann, A., Ferroelectric Properties of Perovskite Thin Films and Their Implications for Solar Energy Conversion. Advanced Materials, 31(26), art. 1806661, 2019. DOI: https://doi.org/10.1002/adma.201806661.

[14] Luo, Q., 8 - Applications in photovoltaics. Solution Processed Metal Oxide Thin Films for Electronic Applications, Z. Cui and G. Korotcenkov, Eds., Elsevier, pp. 109–140, 2020. DOI: https://doi.org/10.1016/B978-0-12-814930-0.00008-6.

[15] Zhao, Q., Zhou, B., Luo, L., Duan, Z., Xie, Z. and Hu, Y., A literature overview of cell layer materials for perovskite solar cells. MRS Commun, 2023. DOI: https://doi.org/10.1557/s43579-023-00467-7.

[16] Hossain, M.K. et al., An extensive study on multiple ETL and HTL layers to design and simulation of high-performance lead-free $CsSnCl_3$-based perovskite solar cells. Sci Rep, 13(1), art. 2521, 2023. DOI: https://doi.org/10.1038/s41598-023-28506-2.

[17] Shpatz, A., and Etgar, L., Study of electron transport layer-free and hole transport layer-free inverted perovskite solar cells. Solar RRL, 6(1), art. 2100578, 2022. DOI: https://doi.org/10.1002/solr.202100578.

[18] Dong, J. et al., Efficient perovskite solar cells employing a simply-processed CdS electron transport layer. J Mater Chem C Mater, 5(38), pp. 10023–10028, 2017. DOI: https://doi.org/10.1039/C7TC03343E.

[19] Luo, C. et al., Constructing CdS-based electron transporting layers with efficient electron extraction for perovskite solar cells. IEEE J Photovolt, 11(4), pp. 1014–1021, 2021. DOI: https://doi.org/10.1109/JPHOTOV.2021.3077445.

[20] Shetty, C., Veena Devi Shastrimath, V. and Bairy, R., Tuning the structural, morphological and optical properties of Sr-doped BFO thin films. Phase Transitions, 95(3), pp. 202–211, 2022. DOI: https://doi.org/10.1080/01411594.2022.2032056.

[21] Renuka, H. et al., Enhanced photovoltaic response in ferroelectric Ti-doped BFO heterojunction through interface engineering for building integrated applications. Solar Energy, 225, pp. 863–874, 2021. DOI: https://doi.org/10.1016/j.solener.2021.08.002.

[22] Raj, A. et al., Comparative analysis of 'La' modified BiFeO3-based perovskite solar cell devices for high conversion efficiency. Ceram Int, 49(1), pp. 1317–1327, 2023. DOI: https://doi.org/10.1016/j.ceramint.2022.09.112.

[23] Gebhardt, J. and Rappe, A.M., Doping of $BiFeO_3$: a comprehensive study on substitutional doping. Phys Rev B, 98(12), art. 125202, 2018. DOI: https://doi.org/10.1103/PhysRevB.98.125202.

[24] Chang, S., Chen, C., Jiang, X., Zhao, C. and Chen, J., Improved chemical defects, domain structure and electrical properties of $BiFeO_3$–$BaTiO_3$ lead-free ceramics by simultaneous Na/Bi codoping and quenching process. Ceram Int, 49(10), pp. 16191–16198, 2023. DOI: https://doi.org/10.1016/j.ceramint.2023.01.217.

[25] Mao, W. et al., Effect of Ca doping on photovoltaic effect of $BiFeO_3$. Applied Physics A, 127(7), art. 508, 2021. DOI: https://doi.org/10.1007/s00339-021-04651-1.

[26] Wang, X. et al., Novel electrical conductivity properties in Ca-doped $BiFeO_3$ nanoparticles. Journal of Nanoparticle Research, 17(5), art. 209, 2015. DOI: https://doi.org/10.1007/s11051-015-3018-1.

[27] Zhang, H. et al., Novel behaviors of multiferroic properties in Na-Doped $BiFeO_3$ nanoparticles. Nanoscale, 6(18), pp. 10831–10838, 2014. DOI: https://doi.org/10.1039/C4NR02557A.

[28] Li, J. and Guan, X.Y., Structural and optical properties of Ce doped $BiFeO_3$ nanoparticles via sol–gel method. Micro Nano Lett, 14(13), pp. 1307–1311, 2019. DOI: https://doi.org/10.1049/mnl.2019.0236.

[29] Tang, P., Cao, M., Yu, J., Wang, L. and Zhang, D., Influence of Ba–Cr substitution on structural, optical and magnetic properties of nanocrystalline $BiFeO_3$. Journal of Materials Science: Materials in Electronics, 32(8), pp. 11028–11042, 2021. DOI: https://doi.org/10.1007/s10854-021-05762-4.

[30] Ameer, S., Jindal, K., Tomar, M., Jha, P.K. and Gupta, V., Effect of Li doping on the electronic and magnetic properties of $BiFeO_3$ by first principles. Integrated Ferroelectrics, 193(1), pp. 123–128, 2018. DOI: https://doi.org/10.1080/10584587.2018.1514875.

[31] Kumar, A.M., Peter, I.J., Ramachandran, K., Mayandi, J. and Jayakumar, K., Influence of Al-Cu doping on the efficiency of $BiFeO_3$ based perovskite solar cell (PSC). Mater Today Proc, 35, pp. 62–65, 2021. DOI: https://doi.org/10.1016/j.matpr.2019.05.454.

[32] Chatterjee, S., Bera, A. and Pal, A.J., p–i–n Heterojunctions with $BiFeO_3$ Perovskite Nanoparticles and p- and n-Type Oxides: Photovoltaic Properties. ACS Appl Mater Interfaces, 6(22), pp. 20479–20486, 2014. DOI: https://doi.org/10.1021/am506066m.

[33] Sharma, S., Reshi, H.A., Siqueiros, J.M. and Raymond Herrera, O., Stability of rhombohedral structure and improved dielectric and ferroelectric properties of Ba, Na, Ti doped $BiFeO_3$ solid solutions. Ceram Int, 48(2), pp. 1805–1813, 2022. DOI: https://doi.org/10.1016/j.ceramint.2021.09.261.

[34] Si, S., Deng, H., Wang, T., Yang, P. and Chu, J., Structural phase transition, optical bandgap, interband electronic transition, and improved magnetism in bivalent Ca-, Sr-, Pb-, and Ba-doped $BiFeO_3$ ceramics. Journal of Materials Science: Materials in Electronics, 31(11), pp. 8464–8471, 2020. DOI: https://doi.org/10.1007/s10854-020-03381-z.

[35] Bautista-Morantes, A.B., Calderón-Carvajal, C.O., Gómez-Cuaspud, J.A. and Vera-López, E., Synthesis of $Na_{0.02}Bi_{0.98}FeO_{3-\delta}$ through the standardized preparation of $BiFeO_3$. Mater Sci Energy Technol, 2023. DOI: https://doi.org/10.1016/j.mset.2023.10.003.

[36] Kumar, A., Shkir, M., Somaily, H.H., Singh, K.L., Choudhary, B.C. and Tripathi, S.K., A simple, low-cost modified drop-casting method to develop high-quality $CH_3NH_3PbI_3$ perovskite thin films. Physica B Condens Matter, 630, art. 413678, 2022. DOI: https://doi.org/10.1016/j.physb.2022.413678.

[37] Kumar, A., Zhang, Y., Li, D. and Compton, R.G., A mini-review: How reliable is the drop casting technique? Electrochem commun, 121, art. 106867, 2020. DOI: https://doi.org/10.1016/j.elecom.2020.106867.

[38] Kambezidis, H.D., 3.02 - The Solar Resource. Comprehensive Renewable Energy (Second Edition), T. M. Letcher, Ed., Oxford: Elsevier, pp. 26–117, 2022. DOI: https://doi.org/10.1016/B978-0-12-819727-1.00002-9.

[39] Markvart, T. and Castañer, L., Chapter I-1-A - Principles of solar cell operation. McEvoy's Handbook of Photovoltaics (3rd Ed.). Academic Press, 2018, pp. 3–28. DOI: https://doi.org/10.1016/B978-0-12-809921-6.00001-X.

[40] Ceballos-Sanchez, O. et al., Study of $BiFeO_3$ thin film obtained by a simple chemical method for the heterojunction-type solar cell design. J Alloys Compd, 832, art. 154923, 2020. DOI: https://doi.org/10.1016/j.jallcom.2020.154923.

[41] Xie, Z. et al., Photovoltaic, photo-impedance, and photo-capacitance effects of the flexible (111) $BiFeO_3$ film. Appl Phys Lett, 115(11), art. 112902, 2019. DOI: https://doi.org/10.1063/1.5120484.

[42] Fan, Z., Yao, K. and Wang, J., Photovoltaic effect in an indium-tin-oxide/ZnO/$BiFeO_3$/Pt heterostructure. Appl Phys Lett, 105(16), art. 162903, 2014. DOI: https://doi.org/10.1063/1.4899146.

[43] Sattarian, H., Tohidi, T. and Rahmatallahpur, Sh., Effect of TEA on characteristics of CdS/PbS thin film solar cells prepared by CBD, [Online]. Materials Science-Poland, 34, pp. 540–547, 2016. [visit: January 25, 2025], Available at: https://api.semanticscholar.org/CorpusID:100354693.

[44] Rashid, H. et al., Physical and electrical properties of molybdenum thin films grown by DC magnetron sputtering for photovoltaic application. Results Phys, 14, art. 102515, 2019. DOI: https://doi.org/10.1016/j.rinp.2019.102515.

[45] Hajjiah, A., Badran, H., Kandas, I. and Shehata, N., Perovskite solar cell with added Gold/Silver Nanoparticles: enhanced optical and electrical characteristics. Energies (Basel), 13(15), art. 153854, 2020. DOI: https://doi.org/10.3390/en13153854.

[46] Lakmal, A.A.I., Kumarasinghe, R., Seneviratne, V.A., Thanihaichelvan, M. and Dassanayake, B.S., Effect of CdS layer thickness on thermally evaporated-CdS/CdTe solar cell efficiency. Journal of Materials Science: Materials in Electronics, 33(19), pp. 15627–15637, 2022. DOI: https://doi.org/10.1007/s10854-022-08467-4.

[47] Hubbard, S., Recombination. Photovoltaic Solar Energy, 2016, pp. 39–46. DOI: https://doi.org/10.1002/9781118927496.ch5.

[48] Khan, M. et al., Improving the efficiency of dye-sensitized solar cells based on rare-earth metal modified bismuth ferrites. Sci Rep, 13(1), art. 3123, 2023. DOI: https://doi.org/10.1038/s41598-023-30000-8.

[49] Singh, J.K., Mandal, S.K., and Banerjee, G., Refractive index of different perovskite materials. J Mater Res, 36(9), pp. 1773–1793, 2021. DOI: https://doi.org/10.1557/s43578-021-00257-8.

[50] Kim, M.S., Lee, J.H. and Kwak, M.K., Review: surface texturing methods for solar cell efficiency enhancement. International Journal of Precision Engineering and Manufacturing, 21(7), pp. 1389–1398, 2020. DOI: https://doi.org/10.1007/s12541-020-00337-5.

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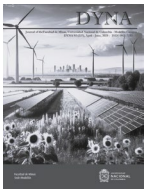

UNIVERSIDAD NACIONAL DE COLOMBIA

Peace and Region Semester, a strategy for comprehensive university training and contribution to regional development

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Abstract
Service-Learning (S-L) is a pedagogical strategy employed by Higher Education Institutions (HEIs) to promote the comprehensive and relevant education of their students, as well as to facilitate the social outreach of these institutions in their geographical area of influence. An example of the implementation of this strategy is the Peace and Region Semester (PRS) at the University of Ibagué, located in the Tolima region of Colombia. The results of the impact analysis generated by the PRS on a pilot group of 105 students who participated in the PRS during the 2023A period, using various statistical techniques, suggest that this pedagogical strategy does contribute to the comprehensive education of students and serves as a pathway for the university to make an effective contribution to regional development.

Keywords: service learning; social impact; university education; competency measurement; project management.

Semestre Paz y Región, una estrategia para la formación universitaria integral y la contribución al desarrollo regional

Resumen
El Aprendizaje en Servicio (ApS) es una estrategia pedagógica empleada por las Instituciones de Educación Superior (IES) para promover la formación integral y pertinente de sus estudiantes, así como para facilitar la proyección social de estas Instituciones en su área geográfica de influencia. Un ejemplo de la implementación de esta estrategia es el Semestre Paz y Región (SPR) de la Universidad de Ibagué, ubicada en la región del Tolima en Colombia. Los resultados del análisis del impacto generado por el SPR en un grupo piloto de 105 estudiantes que realizaron el SPR en el periodo 2023A, utilizando diversas técnicas estadísticas, sugieren que esta estrategia pedagógica si contribuye a la formación integral de los estudiantes, y es el camino que facilita que la Universidad aporte de manera efectiva al desarrollo regional.

Palabras clave: aprendizaje en servicio; impacto social; educación universitaria; medición de competencias, gestión de proyectos.

1 Introduction

Comprehensive education is a pedagogical strategy focused on the development of skills and competencies, which allow individuals to interact effectively in society through the acquisition of technical and professional knowledge, ethical values, social skills and a critical and reflective attitude when interacting with their environment. When following this strategy, educational institutions must assume the responsibility of training individuals capable of contributing to economic and social development in the search for a more equitable and just society [1,2].

On the other hand, Service Learning (S-L) is an educational methodology that unites academic learning with community service, where students apply their knowledge and skills in projects that address real needs in their environment, promoting social commitment to strengthen communities and fostering an attitude of service and responsibility among students [3]. Experiences reported at the university level in international environments have been successful in face-to-face learning environments [4-6] as well as in digital learning environments [7].

Both strategies have been adopted by the University of Ibagué (Unibagué) in order to create the Peace and Region

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Semester (PRS), an academic and practical strategy whose purpose is to complement the disciplinary and comprehensive training of students in their last semester, as well as to promote sustainable human development in the region [8]. Throughout the twelve years of operation in which this strategy has been carried out, it has not been possible to define a model that allows the PRS to comprehensively evaluate the impact it on students, territories and different organizations involved.

To that end, Unibagué aims to promote the transfer of knowledge and the active participation of local stakeholders in social innovation processes, thereby enabling communities to strengthen their autonomy and access greater opportunities to improve their quality of life. These strategies are designed to build a sustainable model that integrates academia with the local environment, ultimately fostering a positive impact on local socioeconomic development [9]. The fulfillment of this promise within the region is achieved thanks to the S-L model developed in PRS, which helps students to understand the problems of the territory, understand its dynamics and commit themselves to providing solutions to the different needs presented by the organizations and municipalities where they have been linked. Likewise, the regional advisor assigned together with the teachers of the professional programs, play a fundamental role in providing social and pedagogical intention through their accompaniment to the different projects proposed, in order to generate capacities in the communities and entities of the territory [10-12].

For Higher Education Institutions such as Unibagué, which prioritizes a clear regional commitment, it is of vital importance to evaluate the scope of its actions in the territory and to determine how its work is valued and developed by the actors involved in its interdisciplinary practices [13,14]. Therefore, Unibagué's social outreach seeks to make the context of its geographical area of influence known to all its stakeholders and thereby engage various actors of the academic community in the generation of social transformation processes in the territory [15,16].

The PRS strategy lacked standardized metrics and evaluation methodologies that would allow it to recognize opportunities for improvement and the impacts achieved on its stakeholders. Consequently, the PRS did not have the possibility of verifying the socio-formative effect produced in the staff implementing the community projects, and in the organizations and public benefited.

Therefore, the need arose to establish a methodology and validate it to measure the social impact that the PRS generates for its students [17]. The PRS experience needs to be evaluated from different perspectives and fields of study, due to the formative nature with which this strategy was designed [18,19]. This study presents the results of the measurement of the contributions that the PRS strategy generates in their students.

2 Methodology

The measurement of PRS practice as an entity that integrates community service with learning that allows strengthening and transferring the knowledge acquired in the classroom to communities outside the academic world [20,21], was based on the effort to quantify the contribution of PRS to the formation of generic and specific competencies in students.

Data collection was carried out using two instruments: Questionnaire for the *Assessment of the contribution to generic competencies* and the questionnaire for the *Assessment of the experience in the* PRS. In both cases, 105 responses were obtained from 278 students who were enrolled in PRS in the 2023A academic period (representative sample at a confidence level of 95% and a margin of error of 8%).

The questionnaire of *Assessment of the contribution to generic competencies* was structured with 13 questions of the statement type "The Peace and Region experience allowed me to:", through a Likert scale from 1 to 5, to measure the impact for the development of the four general competencies desired in the graduates of Unibagué:

- *Learning to learn* (C1): It is the ability to adequately use cognitive and metacognitive learning strategies to optimize the learning process. It also implies the ability to reflect on how knowledge is shared and how to act accordingly, self-regulating the learning process itself through the use of flexible strategies appropriate to new situations [22,23].
- *Teamwork* (C2): It is the strengthening of capacities to interact with different social groups in a horizontal process and with a willingness to learn in the face of culturally diverse knowledge. At the same time, skills are stimulated to interact and develop activities with other people in function of common objectives and in different contexts [24,25].
- *Personal autonomy and initiative* (C3): It is the ability to imagine, undertake, develop and evaluate individual or collective actions or projects with creativity, confidence, responsibility and critical sense. This allows them to become aware of their knowledge, skills and environment in order to act on it, while enabling the discovery of their own opportunities for the implementation of individual and collective projects [26,27].
- *Citizenship education* (C4): It is the deepening of the duties that as human beings must be assumed in daily coexistence and with a future perspective. It is about moving towards a citizenship in which critical reflection serves as a bridge for committed action [28,29].

The questionnaire included an open-ended question at the end of the questionnaire to inquire about the greatest impact generated by the PRS on their personal and professional life.

On the other hand, the application of the institutional instrument of *Evaluation of the experience in the* PRS to the same group of students, allowed for the obtain of information on various aspects of the experience, such as:

- Achievement of the specific competencies expected in PRS: On a Likert scale of 1 to 5, respondents rated the contributions to achieve the competencies in: a) Teamwork and assertive communication (TAC), b) Awareness of territorial issues (ATI), c) Adapting to diverse contexts (ADC), d) Problem solving (PS), e) Learning to learn (LL), and, finally, f) Understanding the environment (UE).
- Perceived contribution to Comprehensive Training (CT): Students rated on a categorical scale whether PRS contributed "Significantly", "In some aspects" or "Little or not at all" to their formation as citizens and professionals.

- Perceived contribution to Regional Development (RD): This was assessed through a three-level categorical scale: "Significantly", "In some aspects" or "Little or not at all", considering their contribution to the improvement of several critical areas in the municipality where they were assigned.

The general characterization variables of the PRS, that were considered to analyze differences in students' valuation of the PRS' contribution, were:

- Disciplinary field of the student (Df). Each student was classified in one of three categories: "Engineering" (ENG), "Management Sciences" (MANG), and "Humanities-Political Sciences" (HPC).
- Gender of the student (Gn) was divided in two categories: "Male" (M) and "Female" (F).
- Municipality of Tolima where the student was assigned (Mp), considering two categories: "Capital city" (CC), "Non capital city" (NCC).
- Zone where the experience took place (Zn), distinguishing between two categories: "Urban zone" (UZ) and "Rural zone" (RZ).
- Project Line (Pl) in which the PRS was focused, considering four categories: a) "Strengthening of the private enterprises, associations and non-profit organizations" (SEO); b) "Strengthening of public services entities" (IMPS); c) "Strengthening of the health and education entities" (SHE); and d) "Strengthening of public management in state entities" (SPM).
- Type of Entity (Te) where the experience took place, considering three categories: "Government and Public Management Entities" (GPE), "Productive and Social Organizations" (PSO), and "Educational and Health Entities (EHE).
- Advisor Experience (Ae): They were classified in two categories: "Expert Advisor" (EXP) with three years or more in the PRS, and "Novice Advisor" (NEXP) with less than three years in the PRS.

Initially, the reliability of the survey instrument was confirmed using Cronbach's alpha coefficient. The values obtained exceeded 0.70 for each set of questions administered to measure each competency, indicating that the items consistently measured the same construct and providing a solid basis for further analysis of the results.

In order to synthesize the information contained in the items associated with each of the generic competencies, an Exploratory Factor Analysis (EFA) was applied. This statistical technique enables the identification and grouping of observed variables into underlying factors, thereby reducing data complexity and facilitating the interpretation of latent dimensions. The selection of EFA to examine the PRS experience was justified by the nature of the variables, which were collected using Likert-type scales. Although these scales yield ordinal data, they are commonly treated as quasi-continuous in this type of analysis, provided that the scales comprise at least five response categories and certain normality assumptions are met, thereby allowing the extraction of relevant information regarding the underlying structures.

The Factor Analysis was based on the common factor model, which postulates that each observed variable X_j can be expressed as a linear combination of m factores latent factors plus an error term ε_j; where λ_j represents the matrix of factor loadings and F_m the vector of latent factors [30, 31]. Formally, this is expressed as:

$$X_j = \lambda_{j1}F_1 + \lambda_{j2}F_2 + \cdots + \lambda_{jm}F_m + \varepsilon_{j,} \qquad J = 1, \ldots, p.$$

or in matrix form:

$$X_j = \lambda F + \varepsilon$$

For the extraction of factors, the Principal Components (PC) method was employed, recognized as one of the most commonly used parameter estimation methods in Factor Analysis. The optimal number of factors was determined by applying Kaiser's eigenvalue criterion, retaining those factors with eigenvalues greater than 1. This procedure was complemented by an examination of the scree plot and an evaluation of the cumulative percentage of variance explained, with the aim of accounting for a significant proportion of the total variance (ideally close to 100%).

Additionally, the Kaiser-Meyer-Olkin (KMO) index was calculated to assess sample adequacy for conducting the factor analysis; high KMO values (typically above 0.70) confirm that the correlations among items are sufficiently robust to justify factor extraction (Tab. 1).

3 Results

The results of this study are divided into three sections: contribution to generic competencies, contribution to specific competencies and analysis of differences by general characterization variables.

3.1 PRS contribution to the generic competencies

For this analysis, we first resorted to Principal Component Factor Analysis (PA) to reduce the estimation of each construct associated with each of the four generic competencies defined to a single measure (the 1st Component). The PA performance measures demonstrated an adequate fit of the technique to the data collected for the corresponding competencies together with their weighted averages (Tables 1, 2).

As suggested by Fig. 1 and Table 3, the averages for each competency evaluated in the graduating students showed a highly positive value in the four generic competencies evaluated (C1 to C4). Particularly noteworthy is the higher value given by the surveyed group to the contribution of the PRS to the development of competencies associated with the development of autonomy and personal initiative, as well as to the development of citizenship training. In the first case, this is explained because the PRS represents for most of the students a move away from the University environment, as well as from their family environment, to enter for four months in the context of the assigned problems in a population of the territory. In the second case, this is explained by the fact that students are exposed to the problems of the region that motivate them to change their attitudes and opportunities to reinforce their formation as citizens. The high scores show a generalized positive impact of the PRS academic strategy for the development of generic competencies expected in students graduating from Unibagué.

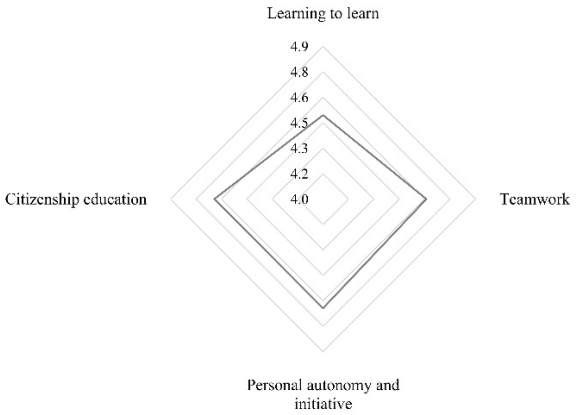

Figure 1. Average score per competency evaluated.
Source: This study

Table 1.
Results of the Principal Component Factor Analysis (n=103)

Question#	Weight	C	KMO	Cronbach's alpha	Var%
1	0.590	C1	0.764	0.746	57.03
2	0.578				
5	0.502				
9	0.611				
3	0.649	C2	0.806	0.841	67.78
4	0.700				
6	0.719				
7	0.643				
8	0.847	C3	0.5	0.817	77.80
10	0.847				
11	0.691	C4	0.707	0.836	75.32
12	0.763				
13	0.806				

Source: This study

Table 2.
Questionnaire of questions by PRS exit competency.

#	Affirmation	C
1	Acquire new learning or knowledge through my participation in the project components and understanding of the environment.	C1
2	Apply in professional and personal contexts, the skills, habits and values that I acquired in my integral formation process.	
5	Express my ideas and suggestions to my coworkers, in a clear and precise manner.	
9	To question myself about the position I have before reality and the dynamics of the environment.	
3	Improve the way I communicate with work teams and my superiors.	C2
4	Improve my ability to adapt to the environment in any context where I participate.	
6	Learning to make decisions by working collectively and collaboratively.	
7	Obtain the ability to contribute to an adequate coexistence in the social contexts where I participate.	
8	Reflect and act in order not to remain indifferent to the needs and problems of the social environment.	C3
10	To have a greater sense of responsibility, punctuality and commitment to my work.	
11	To apply my knowledge and skills for the common good as one of my purposes as a professional.	C4
12	To want to be a professional who contributes to the improvement of my immediate environment.	
13	Evaluate and reflect on the problems and challenges of my work and social environment, in order to propose scenarios or initiative proposals that provide solutions.	

Source: This study

Table 3.
Weighted average by exit competency PRS.

C	Average	Deviation	Max	Min
C1	4.50	0.62	5.0	3.0
C2	4.61	0.55	5.0	3.0
C3	4.64	0.54	5.0	3.0
C4	4.64	0.57	5.0	3.0

Source: This study

In this regard, the testimonies of the students surveyed corroborate the contributions of the PRS to their integral formation, from the four competencies evaluated, as can be seen below:

- Learning to learn (C1): Students agree that the PRS experience allowed them to adopt new knowledge that they did not know because it was foreign to their undergraduate degree and professional focus. Likewise, it allowed them to increase their capacities and skills, since the experience takes place in the municipalities, where students have to coexist with the communities for 15 weeks. This achievement is evidenced in the following testimony:

  > "In my case, the Paz y Región experience allowed me to awaken and get to know many ideas, knowledge and skills that were perhaps dormant inside me, as well as allowing me to visualize myself at a multidisciplinary level".

- Teamwork (C2): Some of the skills that were strengthened were decision-making, collaborative work and communication with the people around them. The students affirm that their ability to relate to others in personal and work environments was improved during their stay in the organization where they developed their PRS experience. This is supported by the following testimony:

  > "Working with people with disabilities was a big challenge for me at the beginning, I was afraid of making mistakes or maybe not being able to communicate with them, but in reality it was an enriching and very nice experience, I learned a lot from each one of them and to communicate in different ways, for me it will always be the most beautiful learning and the biggest challenge".

- Personal autonomy and initiative (C3): The PRS experience also contributed to self-management of time and sense of belonging with the student's work in the organization, since the student is confronted with countless situations where they have to make decisions quickly, also because the experience becomes a space for self-recognition and reflection of their own life projects, as seen in the following testimony:

  > "The big impact it generated on a personal and professional level was the responsibility of every day delivering something on time, as there were people involved in between who could be affected by not completing the corresponding tasks on time".

- Citizenship training (C4): Finally, the PRS contributes to the student's awareness and knowledge of the social context by exposing him/her to the different realities and

dynamics of the region outside his/her daily life, as can be seen in the following excerpt:

> "Getting to know different contexts that people live in the municipality where I live, contexts of which I was ignorant... it is undoubtedly one of the greatest learnings I have had in student experience, it generated a great impact on my way of seeing life and how I want to focus my professional life."

3.2 Contribution to the specific competencies expected

For this analysis, we used average values generated by each student's evaluation of the six specific competencies expected in PRS: a) Working in teams and communicating assertively (TEyCA), b) Becoming aware of the problems of the territory (TCPT), c) Adapting to diverse contexts (ACD), d) Solving problems (SP), e) Learning to learn (AA), and finally, f) Understanding the environment (CE). The measures are average values and their position relative to each other, on a scale of 1 to 5 (Fig. 2).

The data presented in Fig. 2 and Table 4, indicate average values greater than 4.30/5.00 for all the specific PRS competencies assessed. This suggests a positive and sustained impact of the program on the development of soft skills in students, such as the competencies to adapt to diverse contexts (ADC) and to learn to learn (LL), and to a lesser degree, on the ability to become aware of territorial issues (ATI).

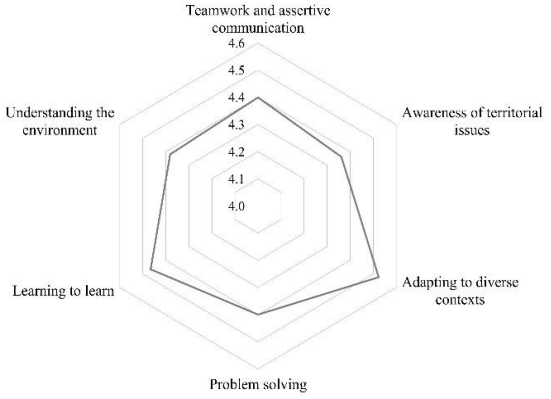

Figure 2. Average by specific competency evaluated in PRS
Source: This study

Table 4.
Assessment of the achievement of the specific competences expected in PRS

C	Average	Deviation	Max	Min
TEyCA	4.40	0.85	5	1
TCPT	4.36	0.90	5	1
ACD	4.52	0.81	5	1
SP	4.40	0.93	5	1
AA	4.47	0.90	5	1
CE	4.38	0.86	5	1

Source: This study

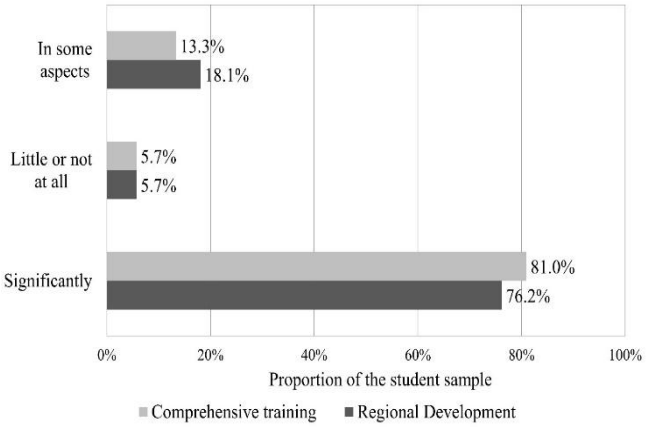

Figure 3. Assessment of the general impact of the PRS
Source: This study

The average evaluation of the PRS' contribution to Comprehensive Training and Regional Development, is summarized in Fig. 3. It shows that the PRS as a pedagogical strategy contributes significantly to Comprehensive Training according to the opinion of 80.95% of the students surveyed. Similarly, it shows that the PRS as a pedagogical strategy contributes significantly to Regional Development according to the opinion of 76.19% of the students surveyed. As Fig. 3 confirms, the students' perception of the contribution of the PRS shows a similar pattern in both aspects evaluated.

3.3 Analysis of differences in the valuation of the PRS

Finally, this study explored whether the generic variables associated with the student profile (gender, undergraduate) or the profile of the PRS practice (thematic line, intervention entity, tutoring experience, municipality and area), present significant differences in the valuation of the specific impacts generated by the PRS.

For this purpose, the average value of the evaluation of the six specific competencies, coded as: TEyCA, TCPT, ACD, SP, AA, CE, was taken and the new variable AVEC was generated. The Kruskal-Wallis nonparametric statistical test for independent samples was used to estimate whether there were differences between categories, with a significance level of 0.05 for the test decision. The results of this analysis are summarized in Tab. 5.

Regarding the student profile, there is evidence of a greater impact of the PRS on students who have a perception of positive change with respect to their PRS experience with an average of 4.53, and no difference in the impact of the program based on the undergraduate degree that the student is studying or by gender. Likewise, with respect to the internship profile, a greater impact was evidenced in the assignment in educational and public management entities with an average of 4.60 and 4.53 respectively. On the other hand, it was corroborated with the p-value that there is no difference in the perception of value when taking PRS, when variables such as the municipality of assignment, area, experience of the advising teacher and the thematic line of the project are considered.

Table 5.
Difference analysis in the valuation of the PRS

Label	Categories	AVEC Average	p-value test	Significant difference
Gender (Gn)	F	4.48[a]	0.111	No
	M	4.30[a]		
Discipline (Df)	ENG	4.42[a]	0.358	No
	MANG	4.31[a]		
	HPC	4.53[a]		
Municipality (Mp)	CC	4.46[a]	0.689	No
	NCC	4.37[a]		
Zone (Zn)	RZ	4.27[a]	0.730	No
	UZ	4.44[a]		
Project line. (Pl)	SEO	4.37[a]	0.403	No
	IMPS	4.25[a]		
	SHE	4.37[a]		
	SPM	4.66[a]		
Type Entity (Te)	GPE	4.50[a]	**0.034**	**Yes**
	PSO	**4.19[b]**		
	EHE	4.60[a]		
Advisor Ex. (Ae)	EXP	4.34[a]	0.066	No
	NEXP	4.59[a]		

Note 1. Similar letter means not difference between those categories
Note 2. Kruskal-Wallis test for independent samples (α=0.05).
Source: This study

3.4 Discussion of results

This analysis allows us to determine, through the application of the two instruments, that the S-L experiences contribute significantly to the integral formation of the students, especially strengthening their general and transversal competencies related to autonomy and personal initiative [27,29], citizenship, teamwork [24] and learning to learn [22]. However, one of the essential characteristics of the Peace and Region Semester is that it configures interdisciplinary learning scenarios, so that students are personally and professionally challenged by having to work with others in real contexts.

This work is consistent with the contributions of Escofet, A. et al. [32], who developed and validated a questionnaire for the assessment of S-L projects in university contexts. In particular, they show, as in this article, that this pedagogical methodology allows students to develop in complex contexts, obtaining from it learning that they then apply in their personal and academic dimensions.

Similarly, the study of Hechenleitner et al. Page 6 and 7 [33] evaluated the impact of a S-L project on kinesiology students at a traditional Chilean university. Their evaluation showed that this type of project helps students to acquire greater social sensitivity to the problems of the territory, a category that is related to the citizenship training component that was evaluated and which obtained an average of 4.64. In this sense, many of the young university students are not aware of the diverse and profound realities of the territories, especially the rural ones, so interacting with the communities allows them to develop a service-oriented vocation.

Autonomy and personal initiative is a competence that allows students to make decisions in their daily lives based on their knowledge, experiences, values and beliefs, so S-L experiences such as the Peace and Region Semester facilitate self-reflective processes that encourage students to question their being and doing, a situation that is not possible to work on in a comprehensive manner in the classroom. In turn, Acosta's study [34] developed and showed from an assessment instrument that these experiences promote the ability to self-manage, plan, manage projects and actions of common benefit, among others.

This research did not include other competencies and characteristics that emerge from service-learning pedagogies in IE and that may be important to take into account in future studies—for example, the type of community with which they work, the hidden curriculum, the level of studies achieved by the students, the ability to work in an interdisciplinary or transdisciplinary way [35], the ability to learn from others, etc.

4 Conclusions

This study has provided the opportunity to have a tool to measure the impact on students who have taken part in the PRS at Unibagué. This first methodological proposal validated with a pilot group of graduates from semester 2023A, provides a new instrument for measuring S-L at Unibagué and for any other Higher Education Institution that develops similar teaching and learning practices.

According to the findings, it is concluded that the PRS experience contributes to the integral formation of the students and graduates by emphasizing the development of skills and knowledge beyond the disciplinary field. Likewise, the highly positive value in the four generic competencies evaluated is highlighted, all of them being above 4 points on a scale where the maximum is 5 possible points, with Autonomy and self-initiative and Citizenship formation being the best valued competencies.

Similarly, the PRS experience contributes to the development of soft skills in students, such as the ability to adapt to diverse contexts (ADC) and to learn how to learn (AA), and to a lesser degree, the ability to become aware of the problems of the territory (APT).

On the other hand, the student's initial perception towards the PRS experience, as well as the type of institution where this experience takes place, are fundamental factors influencing statistically significant differences when evaluating perceived gains in soft skills. Specifically, students who begin with a positive attitude and are assigned to PSO demonstrate significantly greater perceived improvements in these skills.

Through this research, Unibagué has taken a first step to solve the need to measure the impact that PRS generates in the territory by evaluating the perception of its student-graduates. In addition, this project has created a new input to measure the extension of its academic activities and practices based on the commitment it has with the region. Therefore, the implementation of this type of metrics will allow the University to understand the tangible commitment that PRS students have achieved in their role as agents of change for the welfare of the communities located in the geographical areas of influence.

For future research, it is planned to use the outputs of this study to establish a more robust model that incorporates the perspectives of other actors involved in the process, such as Faculty-Advisors, Intermediaries, Interlocutors, and the communities or organizations that benefit from PRS.

References

[1] Nova-Herrera, J., Comprehensive training in higher education: content analysis of political discourses, Praxis & Saber, 8(17), pp. 181-200, 2017. DOI: https://doi.org/10.19053/22160159.v8.n17.2018.7206

[2] Abel, R., Ortiz, A., Yordanka, D., Mirás, G., Maryuri, D., y González, G., Formación integral en la educación superior: una visión cubana, Estudios del Desarrollo Social: Cuba y América Latina, 7(3), 2019. Disponible en: https://www.redalyc.org/articulo.oa?id=585961833005

[3] Mateu, S., Service-learning methodology as an educational factor of resilience, INFAD Journal of Psychology, International Journal of Developmental and Educational Psychology, 4(1), pp. 255-266, 2019. DOI: https://doi.org/10.17060/ijodaep.2019.n1.v4.1554

[4] Pless, N., Maak, T., and Stahl, G.K., Developing responsible global leaders through international service-learning programs: the Ulysses experience. Academy of Management Learning and Education, 10(2), pp. 237-260. DOI: https://doi.org/10.5465/amle.10.2.zqr237

[5] Kim, H., Choi, Y., and Han, J., Exploring key service-learning experiences that promote students' learning in higher education, Journal of Service-Learning in Higher Education, 12, pp. 1-15. DOI: https://doi.org/10.1007/s12564-023-09833-5

[6] Myers, M.J., 2023. 'Poner En Práctica' (Put into Practice): impacts of service-learning for university students in the Dominican Republic, International Journal of Research on Service-Learning and Community Engagement, 11(1), art. 91727, 2023. DOI: https://doi.org/10.37333/001c.91727

[7] Ruiz, M., and García, J., Aprendizaje-Servicio en escenarios digitales de aprendizaje: propuesta innovadora en la educación superior, RIED-Revista Iberoamericana de Educación a Distancia, 23(1), pp. 183-198, 2020. DOI: https://doi.org/10.5944/ried.23.1.24391

[8] Consejo Superior de la Universidad de Ibagué, Proyecto Educativo Institucional – PEI – Acuerdo 315 de 2014, Ibagué: Ediciones Unibagué, 2014.

[9] Forero-Jiménez, M.Y., Modelo de responsabilidad social universitaria: una propuesta para las instituciones colombianas, Revista de Investigación, Desarrollo e Innovación, 9(2), pp. 249-260, 2019. DOI: https://doi.org/10.19053/20278306.v9.n2.2019.9160

[10] González-Aportela, O., Batista-Mainegra, A., y Fernández-Larrea, M. G., Sistema de gestión de la calidad del proceso de extensión universitaria, una experiencia en la Universidad de La Habana, Revista Electrónica Calidad en la Educación Superior, 11(2), pp. 105-134, 2020. DOI: https://doi.org/10.22458/caes.v11i2.3324

[11] Duarte da Silva L., and Alves, L.R., The management of university extension: a new synergy between the three pillars of university higher education, Invenio, [online]. 18(34), pp. 9-22, 2015. Available at: https://www.redalyc.org/articulo.oa?id=87739279002

[12] Vallaeys, F., University Social Responsibility: the URSULA model, strategies, tools, indicators, Lima: Union of Latin American University Social Responsibility, 2019.

[13] Santamaria M., and Centurion, A., Socio-educational program of Solidarity Learning and Service to improve the level of social awareness in university students, TZHOECOEN, 10, pp. 66-74, 2018. DOI: https://doi.org/10.26495/rtzh1810.125044

[14] García-Pérez Á., y Mendía, R., Acompañamiento educativo: el rol del educador en aprendizaje y servicio solidario, profesorado, Revista de Currículum y Formación de Profesorado, [en línea]. 19(1), pp. 42-58, 2015. Disponible en: https://www.redalyc.org/articulo.oa?id=56738729004

[15] Espinoza-Santeli, G., and Guachamín-Montoya, M., University social responsibility in Ecuador, Estudios de la Gestión [online]. (1), pp. 9-27, 2017. Available at: https://hdl.handle.net/10644/5473

[16] Benneworth, P., and Fitjar, R., Contextualizing the role of universities to regional development: introduction to the special issue, Regional Studies, Regional Science, 6, pp. 331-338, 2019. DOI: https://doi.org/10.1080/21681376.2019.1601593

[17] Jaillier-Castrillón, E., Cardona-Buriticá, J.G., Ramírez-Ramírez, L.F., Cano-Rodríguez, L.T., Arboleda-Jaramillo, C.A., Pérez-Sánchez, E.O., Applying and measuring social innovation Experiences in higher education institutions, Editorial Universidad Pontificia Bolivariana, Medellin, Colombia, 2021, 344 P.

[18] Orozco-Silva, L.E., La Universidad Necesaria, Ediciones Unibagué, Ibagué, Colombia, 2021.

[19] Vallejo, C., Reyes, J., Torrente, J., Rojas, G., González, G., Torres, F., Zabala, F., Peñalosa, L., y Salazar, C., Universidad y región. Modelo de universidad para el desarrollo regional, Ediciones Unibagué, Ibagué, Colombia, 2020. ISBN: 9789587543506.

[20] Thomson et al, Service Learning and community engagement: a comparison of three national contexts, VOLUNTEERS: International Journal of Voluntary and Nonprofit Organizations, 22, pp. 214-237, 2011. DOI: https://doi.org/10.1007/s11266-010-9133-9

[21] Kezar, Redesigning for collaboration in learning initiatives: an examination of four highly collaborative campuses, Journal of Higher Education, 77(5), pp. 804-838, 2006. DOI: https://doi.org/10.1353/jhe.2006.0043

[22] Gargallo-López, B., Pérez-Pérez, C., García-García, F.J., Giménez-Beut, J.A., y Portillo-Poblador, N., La competencia aprender a aprender en la universidad: propuesta de un modelo teórico, Educación XX1, 23(1), pp. 19-44, 2020. DOI: https://doi.org/10.5944/educXX1.23367

[23] Herreros-Martínez, P.J., Competencias clave para el aprendizaje permanente. Un marco de referencia europeo, Supervisión 21: Revista de Educación e Inspección, (34), pp. 1-9, 2014. Available at: https://eur-lex.europa.eu/legal-content/ES/TXT/PDF/?uri=CELEX:32006H0962&fr

[24] Alonso, Y., Cano-Rosás, M., Jimenez, E., and Pousada, T., Attitude towards teamwork in university students, Congresos de la Universitat Politècnica de València, IN-RED 2018: IV Congreso Nacional de Innovación Educativa y Docencia en Red, 1, 2018. DOI: https://doi.org/10.4995/INRED2018.2018.8631

[25] Moreno, F., La formación pedagógica en la competencia trabajo en equipo en el nivel superior, International Journal of Learning, 9, pp. 57-74, 2023. DOI: https://doi.org/10.18848/2575-5544/CGP/v09i02/57-74

[26] Escamilla-González, A., Competencias básicas claves y propuestas para su desarrollo en los centros, Editorial Grao, Barcelona, España, 2008. ISBN: 9788478277711

[27] Espinach-Orús, X., Julián-Pérez, F., Alcalà-Vilavella, M., and Verdaguer-Pujadas, N., Self-management of learning and personal autonomy and initiative, in: Univest III International Congress, [online]. 103, 2011. Available at: https://hdl.handle.net/10256/3759

[28] Venet-Muñoz R., La formación ciudadana en el contexto universitario. Una mirada axiológico-cultural desde la educación para la paz y la no violencia, Conrado, [online]. 15(70), pp. 435-443, 2019. Available at: https://www.uteq.edu.ec/es/investigacion/articulo/218

[29] Orellana-Fonseca, C.E., y Muñoz-Labraña, C., Escuela y formación ciudadana: concepciones de ciudadanía, formación ciudadana y del rol de la escuela. Revista Electrónica Interuniversitaria de Formación del Profesorado, 22(2), art. 370561, 2019. DOI: https://doi.org/10.6018/reifop.22.2.370561

[30] Thurstone, L.L., Multiple-factor analysis. University of Chicago Press, Chicago, USA, 1947.

[31] Harman, H.H., Modern factor analysis, third edition. University of Chicago Press, Chicago, IL, USA, 1976.

[32] Escofet, A., Folgueiras, P., Luna, E. y Palou, B., Elaboración y validación de un cuestionario para la valoración de proyectos de aprendizaje-servicio, Rev. Mex. Investig. Educ., [Online]. 21(70), pp. 929–949, 2016. Available at: https://www.scielo.org.mx/pdf/rmie/v21n70/1405-6666-rmie-21-70-00929.pdf

[33] Hechenleitner-Carvallo, M. y Romero-Mardones, F., Percepción sobre la metodología aprendizaje servicio en estudiantes de kinesiología de una universidad tradicional chilena, Rev. Investig. Educ. Med., 11(41), pp. 61–70, 2021. DOI: https://doi.org/10.22201/fm.20075057e.2022.41.21378

[34] Acosta, K., Percepciones sobre el aprendizaje-servicio en profesores en formación RIDAS Rev. Iberoam. Aprendiz. Serv., (13), pp. 85–98, 2022. DOI: https://doi.org/10.18172/con.4656

[35] Llano-Arana L. et al., La interdisciplinariedad: una necesidad contemporánea para favorecer el proceso de enseñanza aprendizaje, MediSur, [Online]. 14(3), pp. 320–327, 2016. Available at: https://www.redalyc.org/comocitar.oa?id=180045822018

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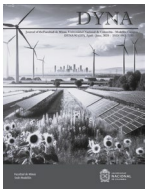

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Exploring infill pattern and density effects on the tensile properties of 3D printed ABS

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Abstract
Fused Deposition Modeling (FDM) is recognized as an efficient method for creating durable, complex parts quickly and affordably. This study examines how different infill patterns and densities affect the mechanical properties of ABS, with specimens produced via FDM for tensile testing. Fourier-transform infrared spectroscopy with attenuated total reflection (FTIR-ATR) identified the functional groups in ABS, while microscopic analysis assessed layer bonding. Results showed that tensile strength increased with higher infill densities and revealed that bonding characteristics of various infill patterns significantly impacted mechanical performance at densities from 25% to 100%. Interestingly, the same infill pattern displayed varied mechanical and bonding properties depending on density, highlighting the importance of selecting optimal infill configurations for specific applications.

Keywords: 3D printing; ABS; infill pattern; tensile strength.

Exploración del efecto del patrón y la densidad de relleno en las propiedades a tracción del ABS impreso en 3D

Resumen
El modelado por deposición fundida (FDM, por sus siglas en inglés) es reconocido como un método eficiente para fabricar piezas duraderas y complejas de forma rápida y económica. Este estudio analiza cómo los diferentes patrones y densidades de relleno afectan las propiedades mecánicas del ABS, con especímenes fabricados mediante FDM para ensayos de tracción. Se utilizó espectroscopia infrarroja por transformada de Fourier con reflexión total atenuada (FTIR-ATR) para identificar los grupos funcionales presentes en el ABS, mientras que el análisis microscópico permitió evaluar la adhesión entre capas. Los resultados mostraron que la resistencia a la tracción aumenta con mayores densidades de relleno, y evidenciaron que las características de unión de los distintos patrones de relleno influyen significativamente en el comportamiento mecánico, en un rango de densidad entre el 25% y el 100%. Curiosamente, un mismo patrón de relleno presentó propiedades mecánicas y de adhesión variables según la densidad, lo que resalta la importancia de seleccionar configuraciones de relleno óptimas para cada aplicación específica.

Palabras clave: impresión 3D; ABS; patrón de relleno; resistencia a la tracción.

1 Introduction

Additive Manufacturing (AM) is no longer a novelty, having become widely used across diverse fields, which include industrial settings, and extends to sophisticated biomedical applications. Among the various AM techniques, Fused Filament Fabrication (FFF) stands out as the most common extrusion process, with its widespread use extending even to domestic use. It consists of a process which deposits material layer by layer [1].

Understanding how various parameters influence the efficiency of printing a part or component continues to raise many questions, particularly regarding strength. It is crucial to recognize that 3D printing involves a multitude of variables, such as infill pattern, infill density, temperature, printing time, and layer height, all of which play a significant role in the outcome [2–4].

Many works have dealt with the influence of infill patterns, which are the internal structures of 3D printed objects. They play a

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crucial role in the mechanical properties of printed components. Different infill patterns, such as honeycomb, grid, triangle, and concentric, exhibit varying mechanical performances depending on the applied loads. Research has shown that infill pattern choice significantly affects not only the tensile strength but also the weight, flexibility, and energy absorption of printed parts [5,6]. For instance, the honeycomb pattern often provides a balance between strength and material usage, while grid patterns offer more isotropic mechanical behavior due to their uniform structure [5,7].

In this context, this works aims at exploring the effects of different infill patterns on tensile properties of 3D printed ABS.

2 Materials and Methods

In this work, a premium 3DLab filament was used, which has a cross-section of 1.75 mm in black color. For the printing, a Creality Ender 3 printer was used. It is currently the best-selling printer worldwide, and it possesses printing dimensions of 220 mm x 220 mm x 250 mm, with a heated bed, which can reach up to 110º C. The extruder assembly can reach up to 255º C, which means it is possible to print most available thermoplastic materials. For the design of the 3D models of the test specimens, Solidworks was used, and for the printer programming, open-source software Cura 5.5.0 was used. Table 1 displays printing parameters for the tested specimens.

Table 1.
Printing parameters.

Parameters	Value
Layer height [mm]	0.2
Extrusion nozzle diameter [mm]	0.5
Printing speed [mm/s]	40
Printing temperature [ºC]	240
Bed temperature [ºC]	95
Extrusion flow [%]	100
Infill orientation [º]	0/90
Top/bottom layers	5

Source: the authors.

To understand the relationship between infill density and pattern, coded samples were created as seen in Table 2.

Table 2.
Sample codification and properties.

Code	Infill density [%]	Infill pattern	Weight [g]	Printing time [min]
P1	25	Grid	10	42
P2	25	Cubic	10	43
P3	25	Lines	10	43
P4	50	Grid	12	50
P5	50	Cubic	12	50
P6	50	Lines	12	51
P7	75	Grid	14	58
P8	75	Cubic	14	56
P9	75	Lines	14	57
P10	100	Grid	16	63
P11	100	Cubic	16	62
P12	100	Lines	16	63

Source: the authors.

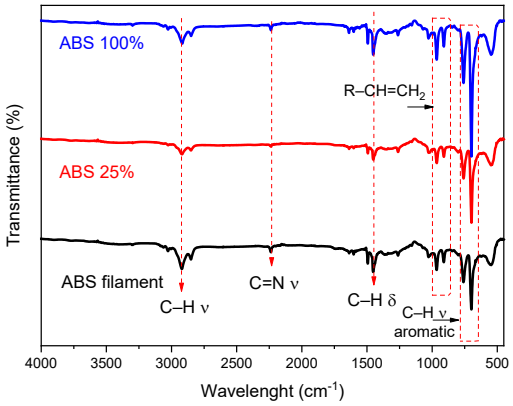

Figure 1. Infrared spectra for pristine ABS, 25% and 100% infill samples. Source: the authors.

After the fabrication of the test specimens, tensile tests were performed on a testing machine DL-30000 EMIC with a maximum load capacity of 300 kN, using a clamp system with a load cell with a 5 kN capacity, which was used during the test. A test speed of 5 mm/min was used, in accordance with ASTM D 638-02a standard. To ensure repeatability, the tensile tests were performed on three specimens fabricated using identical printing parameters.

Fourier-transform infrared spectroscopy with attenuated total reflection (FTIR-ATR) was performed to identify the functional groups present in ABS both before and after printing. The analysis was conducted using a PerkinElmer Spectrum 400 spectrometer. The spectra were acquired in the range of 4000 to 400 cm^{-1}, with a nominal resolution of 4 cm^{-1} and 32 scans. Three conditions were studied: pristine ABS filament, ABS with 25% of density and ABS with 100% density.

3 Results and Discussion

3.1 Fourier Transfom Infrared Spectroscopy

Fourier Transform Infrared Spectroscopy (FTIR) was performed to test the chemical stability of ABS after printing the specimens. With this analysis, it was possible to verify the functional groups existing in the copolymer chain.

It was noted, according to Fig. 1, that there was no change in functional groups, oxidation, or breaking of chemical bonds, indicating that the polymer has good chemical stability under the extreme conditions of 25% and 100% filling. It is possible to observe the typical absorption bands for ABS, as seen in previous works [8].

3.2 Tensile tests

Tensile tests yielded valuable insights into the mechanical behavior of 3D-printed ABS with various infill patterns. For comparative analysis, Fig. 2 presents the tensile stress-strain curves of two contrasting samples, P3 and P12, which exhibited the lowest and highest ultimate tensile strengths,

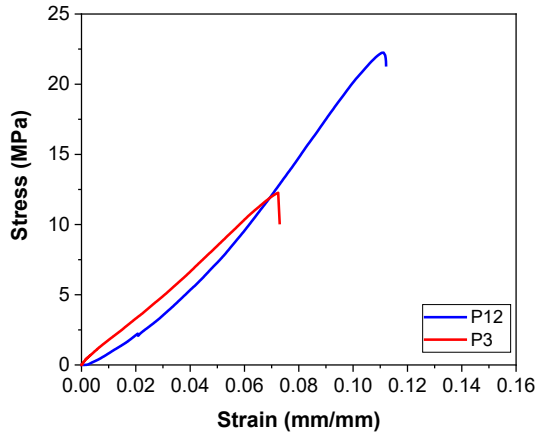

Figure 2. Comparative stress-strain curves for conditions P3 and P12. Source: the authors.

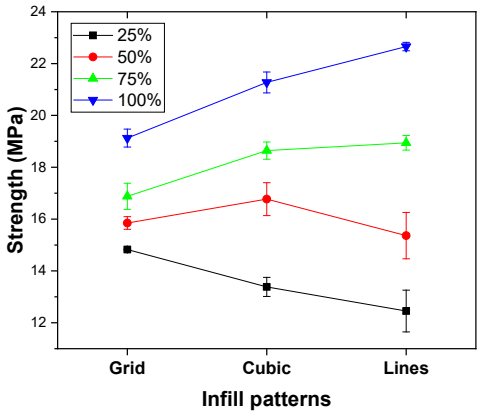

Figure 3. Tensile strength dependance on infill patterns and percentage. Source: the authors.

respectively. Notably, the cross-sectional area used to calculate tensile strength was based on the total nominal cross-section, without accounting for the voids between the printed layers. This approach, while consistent with standard testing protocols, can lead to an underestimation of the material's effective resistance, as observed in similar studies in the literature [9,10].

Previous research has shown that different infill patterns, such as honeycomb or grid, significantly influence the overall tensile strength of 3D-printed materials [11]. The results obtained here align with these findings, confirming that denser, more uniform infill patterns tend to provide superior mechanical properties. However, the interplay between infill pattern and density remains complex, and this study offers additional insights by examining this relationship in ABS specifically. The highest-performing infill patterns in this study, such as P12, demonstrated enhanced tensile strength in line with the results found, who also reported that optimized infill patterns could improve the mechanical performance of printed components.

For further evaluation, Fig. 3 compares ultimate tensile strength of different infill patterns with different densities. As expected, higher infill densities generally resulted in increased tensile strength [12,13]. Interestingly, the grid pattern exhibited the smallest margin of improvement in tensile strength between the lowest and highest densities, indicating a more consistent performance across densities. In contrast, the line pattern showed the greatest increase in tensile strength, highlighting its sensitivity to changes in infill density. Lines pattern, in comparison to cubic and grid, displayed increased tensile strength in previous works as well [14], which can be attributed to the increased material deposition due to the direct load paths created.

Another interesting point is that the specific strength (in MPa g^{-1}) or strength to mass ratio, which accounts for the weight the specimens have, displays different behaviors. Interestingly, grid infill pattern at 25% density displayed highest efficiency. However, it significantly drops at greater densities. For line pattern, specific strength increases according to density, while for cubic it reaches a maximum specific strength at 50% density.

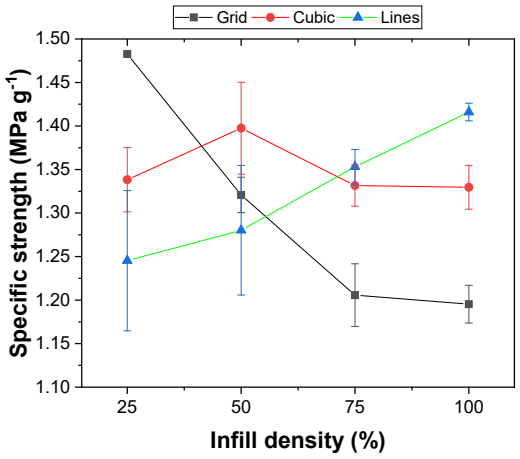

Figure 4. Specific strength dependance on infill density. Source: the authors.

3.3 Microscopic analysis

Microscopy analysis was also performed, to investigate cross section properties of tested specimens. While cross-section in 3D printed components is complex and may not be precisely estimated, microscopic analysis may provide an insight on resistance area. Fig. 5 displays differences between grid, cubic, lines with 25% density and their counterparts with 100% density.

It is important to note that even at 100% infill density, voids and gaps remain, which reduce the effective load-bearing area. For instance, in the grid pattern, interlayer gaps persist, while the cubic pattern becomes significantly more densely packed at 100% density compared to 25% density. This can be perceived by seeing printing paths on Cura software (Fig. 6). For further analysis, the images were processed to obtain quantitative data of filling for each scenario in a Python based script. The script excluded pixels that did not correspond to the characteristic color of the filled regions. Both visual and numerical basis results are displayed in Fig. 6 as well.

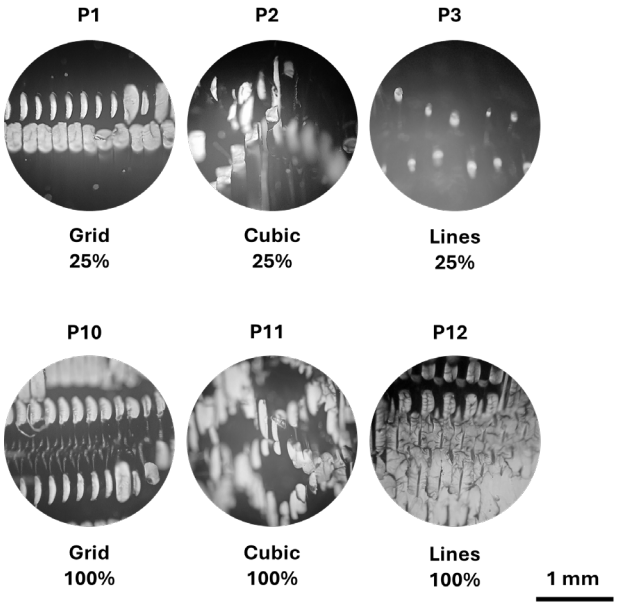

Figure 5. Micrographs displaying the fracture cross-section of three types of infill at an infill density of 100%.
Source: the authors.

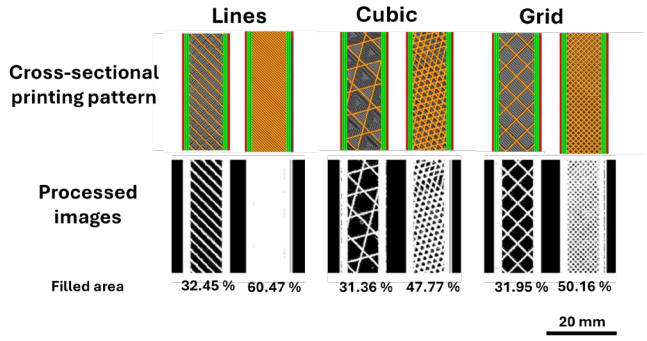

Figure 6. Top row: Representative cross-sectional views of the printed specimens for each infill pattern. Bottom row: Image-processed binarized sections used to calculate the effective filled area. The percentage indicates the fraction of the cross-section occupied by material, allowing direct comparison of infill efficiency across different geometries.
Source: the authors.

The line pattern shows the most substantial increase in effective resistant areas, a result that aligns with the observed tensile test performance. According to Popescu [4], who conducted a review on process parameter influence on mechanical properties, filament bonding determines strength, so the bonding of the layers is favored in more closely packed infill patterns, such as the one in P12. This is also supported by other works [11,15], where it is argued that the inter-layer bonding between consecutive layers. Additionally, while an increase in density leads to a higher mass, it does not directly correlate with a proportional increase in strength. This highlights the importance of selecting the appropriate infill pattern to optimize component performance, balancing both mechanical properties and material efficiency. Such analyses have gained attention in recent years, particularly when ultralight components come into play [16].

4 Conclusions

This study investigated the combined influence of infill pattern and infill density on the mechanical strength of 3D-printed components, offering insights into design considerations for improved performance. Key findings include:

- The experimental design effectively demonstrated the interaction between infill pattern and infill density, providing valuable insights into their combined effects on material strength.
- All infill patterns showed increased tensile strength with higher densities. To enhance comparison, specific strength (MPa g^{-1})—tensile strength normalized by mass—was also analyzed. It revealed distinct trends: the grid pattern showed a decrease, the lines pattern an increase, and the cubic pattern exhibited no consistent behavior, with values falling within the margin of error.
- The resistant area formed by each infill pattern significantly impacts the mechanical response. Even at 100% density, some patterns (e.g., grid and cubic) resulted in voids or gaps that reduced overall strength.
- For efficient and application-specific design, both mass and strength must be considered. If possible, a targeted study should be conducted to identify the most suitable infill pattern for the intended use case.

References

[1] Ebel, B., Sinnermann, T., Fabrication of FDM 3D objects with ABS and PLA and determination of their mechanical properties, [Online]. RTejournal, (1), pp. 1–9, 2014. Available at: https://rtejournal.de/rte/article/view/2014_3

[2] Alagheband, M., Zhang, Q., Jung, S., Investigating the influence of infill patterns and mesh modifiers on fatigue properties of 3D printed polymers. International Journal of Fatigue, 187, art. 108463, 2024. DOI: https://doi.org/10.1016/j.ijfatigue.2024.108463.

[3] Dizon, J.R.C., Espera, A.H., Chen, Q., Advincula, R.C., Mechanical characterization of 3D-printed polymers, Additive Manufacturing, (20), pp. 44–67, 2018. DOI: https://doi.org/10.1016/j.addma.2017.12.002.

[4] Popescu, D., Zapciu, A., Amza, C., Baciu, F., Marinescu, R., FDM process parameters influence over the mechanical properties of polymer specimens: a review. Polymer Testing, (69), pp. 157–66, 2018. DOI: https://doi.org/10.1016/j.polymertesting.2018.05.020.

[5] Dudescu, M.C., Racz, L., Popa, F., Effect of infill pattern on fatigue characteristics of 3D printed polymers, Materials Today: Proceeding, 78(2), 2023, pp. 263–9. DOI: https://doi.org/10.1016/j.matpr.2022.11.283.

[6] Sriya-Ambati, S., Ambatipudi, R., Effect of infill density and infill pattern on the mechanical properties of 3D printed PLA parts, Materials Today: Proceeding, 64(1), 2022, pp. 804–7. DOI: https://doi.org/10.1016/j.matpr.2022.05.312.

[7] Din, S., Xu, W., Cheng, L.K., Dirven, S., A Stretchable Multimodal Sensor for Soft Robotic Applications, IEEE Sensors Journal, 17(17), pp. 5678–5686, 2017. DOI: https://doi.org/10.1109/JSEN.2017.2726099.

[8] Fiorio, R., Díez, S.V., Sánchez, A., D'hooge, D.R., Cardon, L., Influence of different stabilization systems and multiple ultraviolet a (UVA) aging/recycling steps on physicochemical, mechanical, colorimetric, and thermal-oxidative properties of ABS, Materials, 13(1), pp.1–14, 2020. DOI: https://doi.org/10.3390/ma13010212.

[9] Appalsamy, T., Hamilton, S.L., Kgaphola, M.J., Tensile Test Analysis of 3D Printed Specimens with Varying Print Orientation and Infill Density, Journal of Composites Science, 8(4), pp. 1–15, 2024. DOI: https://doi.org/10.3390/jcs8040121

[10] Hozdić, E., Characterization and Comparative Analysis of Mechanical Parameters of FDM- and SLA-Printed ABS Materials, Applied Sciences (Switzerland), 14(2), pp. 1–22, 2024. DOI: https://doi.org/10.3390/app14020649

[11] Qamar-Tanveer, M., Mishra, G., Mishra, S., Sharma, R., Effect of infill pattern and infill density on mechanical behaviour of FDM 3D printed Parts- a current review, Materials Today: proceedings, 62(1), pp. 100–8, 2022. DOI: https://doi.org/10.1016/j.matpr.2022.02.310.
[12] Tzotzis, A., Manavis, A., Efkolidis, N., García-Hernández, C., Kyratsis, P., Analysis of the Influence of Structural Characteristics on the Tensile Properties of Fused Filament Fabricated ABS Polymer Using Central Composite Design, Applied Mechanics, 5(1), pp. 20–35, 2024. DOI: https://doi.org/10.3390/applmech5010002.
[13] Daly, M., Tarfaoui, M., Bouali, M., Bendarma, A., Effects of Infill Density and Pattern on the Tensile Mechanical Behavior of 3D-Printed Glycolyzed Polyethylene Terephthalate Reinforced with Carbon-Fiber Composites by the FDM Process, Journal of Composites Science, 8(4), pp. 1–15, 2024. DOI: https://doi.org/10.3390/jcs8040115.
[14] Sharma, S., Gupta, V., Mudgal, D., Effect of infill pattern on the mechanical properties of polydopamine-coated polylactic acid orthopedic bone plates developed by fused filament fabrication, Polymer Engineering and Science, 63(2), pp. 353–65, 2023. DOI: https://doi.org/10.1002/pen.26210.
[15] Agrawal, A.P., Kumar, V., Kumar, J., Paramasivam, P., Dhanasekaran, S., Prasad, L. An investigation of combined effect of infill pattern, density, and layer thickness on mechanical properties of 3D printed ABS by fused filament fabrication. Heliyon, 9(6), art. 16531, 2023. DOI: https://doi.org/10.1016/j.heliyon.2023.e16531.
[16] Calleja-ochoa, A., Gonzalez-barrio, H., de Lacalle, N.L., Martínez, S., Albizuri, J., Lamikiz, A., A new approach in the design of microstructured ultralight components to achieve maximum functional performance, Materials, 14(7), pp. 1–12, 2021. DOI: https://doi.org/10.3390/ma14071588.

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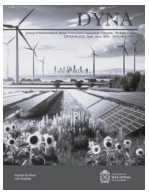

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Development of a water level monitoring and control system for pumping stations in agricultural systems

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Abstract
Monitoring water levels in reservoirs and suction pipes is essential to avoid failures in pumping and agricultural systems. This study aimed to develop an intelligent system for automated monitoring of water levels in irrigated agricultural reservoirs, ensuring safer operation of pumping stations and aiding decision-making. The system enables visualization, water level management, and protection of motor pumps. After assembly and programming, the prototype was installed in a reservoir. Tests showed a difference of less than 5 mm between manual and system measurements. Google Sheets was used for accurate data analysis. The control system includes a contactor, thermal relay, bipolar circuit breaker, simple control relay (activated by the ESP32), and two buttons — one normally closed and one normally open. The proposed intelligent system proved effective for automated water level management in reservoirs.

Keywords: agriculture; water management; limnigraph; ultrasonic sensor.

Desarrollo de un sistema de monitoreo y control del nivel de agua para estaciones de bombeo en sistemas agrícolas

Resumen
El monitoreo de los niveles de agua en los reservorios y tuberías de succión es esencial para evitar fallos en los sistemas de bombeo y en los sistemas agrícolas. Este estudio tuvo como objetivo desarrollar un sistema inteligente para el monitoreo automatizado de los niveles de agua en reservorios de riego agrícola, garantizando un funcionamiento más seguro de las estaciones de bombeo y apoyando la toma de decisiones. El sistema permite la visualización, gestión del nivel de agua y protección de las motobombas. Tras el montaje y la programación, el prototipo fue instalado en un reservorio. Las pruebas mostraron una diferencia de menos de 5 mm entre la medición manual y la realizada por el sistema. Se utilizó Google Sheets para el análisis preciso de los datos. El sistema de control incluye un contactor, relé térmico, disyuntor bipolar, relé de control simple (activado por el ESP32) y dos botones, uno normalmente cerrado y otro normalmente abierto. El sistema propuesto demostró ser eficaz para la gestión automatizada del nivel de agua en reservorios.

Palabras clave: agricultura; gestión del agua; limnígrafo; sensor ultrasónico.

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1. Introduction

The use of technology is currently necessary to assist in the management of natural resources, as well as to support decision-making in agricultural systems. Scientific research applied to agriculture generally requires the use of devices to measure and collect data, which often implies significant costs for project development. However, when technology is developed in a more simplified way, it becomes an ally to the producer, providing greater efficiency and economy.

Although there is no universally accepted definition of what "low-cost" instrumentation is, it refers to any type of sensor, data collector, and data storage device that costs less than conventional instrumentation [1]. The construction of a data logger-sensor set develops skills and competencies that enhance creativity and facilitate the understanding of physical principles and their interactions with the studied phenomena [2–4].

The application of instrumentation for process automation in agricultural systens with more readily available and easy-to-handle components can potentially revolutionize the field of agricultural instrumentation and environmental monitoring, providing high-density spatial-temporal data [5], helping in processes such as the measurement of environmental variables [6], or in the monitoring of soil moisture [7,8], among others [9–13].

Farming systems can be automated using the Internet of Things (IoT), allowing tasks like water distribution verification via irrigation channels and alert systems for low levels [14]. However, implementing these intelligent systems requires qualified technicians for installation, operation, and maintenance [15].

To have an IoT, connected intelligent objects are necessary, where the 'objects' (things) must be designed with embedded hardware, and the term 'intelligent' in turn requires software programming with instructions for the hardware, to provide intelligence to the objects; finally, 'connected', using communication architectures and models to interact with other objects through the internet. For example, [16] proposed an IoT system for monitoring and controlling irrigated systems and found that this system reduced human intervention and wasted water and energy. [17] stated that IoT uses the principles of precision agriculture and can be used to manage water resources in agricultural systems, such as irrigation management and monitoring the water level of reservoirs in real time.

It is crucial to highlight that the availability of water in irrigation projects represents one of the main challenges faced in a pumping system, especially in irrigated areas that do not have a security system in case of water scarcity. In this context, the monitoring system has the purpose of solving this issue, in addition to providing data for more effective planning of water availability and the implementation of low-level alert systems [18]. The monitoring system is one of the main tools, with its real-time control and data generation that enable more efficient analysis and operation [19].

Monitoring the water level in suction pipes is very important to avoid the occurrence of undesirable phenomena in the pumping system. Nowadays, intelligent water supply systems in irrigation projects, especially with long channel lengths, are necessary, as their use can bring numerous advantages for farmers, if they are well implemented [20]. In this sense, the aim of this study was to develop an intelligent system for automated monitoring of water levels in reservoirs within irrigated agricultural systems, to ensure safe operating conditions in pumping stations and support decision-making by managers.

2. Methodology

2.1 Study area

The work was developed to meet the demands of rural producers in the Irrigated Perimeter of the Formoso Project, located in the municipality of Bom Jesus da Lapa, Bahia, Brazil. The perimeter is managed by the Formoso Irrigation District, which performs operation and maintenance of the common and collective structures of the irrigated area. In this case, the District is responsible for the abstraction, diversion, pumping, adduction and distribution of water to the fields.

The Formoso Irrigation Perimeter has a total area of 19,500 hectares, with 12,100 hectares of irrigable area. This area was implemented by the Federal Government, through Codevasf, on the banks of the Corrente River, in the region of the municipality of Bom Jesus da Lapa, with the goal of promoting agricultural and livestock development in the region [21].

2.2 System design

The methodological procedure for the development of the system is divided into several stages, from the conception of the project to the collection and analysis of the obtained data. The procedure follows a simple flowchart of task execution, but each stage is important to ensure the successful observation of the data at the end of the study. Fig. 1 shows the flowchart that outlines the methodological sequence of tasks, using an adaptation of the methodology proposed by [15].

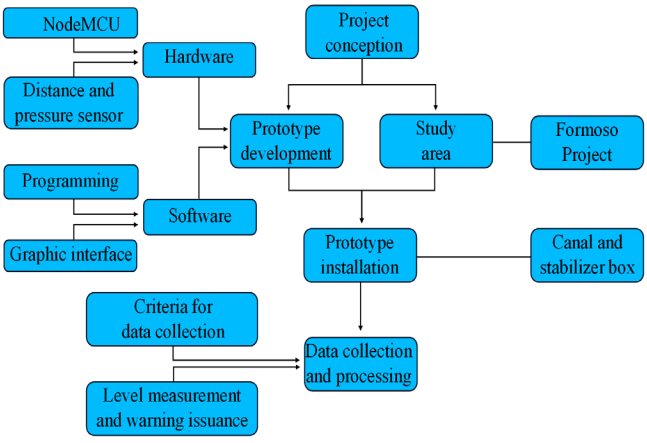

Figure 1. Project design flowchart.
Source: Adapted from [15].

The water level monitoring system in channels and safety conditions in pumping stations is designed to visualize and manage available water depth while protecting pumps. This system is particularly useful in locations where managing water levels and detecting failures is challenging.

With an intelligent meter, this monitoring work can allow automation with a simple, relatively low-cost system. This makes it possible, through the prototype, to have quick decision-making regarding how to manage the available resources, or even to automate the decision-making process by integrating the meter with some type of intelligent management system. The system is composed of the water storage unit where the ultrasonic sensor and the processing unit will be placed, a web server that will store the data, internet and a cell phone that will receive the measured data through a spreadsheet. The prototype is composed of two main devices: the ESP32 and the ultra-sonic sensor.

2.3 Prototype development

To develop the prototype of the water level monitoring system in channels and safety in pumping stations, it will be necessary to divide the stage into two parts: hardware and software.

The hardware part comprises the physical components of the prototype, which are: the ESP32 board, ultrasonic distance sensor, set of indicator LEDs, relay and magnetic switch, in addition to some other peripheral components, with a power supply, cables and others, which help in visualizing some information at the time of installation. The methodology suggested by [15] and [22] was used. The adaptation presented were simplicity in design, assembly, and management, transmission to the internet via Google Sheets, ultrasonic sensor calibration, and control system.The ESP32 (Fig. 2a) is a prototyping board that has integrated WIFI, capable of receiving information from external sensors, through analog and digital ports, and processing this data according to the user's needs. To read the data, an ultrasonic sensor, model JSN-SR04T (Fig. 2b), was used.

The software is the logical part of the prototype, and through it the information is received, processed and stored. Through the software, it will be possible to develop projects, from the simplest to the most complex, as long as the user has sufficient knowledge in programming in the language used by the ESP32. This programming is developed within the Arduino IDE environment, which is the environment of the Arduino platform, another line of prototyping boards, but which integrates the ESP32.

As one of the most widespread prototyping boards in the world, Arduino has a more user-friendly environment for the programmer, with more updates and ease, especially in the programming language, which is compatible with the ESP boards, which is why its IDE was used to develop the project.

The data obtained by the prototype needs to be remotely accessible, for this the Adafruit website is used, which provides an IoT (Internet of Things) Cloud Service platform for users to send and store the data obtained in projects.

For this project, the water depth in the reservoirs and the occurrences of water shortage activation were sent. Adafruit IO allows up to 30 data points to be sent per minute to the site, but for this project it will not be necessary to make so many readings. The received data is organized into a table in Google Sheets, with the date and time of receipt.

2.4 Prototype installation

After completing the prototype assembly and programming stages, it was in-stalled in a reservoir. For this, the board was placed inside a container, to avoid humidity, as well as the sensor, which is pointed in the direction of the water depth.

Figure 2. NodeMCU prototyping board (a) and ultrasonic sensor (b).
Source: https://bit.ly/3UUqeXn (a) and http://bit.ly/4be4coo (b).

The installation of the prototype was fixed by a support, positioned at the top of the reservoir to facilitate the installation. For the installation, a power outlet was necessary, so that the ESP32 is connected to the power through the 5V power supply, and a nearby WiFi point, so that the board can connect to the internet and send the obtained data.

2.1 Data collection and processing

Since it is a device in a development system, the prototype may present some in-accuracies in the readings, so it is necessary to process the collected data through software. The distances obtained by the system will be verified and analyzed through correlation verification with the data obtained from manual measurements. These values may come from a reading failure by the sensor or something that has crossed in front of the sensor.

After the data has been processed, the information on the water level and the water shortage alert system will be sent to the Adafruit IO cloud, where graphs and a de-tailed history of water storage in the channel will be generated.

2.2 Sensor validation

In general, measurement systems are considered acceptable when they have a dispersion error of less than 10%. Based on this information, samples of the proposed system were collected to evaluate its reliability and acceptance. Three composite samples of twelve points at known distances were collected and after collecting the data, the calculations of mean and standard deviation of the system were employed. In each sample, it was defined that the reservoir started with a water depth that was 0.22 m away from the sensor. With the operation of the pump, the depth increased the distance from the sensors and these values were measured with the aid of a metal limnimeter scale.

The data obtained by the system and manually were compared through standard regression analysis with the Correlation Coefficient (r) and Determination (r^2), where:

$$r = \frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}} \quad (1)$$

where, n is the number of observations, P_i refers to the values of the distance variable obtained in the ultrasonic sensor database, $\bar{P}$ is the average of the values of the distance variable obtained in the ultrasonic sensor database, O_i to the observed data through the distance obtained with a tape measure and $\bar{O}$ is the average of the observed data through the distance obtained with a scale.

3. Results and Discussion

3.1 System assembly

The system has great simplicity in design, assembly, and management, in addition to the benefits provided by the intelligent meter, such as the possibility of remotely observing the water volume of the reservoir, with the possibility of issuing alerts for low water levels, turning off the pumping system in critical conditions, and future expansions of data processing just by modifying the programming. The diagram of the system can be observed in Fig. 3. The proposed system is economical, saves energy, and assists in the water's environmental cycle. The system used a microcontroller, Arduino (ESP32), to semi-automate the water pumping process in a reservoir, with the ability to detect the low water level in the reservoir, and thus turn off the pump, display the status on a set of indicator LEDs, and only allow reactivation again with the presence of a person to press the reset button for the protection of the pumping unit.

The assembled circuit is shown in Fig. 4, the main components are the ESP32, the "brain" of the prototype, and the Ultrasonic Sensor, in addition to the LEDs, re-sponsible for assisting in the on-site visualization of the water level obtained by the sensor and processed by the ESP32.

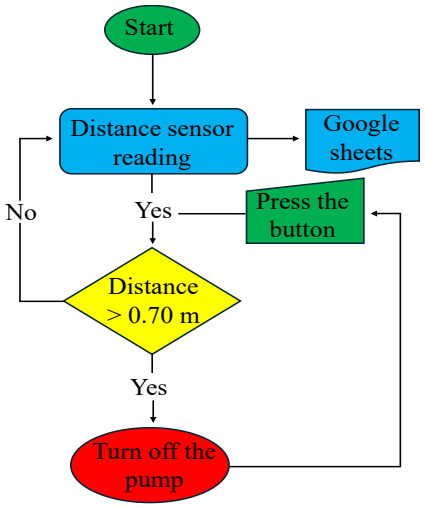

Figure 3. Diagram of the Proposed System.
Source: The Authors.

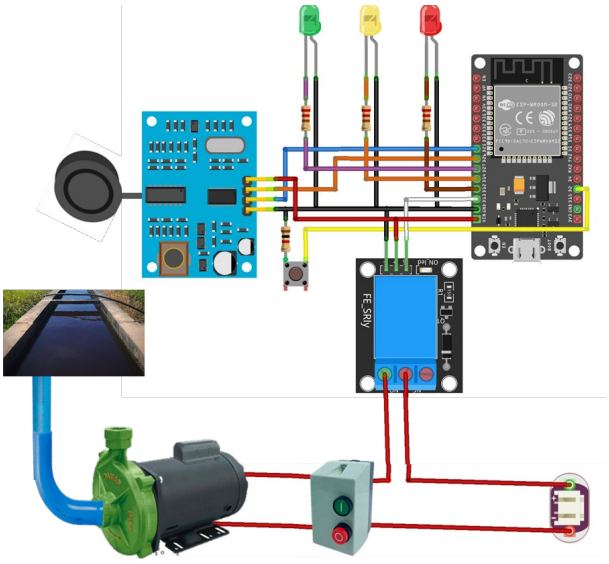

Figure 4. Diagram of component connections.
Source: The Authors.

The Trig pin (receives an electrical pulse and sends a sound pulse) of the JSN-SR04T sensor is connected to the D0 digital port of the ESP32, the Echo pin (re-ceives the return of the sound pulse and sends the data with the time the pulse took to return to the sensor) is connected to the D2 digital port, the sensor is also connected to the 5-volt power supply of the board and to the GND (ground) pin. If the level inside the reservoir is low, a beep sound is generated, and when the level is low, the pump will automatically turn off, protecting the motor against dry operation. However, this system notifies the responsible person by means of a beep sound when the water level is at a critical point. This alert can only be heard when the alerted person is near the tank, and in addition, the user can view the current water status on their smartphone or laptop. Similar projects have observed that the prototypes taught farmers basic computer skills and the wonders of modern ICT applications [23].

3.2 Transmission to the internet via Google Sheets

In order to monitor the data obtained through the JSN-SR04T sensor, so that a precise analysis of the water depth in the reservoir can be obtained, Google Sheets software/application was used, which is an online spreadsheet similar to Excel. The transmission to the spreadsheet occurs through the internet connection. The sending of this data occurs through the URL of the website located in the address bar at the top of the web between slashes, but it must have the interaction of a platform called: Apps Script (script platform that uses JavaScript-based programming language). It can be accessed at: Extensions and then Apps Script. With the interrelationships of the two applications, it will be possible to connect to the Arduino IDE software (development software written in C++ and C, used to perform uploads or loading on boards that are compatible with Arduino) by connecting to the ESP32.

3.3 Calibration of the ultrasonic sensor

The result of the system tests in the reservoir is represented in Fig. 5. The cali-bration data were obtained by the system sequentially from the initial water level of the reservoir, 0.22 m, and the electric pump operated until the programmed 0.55 m. After a comparison between the system's measurements and the results of manual measurement, it was found that the precision of the measurement system is quite good, presenting a slight overestimation in the measurement value by the system, which may even be associated with the variation of the water surface. Similar results to those ob-tained in this system, also using sensors based on the physical principle of ultrasound, were found by [24], where they suggest that the combination of Arduino and ultrason-ic sensors is a technically and economically viable way to accurately measure water levels in channels for distances greater than 20 cm, both for permanent and transient flows, including conditions where turbulence is high. This was supported by the fact that there was little change in the errors in the statistical comparison of measurements between the different regimes.

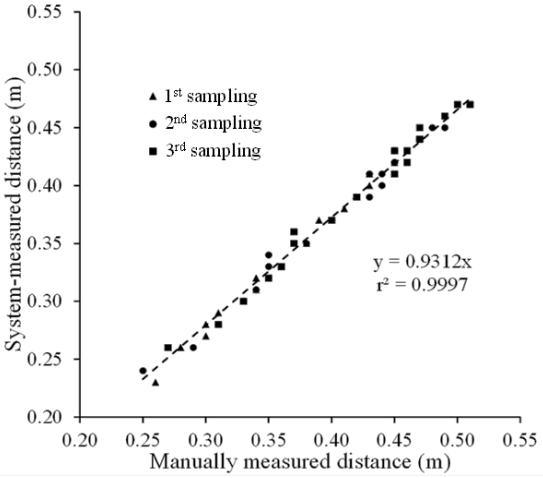

Figure 5. Correlation between manually measured and system-measured distance data.
Source: The Authors.

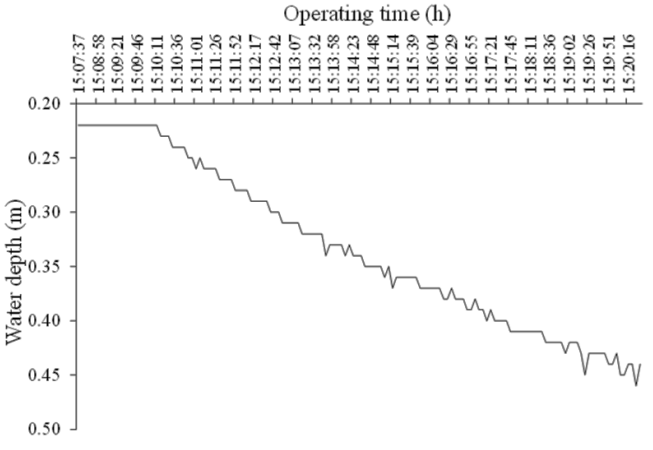

Figure 6. Water depth monitored by the system over the operating time.
Source: The Authors.

In addition to the validation between the collection methodology through the sensor and the standard collection (limnimeter scale), it is possible to observe the his-tory of the reservoir emptying over the operation of the pump (without water replen-ishment) (Fig. 6). The test results suggested that the difference in value between manual measurement and using the system was less than 5 mm, a result also found by [25]. This is in accordance with the resolution of the JSN-SRT04 sensor contained in the sensor datasheet, which is also 5 mm.

3.4 Control system

The control system developed in this work was the single-phase system and is presented with the control diagram (Fig. 7). It is composed of a contactor, a thermal relay, a bipolar circuit breaker, a simple control relay (a relay that represents the actu-ation by the ESP32) and two buttons, one normally closed and the other normally open. The power circuit is represented by an indirect start of a single-phase pump with

the actuation command through the normally closed relay of the ESP32, and the shutdown can be performed by receiving the inverse command from the ESP32. The direct actua-tion system can be resumed if maintenance is required on the ESP32 platform. In addi-tion to the example developed in this work, a single-phase system with a 1 hp pump, the control command can be easily adjusted for a three-phase system, which will have the components illustrated as two-phase replaced by three-phase and minor changes to the control diagram (Fig. 8). This three-phase case is the most commonly used system in agricultural systems, as three-phase electrical energy is the most economical source of energy for irrigation, with lower daily energy costs, maintenance, equipment and controls [26].

After the development of the control system, which has the ability to deactivate the electric pump when the water level is in a critical state, an advance can be noted compared to the study by [27], who developed and tested a low-cost real-time water level monitoring prototype. The system used low-cost equipment and open-source software with the aim of monitoring water levels and alerting. After testing the prototype, it became possible to monitor the water status in a tank, alert users and view past data in real-time, but the existence of a control system that turns off the pump was not observed.

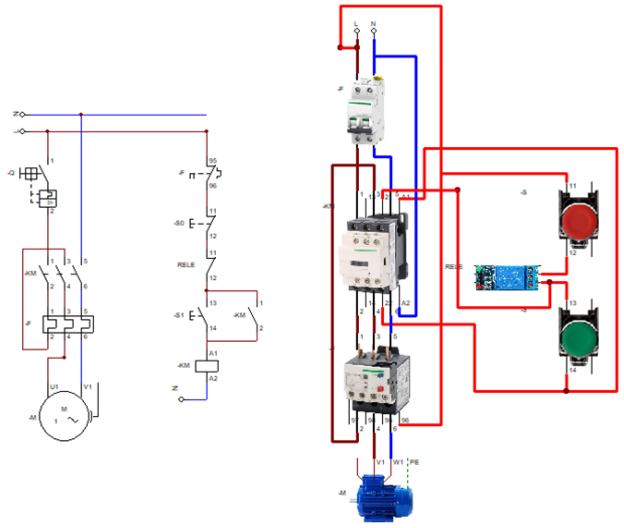

Figure 7. Diagram of the control system for the single-phase system.
Source: The Authors.

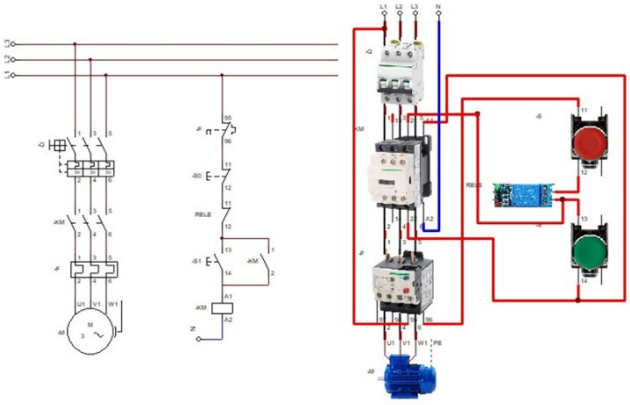

Figure 8. Diagram of the control system for the three-phase system.
Source: The Authors.

Furthermore, for some time now, Programmable Logic Controllers (PLCs) have been available on the market, which can be applied in automation systems in pump station control systems using contactor switches and thermal relays. However, [28], reports that there are difficulties in the construction and assembly process of an equipment that would simulate the PLC input points, difficulty in the PLC selection process that would be most suitable for the project and in the parameterization, which required constant consultation with the manufacturer's support.

When comparing PLCs with Arduino applications, [29] developed a comparative study of PLCs, Raspibarry and Arduino, in which he observed that the Arduino platforms used were highly versatile, allowing the addition of several other modules and sensors to improve the projects. An example of this is the relay connected to one of the Arduino ports, this suggestion makes the project even more efficient because it connects it to the machine's emergency switch or button, causing it to turn off immediately when the absence of a certain condition is detected.

In the context of selecting Arduino platforms for automation applications, such as control command, [30] noted that Arduino has inspired creativity in digital electronics. The impact of its radical development of new ideas is driven solely by the voluntary contributions of users worldwide, as highlighted by [31].

The improvements over study [15] and [22] were properly identified and can be outlined in four main aspects. The first refers to the simplicity in the system's design, assembly, and management, which enables easy replication at low cost and facilitates maintenance. The second improvement lies in the data transmission to the internet via Google Sheets, allowing real-time remote monitoring of the reservoir's water volume—a feature not present in the previous study. The third contribution was the calibration of the ultrasonic sensor, whose tests demonstrated satisfactory accuracy, with a margin of error of less than 5 mm compared to manual measurements, ensuring system reliability. Lastly, the development of a control system capable of automatically shutting off the pump under critical conditions stands out, along with the possibility of adapting it to three-phase systems, which broadens its applicability in agricultural contexts. These enhancements make the system more efficient, safer, and technically feasible for different usage scenarios.

3.5 Main limitations and challenges for system implementation

Despite the effectiveness and low cost of the proposed system, certain limitations must be considered in its implementation. One major drawback is the dependence on proximity for alert notifications. The system emits a beep when the water level reaches a critical point, but this alert can only be heard by someone physically near the reservoir. Additionally, after the system automatically turns off the pump to prevent dry running, it requires manual intervention to press a reset button, which limits remote management and full automation of the system.

Another relevant challenge lies in the need for reliable internet connectivity. The system transmits water level data to Google Sheets via the ESP32 using Apps Script integration. However, many rural areas may suffer from unstable or unavailable Wi-Fi or cellular networks, making real-time monitoring difficult. Furthermore, setting up the data transmission requires knowledge of JavaScript, the Arduino IDE, and web application integration, which may be a barrier for users without technical expertise.

Hardware limitations should also be addressed. The JSN-SR04T ultrasonic sensor, although cost-effective, may present slight overestimations in readings due to water surface variation, turbulence, or external environmental factors. The control system, while functional, requires careful electrical installation with relays, contactors, and safety features. Although the Arduino platform provides flexibility and modularity, scaling the system for more demanding or industrial applications may require transitioning to more robust hardware like PLCs, which involves added complexity in setup and configuration.

4. Conclusions

The results from the project proposal to design an intelligent system for automat-ed management of water depth in a reservoir were satisfactory. The prototype was tested for a period of 30 days, functioning correctly continuously 24 hours a day. User intervention in water monitoring was no longer necessary, allowing farmers to forgo traditional methods of measuring water levels. Thus, the project achieved the general objective of constructing a system for automated visualization and management of the water level in a reservoir, for the control of consumption and management of the available water resource. The hardware device for reading the water volume of a reservoir was successfully developed, with an excellent correlation index between the data obtained through a scale measurements and the ultrasonic sensor data. The software, Google Sheets, for monitoring and processing the data obtained by the hardware works correctly.

The original contributions of this study lie in the development of an intelligent, low-cost, and replicable water reservoir management system designed for agricultural use. Key innovations include a simplified system architecture that facilitates ease of assembly and maintenance, the integration of real-time remote monitoring through Google Sheets—enabling data transmission via ESP32 and Apps Script—and the implementation of an automatic pump shutoff mechanism triggered under critical water level conditions. The system was further enhanced by the accurate calibration of the JSN-SR04T ultrasonic sensor, which demonstrated measurement precision with an error margin of less than 5 mm compared to manual readings. Additionally, the proposed solution includes adaptability for three-phase systems, expanding its applicability in more complex agricultural contexts. Together, these advancements contribute to improved water resource management, operational safety, and energy efficiency in irrigation systems.

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References

[1] Pereira, L.-B., and Santos, M.-R., Dos desenvolvimento de um sistema Embarcado de Baixo Custo para Automatização do manejo de Irrigação Localizada, Revista Velho Chico, (2), pp. 50-56, 2022.

[2] Karami, M., McMorrow, G.-V., and Wang, L., Continuous monitoring of indoor environmental quality using an arduino-based data acquisition system, Journal of Building Engineering, (19), pp. 412-419, 2018. DOI: https://doi.org/10.1016/j.jobe.2018.05.014.

[3] Chan, K., Schillereff, D.-N., Baas, A.-C.-W., Chadwick, M.-A., Main, B., Mulligan, M., O'Shea, F.-T., Pearce, R., Smith, T.-E.-L., van-Soesbergen, A., et al., Low-Cost Electronic Sensors for Environmental Research: pitfalls and Opportunities, prog. phys. Geogr., (45), pp. 305-338, 2021. DOI: https://doi.org/10.1177/0309133320956567.

[4] Carvalho, A.-A., Medeiros, V.-W.-C., and de-Gonçalves, G.-E., Aplicação de sensores de baixo custo na estimativa da evapotranspiração potencial, Journal of Environmental analysis and progress, (6), pp. 119-127, 2021. DOI: https://doi.org/10.24221/jeap.6.2.2021.2843.119-127

[5] Castell, N., Dauge, F.-R., Schneider, P., Vogt, M., Lerner, U., Fishbain, B., Broday, D., and Bartonova, A., Can commercial low-cost sensor platforms contribute to air quality monitoring and exposure estimates? Environ Int, (99), pp. 293-302, 2017. DOI: https://doi.org/10.1016/j.envint.2016.12.007

[6] Reges, J.-P., Oliveira, F.-I., De-Sousa, J.-R., de-B., Carvalho, P.-C.-M., and Alexandria, A.-R., Development of a data Acquisition System for Photovoltaic systems, Revista Brasileira de Energia Solar, (10), pp. 77-87, 2019. DOI: https://doi.org/10.59627/rbens.2019v10i2.281.

[7] Deng, Y., Wang, S., Bai, X., Wu, L., Cao, Y., Li, H., Wang, M., Li, C., Yang, Y., Hu, Z., et al., Comparison of soil moisture products from microwave remote sensing, land model, and reanalysis using global ground observations, Hydrol. Process (34), pp. 836-851, 2020. DOI: https://doi.org/10.1002/hyp.13636

[8] De-Melo, D.-A., Silva, P.-C., da-Costa, A.-R., Delmond, J.-G., Ferreira, A.-F-.A., de Souza, J.-A., de Oliveira-Júnior, J.-F., da-Silva, J.-L-.B., da-Rosa, Ferraz-Jardim, A.-M., Giongo, P.-R., et al., Development and automation of a photovoltaic-powered soil moisture sensor for water management, Hydrology, (10), art. 80166, 2023. DOI: https://doi.org/10.3390/hydrology10080166.

[9] Lino, D.-R., Lima-Neto, B.-P., de-Queiroz, L.-L., Feitosa, P.-B., Rodrigues, A.-A., and Santos-Teixeira, A., Dos irrigação automatizada com plataforma de desenvolvimento arduino na horta didática da Universidade Federal do Ceará, Irriga, (1), pp. 85-93, 2017. DOI: DOI: https://doi.org/10.15809/irriga.2017v1n1p85-93

[10] Campos, H., de-M., Oliveira, H.-F.-E., de-Mesquita, M., Castro, L.-E.-V., and de-Ferrarezi, R.-S., Low-Cost Open-source platform for irrigation automation. Comput, Electron. Agric., (190), art. 106481, 2021.DOI: https://doi.org/10.1016/j.compag.2021.106481

[11] Kumar, V., Singh, C-D., Rao, K.-V.-R., Kumar, M., and Rajwade, Y.-A., Development of a Smart iot-based drip irrigation system for precision farming. Irrigation and Drainage, (72), pp. 21-37, 2023.DOI: https://doi.org/10.1002/ird.2757

[12] Jia, W., Wei, Z., Tang, X., Zhang, Y., and Shen, A., Intelligent control technology and system of on-demand irrigation based on multiobjective optimization, Agronomy, (13), art. 13071907, 2023, DOI: https://doi.org/10.3390/agronomy13071907

[13] Lopes, I., Souza-Barbosa, R., Damascena-dos-Santos, D., and Medrado-de-Melo, J.-M., Melo-Vellame, L., Alves-de-Oliveira, E., Kramer-Schwiderke, S., LoRa-based iot platform for remote soil parameter monitoring. DYNA, 91(231), pp. 86-93, 2024. DOI: https://doi.org/10.15446/dyna.v91n231.111612

[14] Goralski, M.-A., and Tan, T.-K., Artificial intelligence and sustainable development, International Journal of Management Education, (18), art. 100330, 2020. DOI: https://doi.org/10.1016/j.ijme.2019.100330

[15] Silva, R.-J.-G., Sistema de automação do controle de volume de água em reservatório de abastecimento, Trabalho de Conclusão de Curso, Universidade Federal de Campina Grande, Campina Grande, Brasil, 2021.

[16] Yang, B., Wei, W., Chen, M., and Li, X.-N., Research on design of intelligent water-saving irrigation system based on Neural Network. Water

Conserv, Tech. Supervis, (5), pp. 44-48, 2020.DOI: https://doi.org/10.1109/ICAICA50127.2020.9181897
[17] Priya, O.-V., and Sudha, R., Impact of Internet of things (IoT) in smart agriculture. In: Advances in Parallel Computing, Rajesh, M., Vengatesan, K., Gnanasekar, M., Sitharthan R., Pawar, A.B., Kalvadekar, P.N., and Saiprasad, P., Eds., IOS Press BV, (39), pp. 40–47, 2021. ISBN 9781643682181
[18] Obaideen, K., Yousef, B.-A.-A., AlMallahi, M.-N., Tan, Y.-C., Mahmoud, M., Jaber, H., and Ramadan, M., An overview of smart irrigation systems using IoT, Energy Nexus, (7), art. 100124, 2022. DOI: https://doi.org/10.1016/j.nexus.2022.100124
[19] Essamlali, I., Nhaila, H., and Khaili, M., El advances in machine learning and IoT for water quality monitoring: a comprehensive review, Heliyon, (10), art. 27920, 2024. DOI: https://doi.org/10.1016/j.heliyon.2024.e27920
[20] Wu, Z., Huang, Y., Huang, K., Yan, K., and Chen, H., A review of non-contact water level measurement based on computer vision and radar Technology. Water (Switzerland), (15), art. 183233, 2023, DOI: https://doi.org/10.3390/w15183233
[21] Rocha, D.-P. de-A., Projeto formoso impactos socioeconômicos e ambientais no município de Bom Jesus da Lapa-BA, Codevasf, Brasília, 2023.
[22] Suresh, N., Hashiyana, V., Kulula, V.-P., and Thotappa, S., Smart water level monitoring system for farmers, 2019, pp. 213–228.
[23] Suresh, N., Hashiyana, V., Kulula, V.-P., and Thotappa, S., Smart water level monitoring system for farmers, IGI Global, (1), art. ch014, 2019. DOI: https://doi.org/10.4018/978-1-5225-9246-4.ch014
[24] Pereira, T.-S.-R., de-Carvalho, T.-P., Mendes, T.-A., and Formiga, K.-T.-M., Evaluation of water level in flowing channels using ultrasonic sensors. Sustainability (Switzerland), (14), art. 14095512, 2022. DOI: https://doi.org/10.3390/su14095512
[25] Andang, A., Hiron, N., Chobir, A., and Busaeri, N., Investigation of ultrasonic sensor type JSN-SRT04 performance as flood elevation detection. In: Proceedings of the IOP Conference Series: Materials Science and Engineering; Institute of Physics Publishing, art. 550, 2019. DOI: https://doi.org/10.1088/1757-899X/550/1/012018
[26] Khalina, T.-M., Eremochkin, S.-Y., art. Dorokhov, D.-V., The development of an energy efficient electric drive for agricultural machines. IOP Conf. Ser. Mater Sci., (1211), art. 012018, 2022. DOI: https://doi.org/10.1088/1757-899x/1211/1/012018
[27] Chowdury, M.-S.-U., Emran, T., Bin-Ghosh, S., Pathak, A., Alam, M.M., Absar, N., Andersson, K., and Hossain, M.-S, IoT based real-time river water quality monitoring system, Proceedings of the Procedia Computer Science, (155), 2019, pp. 161-168. DOI: https://doi.org/10.1016/j.procs.2019.08.025
[28] Mystkowski, A., and Kierdelewicz, A., Fractional-order water level control based on PLC: hardware-in-the-loop simulation and experimental validation. Energies (Basel), (11), art. 112928, 2018. DOI: https://doi.org/10.3390/en11112928
[29] Santos, E.-M., Aplicação de plataformas de baixo custo na automação de processos industriais, Trabalho de Conclusão de Curso, Universidade Federal de Pernambuco, Caruaru, Brasil, 2021.
[30] Zaragoza, M.-G., and Kim, H.-K., Comparative study of PLC and Arduino in automated irrigation system. International Journal of Control and Automation, (10), pp. 207-2018, 2017. DOI: https://doi.org/10.14257/ijca.2017.10.6.20
[31] Melo, D.-A. de-Silva, P.-C., Costa, A.-R. da-Delmond, J.-G., Ferreira, A.-F.-A., Souza, J.-A. de-Oliveira-Júnior, J.-F. de-Silva, J.-L.-B. da-Jardim, A.-M. da-R.F., Giongo, P.-R., et al., Development and automation of a photovoltaic-powered soil moisture sensor for water management, Hydrology, (10), art. 10080166, 2023. DOI: https://doi.org/0.3390/hydrology10080166

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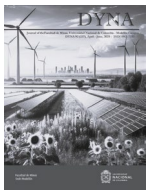

UNIVERSIDAD NACIONAL DE COLOMBIA

Design of an oxygen concentrator according to ISO 80601-2-69 standards

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Abstract
This work focuses on the design, construction and economic analysis of an oxygen concentrator in the city of Moquegua, Peru, under ISO 80601-2-69 standards. The methodology used was experimental, consisting of the design and construction of an oxygen concentrator, as well as its economic analysis. The results of the prototype tests indicate that it provides oxygen with a concentration of 95%, up to 10 litres/min, consuming 280 W of power, being powered by 220 V alternating current, working under a process called oscillating pressure absorption. The final cost of the device was S/1220.80, which contrasts with the cost of similar equipment that in the market have a value of S/1500.00 and that in pandemic 2020 reached S/15000.00. In conclusion, the manufacture of an oxygen concentrator in Moquegua is both technically and economically feasible.

Keywords: oxygen; concentrator; design, feasibility; economics.

Diseño de un concentrador de oxígeno de acuerdo con las normas ISO 80601-2-69

Resumen
Este trabajo se enfoca en el diseño, construcción y análisis económico de un concentrador de oxígeno en la ciudad de Moquegua, Perú, bajo las normas ISO 80601-2-69. La metodología utilizada fue experimental, que consistió en el diseño y construcción de un concentrador de oxígeno, así como el análisis económico del mismo. Los resultados de las pruebas del prototipo indican que proporciona oxígeno con una concentración del 95%, hasta por 10 litros/min, consumiendo 280 W de potencia, siendo alimentado por corriente alterna de 220 V, trabajando bajo un proceso denominado absorción por presión oscilante. El costo final del dispositivo fue de S/1220.80, que contrasta con el costo de equipos similares que en el mercado tienen un valor de S/1500.00 y que en pandemia del 2020 alcanzó los S/15000.00. En conclusión, la fabricación de un concentrador de oxígeno en Moquegua resulta factible tanto técnica como económicamente.

Palabras clave: oxígeno; concentrador; diseño; factibilidad; economía.

1. Introduction

In 2020, the World Health Organisation (WHO) declared COVID-19 a pandemic; from 2020 to 2021, there was an estimated excess mortality of 14.9 million people [1]. Peru reported approximately 213,000 deaths caused by the COVID-19 pandemic, making it one of the countries with the most deaths per million inhabitants in the world. There is consensus that one of the causes of the magnitude of this tragedy in Peru was the lack of medical oxygen [2]. As a result, there has been a growing interest in research on the biological effects and medical importance of oxygen [3]. Alterations in oxygen availability can affect vital functions at the systemic and cellular level and potentially contribute to ageing through various mechanisms [4]. Molecular oxygen is the second most abundant element in the Earth's atmosphere [5]. It is available in gaseous form in our atmosphere at a concentration of approximately 21% [6]. Despite this, few of us are aware that, as human inhabitants of the Earth, we have a unique privilege. As air-breathers, we and most other animals on Earth are the only living creatures in the known universe that have an unlimited supply of oxygen [7].

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Precisely one of the key features that allow our planet Earth to harbour an active and diverse biology is the presence of free molecular oxygen (O2) in the atmosphere [8]. Oxygen is essential for the metabolism of many organisms. Oxygen acts as a terminal electron acceptor in humans, for example, where four electrons are used to create water, which is then lost through skin or respiration [9]. In this regard, a number of studies have suggested that oxygen appears to be inextricably linked to multiple ageing processes [10].

During the first wave of COVID-19, in the year 2020, the demand for medical oxygen quadrupled, i.e. 2,800 tonnes per day. Furthermore, with the second wave, the demand increased to approximately 5,000 tonnes per day [11]. By this time, diagnoses of COVID-19 severity were closely related to prognosis, and strategies for early detection of high-risk patients were developed, using oxygenation indices as an indicator of lung dysfunction [12]. Oxygen is therefore a drug and should be used as such, and prescribers should have a thorough understanding of its use and the existing interfaces for its administration [13].

2. Materials and Methods

The developed prototype works on the principle of Pressure Swing Adsorption (PSA) technology, which uses ambient air as the raw material for oxygen generation. It also complies with the specifications of ISO 80601-2-69, which establishes the requirements that guarantee the safety and performance required for oxygen concentrators. The technology employed is used for the separation of the components of air in its gaseous state. It is therefore known as a selective process and operates in the ambient temperature range.

The currently existing methods for the production of oxygen for medical purposes are shown in the Fig. 1.

The pressure swing process allows a continuous flow of oxygen to be provided with a high level of purity (between 90% - 95%). This adsorption occurs when compressed air molecules tend to adhere to an adsorbent surface. The concentrator will draw in the ambient air and filter it in order to remove dust, pathogens and other impurities. A compressor will force the air into the cylinder containing a sieve, which will absorb the nitrogen and release the concentrated oxygen. For this purpose, molecular sieves

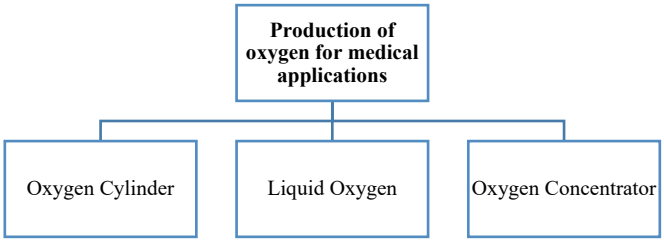


Figure 1. Classification of methods for the production of oxygen for medical applications
Source: Author made

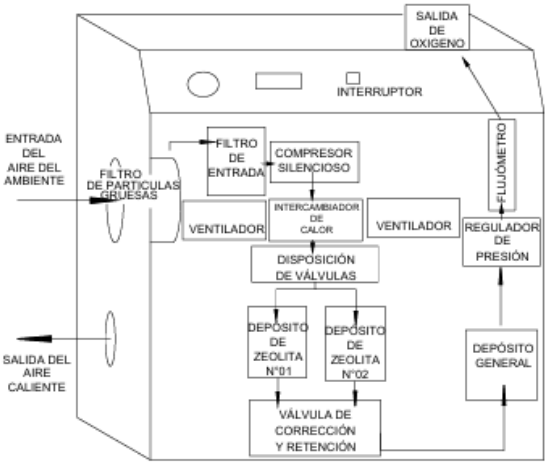


Figure 2. Operating diagram of the oxygen concentrator
Source: Author made

containing Zeolite are used, and when each sieve is depressurised, N2 is released. For the oxygen separation stage, 2 vessels filled with Zeolite are used. There is a large variety of Zeolite, and it is classified by pore size distribution or the cations present. The type of Zeolite chosen is 13X Zeolite, preferably used in normal oxygen purification due to its higher nitrogen attraction. The operating scheme of the prototype is shown in the Fig. 2.

We can calculate the dimensions of the Zeolite container, knowing the following data:

Zeolite density: 40 lb/ft3
Type: 13X
Zeolite mass: 3 lb.
The mathematical expression for the calculation is:

$$\textbf{Volume (V)} = \frac{\text{Mass (m)}}{\text{Density (p)}} \quad (1)$$

$$\textbf{Volume} = \frac{3\ \text{lb}}{\frac{40\ lb}{ft^3}} = 0.0075\ ft^3 = 2.123\ cm^3$$

Then the calculated total volume of Zeolite will be shared in the two identical columns, thus making each of them have a volume of 1,061 cm3.

- The components of the oxygen concentrator are:
- Piston-type motor and air compressor (pistons)
- Two cylinders filled with Zeolite pellets (Zeolite Strainer)
- One pressure compensation tank
- Flow meter adjustment valve
- Four-way solenoid valve
- Correction and Check Valves
- Silicone Hoses
- Hermetic Plate and Tube Heat Exchanger (Cross Flow)
- Product Tank
- Pressure Regulator with Knob
- Flowmeter (Flow Regulator)
- Coarse Particle Filter
- Inlet Filter

- Product Filter
- Exhaust Silencer
- Two Fans
- Condenser 14µF±5% Condenser

Once the necessary calculations had been made, it was necessary to draw up the detailed plans of the prototype to be built. To do this, the dimensions of the concentrator were detailed, ensuring that it could comply with the specifications of the ISO 80601-2-69 Standard. The specific views are shown in the Figs. 3–5.

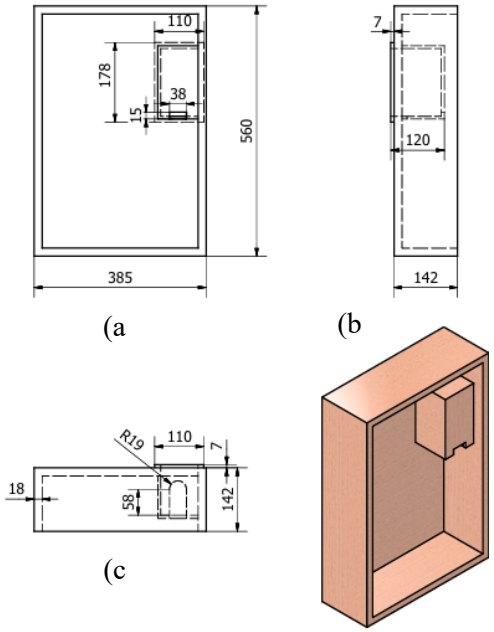


Figure 3. Main views of the rear casing. (a) Front View, (b) Side View, (c) Top View
Source: Author made

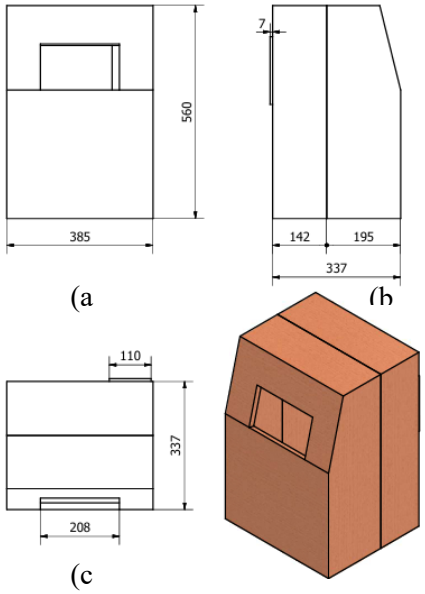


Figure 4. Main views of the assembled housing. (a) Front View, (b) Side View, (c) Top View
Source: Author made

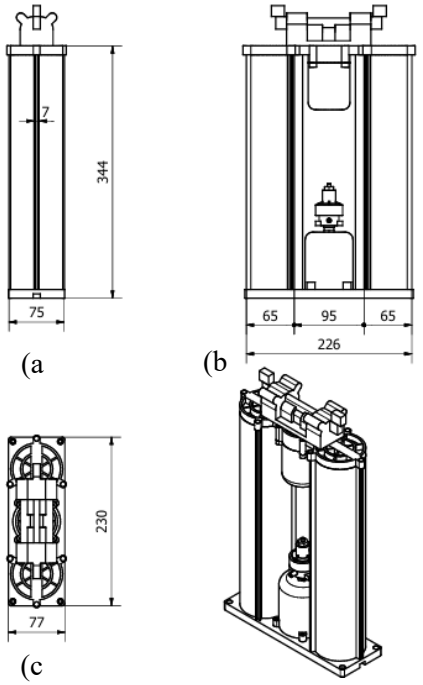
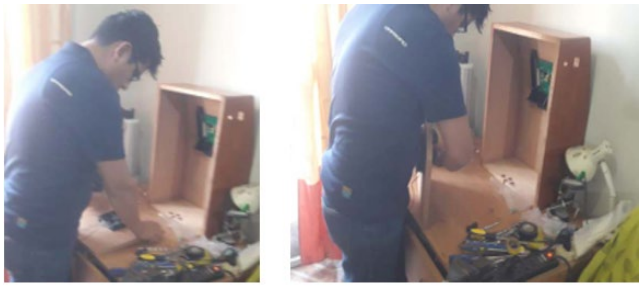


Figure 5. Main views of the Zeolite mechanism and cylinders. (a) Side View, (b) Front View (c) Top View
Source: Author made

3. Results and Discussion

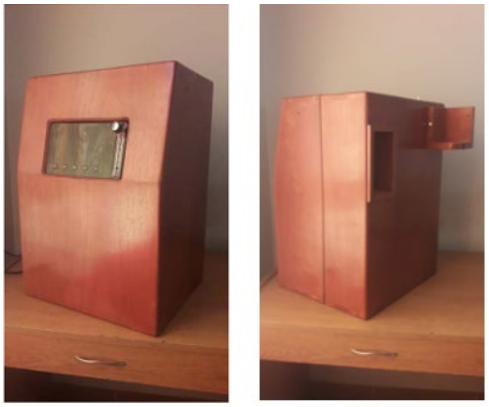
Considering all the parameters, devices and requirements established by the ISO 80601-2-69 Standard, in addition to the technological limitations, a reliable prototype was manufactured, economically profitable, and easy to manufacture in series, capable of providing 95% concentrated oxygen, up to 10 litres/min.

It is powered by Alternating Current (AC), consuming 280 W of electrical power, at a frequency of 60 Hz and for 220 V. voltage. Using this machine under the process called oscillating pressure absorption. This prototype can be easily moved from one place to another when it is required to attend patients, either in health centres or outside. Furthermore, this equipment represents an innovative and efficient solution that could be upgraded for mass production. The manufacturing



(a) (b)

Figure 6. Prototype construction process
Source: Author made



(a) (b)

Figure 7. Final prototype of the concentrator. (a) Front View, (b) Side View
Source: Author made

was carried out using commercial devices and materials available in the national market, facilitating its assembly in the area intended for this purpose. The Fig. 6., shows the assembly process of the oxygen concentrator.

Fig. 7 shows the prototype built ready for operation, the supply of oxygen in the detailed quantities is guaranteed thanks to the flow of oxygen circulating through the equipment.

Tests were carried out to determine its power consumption, and it was found to work adequately to provide oxygen at the right concentration for medical use. This type of technology is capable of working uninterruptedly and its maintenance costs are very low compared to other similar equipment. The viability of this equipment lies in the fact that low-cost materials and equipment have been used, in addition

Table 1.
Oxygen concentrator costs

Item	Description	Quantity	Unit price (S/)	Subtotal (S/)
1	Wooden plugs 18 mm thick for covering	----	----	450.0
2	Thin silicone hose	1 m	----	15.0
3	Thick silicone hose	1 m	----	30.0
4	Shipping costs from Lima to Moquegua	----	----	15.0
5	Clamps	4 pcs	0.50	2.0
6	¾ clamp bolt	10 pcs	----	1.0
7	1 - ½ clamp bolt	4 pcs	0.20	0.8
8	Millimetric bolt	4 pcs	0.50	2.0
9	Silent motor compressor	1 pc	----	230.0
10	Heat exchanger	1 pc	----	125.0
11	Flow meter (Flow regulator)	1 pc	----	42.0
12	Coarse particle filter	1 pc	----	45.0
13	Inlet filter (Epa filter)	1 pc	----	30.0
14	Check valves	1 pc	----	45.0
15	Fans	2 pcs	34.0	68.0
16	Condenser 14 microfarads ±5%.	1 pc	----	20.0
17	Electronic board (imported from China)	1 pc	----	100.0
			Total:	1220.8

Source: Author made

to guaranteeing the reproduction and improvement of this equipment, without taking into account that it is also adaptable to different working environments. The results also show that the objective of building a prototype capable of generating medical oxygen and that it complies with the standards established by the ISO 80601-2-69 Standard has been achieved.

The costs related to the construction of the oxygen concentrator are shown in the table below, specifying in detail each item related to the equipment (Table 1).

This article has been oriented from the beginning towards the development of a medical oxygen concentrator, with a therapeutic concentration suitable to be administered to patients with hypoxaemia (low oxygen saturation in the blood). The total cost of the assembled prototype amounted to the sum of S/1220.80 (one thousand two hundred and twenty soles and 80 cents) which is adequate and accessible in comparison with the costs reached in the year 2024 for similar equipment and which present a price of S/1500.00 and which also contrasts with the costs of the year 2020 in times of pandemic, which made prices around S/15000.0 for oxygen concentrators.

The components are readily available and can be found in the domestic market and some imported components, such as the electronic board, are produced to order in China.

It is important to note that similar studies, such as the one developed in [11] agree that the use of an oxygen concentrator using the pressure swing principle can be a life-saving solution at least in the primary stage of coronavirus infection. Similarly, according to the research developed in [14], for the primary care of hypoxaemic patients, their project is envisaged to provide portable oxygen delivery equipment. Offering a transportable and cost-effective configuration for the treatment of patients with severe hypoxaemia, as well as solving the problem of insufficient oxygen supply by presenting a technology that is affordable and accessible to all.

Moreover, an affordable and sustainable PSA-based oxygen source was developed in the early 2020s and successfully implemented in several low-resource settings with the help of remote educational tools during the pandemic. Explanations via YouTube and a website have greatly contributed to the understanding of the gas separation process in an oxygen concentrator and aided its assembly. A survey and extensive correspondence with people at LRS through comments and emails have helped to summarise this experience in several documents related to the device, including an assembly manual and an optimisation report, which can be found in the Supporting Information [15].

The work developed in [16] studied the individual effects of the main PSA process parameters on the oxygen production performance at a product flow rate of 3.46-19.88 SLPM (standard litres per minute), based on a modified Skarstrom cycle PSA unit using Li-LSX zeolite adsorbents. The energy consumption was reduced by 10.56-18.10% compared to conventional devices. The results are beneficial for developing flexibly controlled oxygen concentrators for practical applications.

Research in [17] highlights that medical oxygen concentrators (MOCs) are designed for fixed product specifications, which limits their use to meet variable product specifications caused by a change in the patient's medical condition or activity. To overcome this difficulty, a flexible single-bed MOC system, capable of meeting different product specification requirements, was designed based on flexible PSA and pressure-vacuum swing adsorption (PVSA) systems.

The results indicate that LiLSX outperforms LiX, and can produce 90% pure oxygen at 21.7 L/min. Furthermore, the flexible PVSA system based on LiLSX can be manufactured for different levels of oxygen purity and flow rate in the range of 93 to 95.7 % and 1 to 15 L/min, respectively. Finally, the research in [18] has a bearing on the development of innovations in oxygen generation, highlighting that a novel oxygen control system was developed and tested to wirelessly control the flow rate of supplemental oxygen during home oxygen therapy. As an external complement to existing oxygen concentrators, demonstrating that this system is an accurate, precise and reliable method for oxygen therapy patients to wirelessly adjust their oxygen flow rate within 41 metres.

4. Conclusions

A physical prototype was made to obtain the real cost of the equipment, assembled in the city of Moquegua. The plans of the equipment were drawn up. Using the Autodesk inventor 2024 program. Where the components that make up the equipment are shown. The elaboration of the device was made, based on investigation, where the different calculations were determined. Resulting in a device with a value of S/. 1220.80 Peruvian soles. The current cost of this device is S/1500.00 in the year 2024 and in a pandemic, it will cost S/15000.00 each device in the year 2020. Justifying that it is easy to assemble.

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References

[1] Los, E., Ford, G., Tuell, D., Macariola, D., and Stone, W., The roles of glutathione and oxidative stress in diabetes and COVID-19. Oxygen, 4(3), pp. 351–362, 2024. DOI: https://doi.org/10.3390/oxygen4030021

[2] Dargent, E. and Gianella, C., País sin Oxígeno: debilidad institucional en COVID-19. Revista de Ciencia Política (Santiago), 44(1), pp. 87–107, 2024. DOI: https://doi.org/10.4067/s0718-090x2024005000104

[3] Huo, M., Wang, L., Chen, Y., and Shi, J., Oxygen pathology and oxygen-functional materials for therapeutics. Matter, 2(5), pp. 1115–1147, 2020. DOI: https://doi.org/10.1016/j.matt.2020.02.013

[4] Van Vliet, T., Casciaro, F., and Demaria, M., To breathe or not to breathe: understanding how oxygen sensing contributes to age-related phenotypes. Ageing Res Rev, 67, art. 101267, 2021. DOI: https://doi.org/10.1016/j.arr.2021.101267

[5] Hocke, K., Oxygen in the earth system. Oxygen, 3(3), pp. 287–299, 2023. DOI: https://doi.org/10.3390/oxygen3030019

[6] Yunus, B., Sri, A., and Teguh, K., Design and construction of portable oxygen concentrator using pressure swing adsorption technology. ASEAN Journal for Science and Engineering in Materials, [online]. 3(1), pp. 43–50, 2024. Available: https://ejournal.bumipublikasinusantara.id/index.php/ajsem/article/view/413

[7] West, J., The strange history of atmospheric oxygen. Physiol Rep, 10(6), 2022. DOI: https://doi.org/10.14814/phy2.15214

[8] Shi, P., et al. Factors contributing to spatial–temporal variations of observed oxygen concentration over the Qinghai-Tibetan Plateau. Sci Rep, 11(1), 2021. DOI: https://doi.org/10.1038/s41598-021-96741-6

[9] Hancock, J., A brief history of oxygen: 250 years on. Oxygen, 2(1), pp. 31–39, 2022. DOI: https://doi.org/10.3390/oxygen2010004

[10] Zou, Q., Lai, Y., and Lun, Z.-R., Exploring the association between oxygen concentration and life expectancy in China: a quantitative analysis. Int J Environ Res Public Health, 20(2), art. 1125, Jan. 2023. DOI: https://doi.org/10.3390/ijerph20021125

[11] Madankar, T.A., and Deshpande, Y., Development of portable oxygen concentrator - A review. E3S Web of Conferences, 430, 2023. DOI: https://doi.org/10.1051/e3sconf/202343001265

[12] López, J., Escarramán, D., Sánchez, J., and Pérez, O., Ratio de oxígeno como determinante de severidad en neumonía COVID-19. Revista Chilena de Anestesia, 52(7), pp. 678–682, 2023. DOI: https://doi.org/10.25237/revchilanestv52n7-08

[13] Martínez, E., Morales, G., Segura, L., and De la Cruz, A. Métodos no invasivos de oxigenación en pacientes con COVID-19. Revisión descriptiva. Medicina Crítica, 36(6), pp. 378–386, 2022. DOI: https://doi.org/10.35366/107461

[14] Rafathnazneen, N., Vijayalaxmi, H., Tamaloon, S., Varun, S., and Jagadish, J., Development of low cost and portable oxygen concentrator. International Journal of Research Publication and Reviews, [online]. 4(5), pp. 1070–1074, 2023. Available at: https://ijrpr.com/uploads/V4ISSUE5/IJRPR12779.pdf

[15] Lustenberger, U., Krestnikova, A., Gröninger, O., Grass, R., and Stark, W., Knowledge transfer in support of the development of oxygen concentrators in emergency settings during the COVID-19 Pandemic. J Chem Educ, 100(5), pp. 1858–1865, 2023. DOI: https://doi.org/10.1021/acs.jchemed.2c00925

[16] Zhang, Q., et al., Experimental study on oxygen concentrator with wide product flow rate range: individual parametric effect and process improvement strategy. Sep Purif Technol, 274, 2021. DOI: https://doi.org/10.1016/j.seppur.2021.118918

[17] Arora and Hasan, F., Flexible oxygen concentrators for medical applications. Sci Rep, 11, 14317, 2021. DOI: https://doi.org/10.1038/s41598-021-93796-3

[18] Gadiraju, N., et al., Design and development of a novel system for remote control of stationary oxygen concentrator flow rate. Medical Devices: Evidence and Research, 16, pp. 91–100, 2023. http://doi.org/10.2147/MDER.S407233

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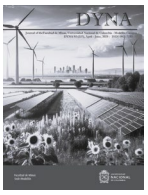

UNIVERSIDAD NACIONAL DE COLOMBIA

Competency certification in the medical industry organizations of Mexicali, B.C., Mexico

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Abstract
Organizations turn to private certifying institutions instead of public certifying agencies. The CONOCER Survey was applied to 304 organizations, out of which 43% do not implement Competency Certification Programs: 36% are unaware of the benefits, 31% are unaware of the institutions and procedures, 26% have a lack of budget and 7% have high turnover. More communication and promotion of government programs are needed [7]. The Chile Valora Program [5,6] confirmed a need of knowledge and trust in the competency certification program. The OECD [18] sustains that in Mexico, a collaboration between the government and the productive sector must be promoted. A public financing program should be developed since only .01% of GDP, among the lowest in the OECD, to activate labor competencies. The methodology applied is the fixed mixed method and parallel convergent typology. A concurrent design for the collection and analysis is necessary.

Keywords: training; job skills; certification; motivation; job satisfaction; project management.

Certificación de competencias en organización de la industria médica de Mexicali, B.C., México

Resumen
Las organizaciones recurren a instituciones certificadoras privadas en lugar de certificadores públicos. La Encuesta CONOCER se aplicó a 304 organizaciones, de las cuales, 43% no implementa Certificación de Competencias: 36% desconocen beneficios y 31% desconoce instituciones y procedimientos, 26% sin presupuesto y 7% tiene alta rotación. Se requiere mayor comunicación y promoción de los programas gubernamentales [7]. El Programa Chile Valora [5,6] confirmó que existía desconocimiento y desconfianza sobre el programa de certificación de competencias. La OCDE [18] sostiene que en México se debe promover la colaboración entre el gobierno y el sector productivo. Se debe desarrollar un programa de financiamiento público ya que se destina .01% del PIB, más bajos de la OCDE, para la activación de competencias laborales. La metodología aplicada es el método mixto fijo y la tipología convergente paralela. Es necesario el diseño concurrente en la recolección y el análisis.

Palabras clave: capacitación; habilidades laborales; certificación, motivación; satisfacción laboral; administración de proyectos.

1. Introduction

There is a conception in the business environment known as the set of knowledge, skills, attitudes, values, and experiences that workers must possess to ensure competitive individual and organizational performance, and their project management. This concept is Labor Competencies, and since all organizations aim to be competitive, organizations must focus on developing their workforce with a level of competence that allows them to achieve their standards and

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goals and consequently allows their workers to perform in an environment that promotes organizational growth and development. That leads them to improve their working conditions and the desired quality of life. This chain reaction has its social benefits and positive community impact. When the abilities require a competent performance, the job description or process manual applies terms such as knowledge, abilities, and attitudes, that is to say, personal attributes or characteristics that are unique, and that allow them to improve their performance, be more competent and productive in an organization [14]. Robbins and Coulter [18] confirm that the skills that create value in an organization are known as core competencies; those competencies and the resources determine an organization's competitive advantage. Dessler and Varela [11] establish that competencies are characteristics that employees demonstrate through their performance, knowledge, skills, and personal behaviors. Undoubtedly, this idea confirms the existence of soft skills, individual and hard skills, and the techniques specific to each function manifested through performance.

When skills or abilities require competent performance in a function, the description or manual of processes uses terms such as knowledge, skills, and attitudes, that is, attributes or personal characteristics of professionals, which are unique, which allow them to improve performance, be even more competent and productive in an organization [9].

Chiavenato [4] establishes a relationship between motivation and competencies. Employee behavior is fundamental in the tactical planning of human resources; therefore, employees must change their attitudes and behaviors to learn and create new skills and competencies. Galleani [12] affirms the behavioral relationship, stating that the characteristics of competencies are motivation, character traits, individual capabilities, theoretical and practical knowledge, and physical and mental abilities. In this case, it is essential to focus on motivations, which establish the behavior of employees towards certain types of work, such as achievement, affiliation, and power.

Given the above, it is concluded that achievement is reached through training and developing competencies necessary for performing a function or promotion within the organization.

This research is based on the premise that some organizations certify their employees through private certifying institutions; this is supported by the response of employers in the CONOCER Survey [7], which allows the identification of a problem in the field of human resources related to the lack of communication and promotion of the existing programs offered by the Government for the benefit of workers.

On the other hand, it mentions that employers must be aware of the benefits of certifying competencies, such as motivation and satisfaction through formal certification programs. This leads us to consider as an element of the problem to find out if organizations use processes for training and certification by competencies and to justify why they do so.

For Werther et al. [25], the fact that organizations are concerned about keeping their employees trained and with a current life and career plan represents the leadership capacity of the employee, translated into their ability to materialize personal and professional plans in the medium and long term.

Without a doubt, this promotes motivation and job satisfaction.

1.1 General and Specific Objectives

The general objective is to analyze the organization's process for Competency Certification in Production and generate a model to understand how Competency Certification influences Motivation and Satisfaction. The specific objectives are to identify the results of the CONOCER Survey [7] about the need for knowledge of public institutions and procedures to implement competency certification programs and generate interest in providing development plans through the government. Review theories of Motivation and Job Satisfaction to know their correlation. Design an instrument to be applied to Production and HR employees and analyze the relationship between Competency Certification, motivation, and job satisfaction. Integrate a model to understand how Competency Certification influences Motivation and Job Satisfaction.

2. Theorical Framework

Therefore, it is confirmed through the CONOCER Survey [7], applied in 2017 to 304 organizations, where 43% of the organizations, that is, 131, need to implement a Training and Development Program based on the Certification by Labor Competencies in their Human Resources management processes.

The main obstacles to implementing the Competency Certification in these 131 organizations are that 36% of employees are unaware of the benefits, 31% are unaware of the Institutions and Procedures, 26% lack a budget, and 7% say they have high turnover among employees. It's also relevant to mention that 56% of employers agree that their competency model promotes employee engagement and motivation, and 50% of companies say they strongly agree that competencies play a vital role in supporting the achievement of their vision and goals [7].

The Chile Valora Program [6] mentions that the certification program allowed 96% of the employees some promotion in their career and professional development, 92% of their employees perceived that they could be promoted, 89% of the employees felt more committed to the company, and 84% had lower job turnover.

OECD [18] mentions that certification programs give employees better job opportunities and better wages, job satisfaction, productivity, and improved innovation practices, all contributing to an increased competitive and innovative population.

All of the above is relevant to the development of organizations and their employees; however, the role played by the employee as a human being, a member of an organization, or a community, should not be left aside; for this reason, there is a similarity with Castillo [3] when he talks about the core value of the human person in organizations and mentions that the person has an infinite value over things, Simply being the one who makes the decisions, executes the processes, and brings the organizational culture to life is more

important than any other asset within the organization. He also mentions that people are directed, and things are administered or managed. Still, part of that management concept must also be related to the interest in seeking development, the common good of its employees, thinking about itself, the employees being well, our customers being satisfied, and the organization obtaining good results. This is also related to Castillo's idea [3], which mentions that leadership's push toward the future will be an action focused on the man rather than the task. On the other hand, he mentions that management allows employees to feel respected and valued; for this reason, entrepreneurs must ensure the growth of their employees so that they feel recognized, valued, and committed to their source of employment.

Jones and George [15] mention that training fosters learning as an essential element, as new knowledge and skills are acquired in all positions and organizations. At the same time, when talking about training, there is no possibility of making a distinction between industries or ranks; everyone has the same need to learn and develop.

Regarding job satisfaction, it is part of man's nature to feel accepted and to belong to an organization. According to Maslow's Hierarchy of Needs, Münch [16] mentions that motivation arises from the needs of human beings, which influence their behavior. At the organizational level, satisfying these needs through work is extremely necessary. The need for love or belonging "are emotional needs such as association, participation, and acceptance in the team; among these are friendship, affection, and love. They are satisfied through sports, cultural and recreational activities, the building of work groups, and a good organizational climate" Münch [17].

In the organizational field, team building and the environment generated by it are vital to achieving adequate employee performance while observing quality and productivity standards. They also generate job satisfaction that promotes a sense of belonging within the team and the organization.

De la Rosa [10] states that motivation and job satisfaction are relevant in every organization since they are the tools to accomplish their objectives. If these elements are not achieved, performance within the team will not be ideal and, on the other hand, absenteeism and turnover will increase.

According to Vásquez-Torres [22], to achieve competitiveness, employees must be trained, and provided with the necessary skills and knowledge to meet market demands, allowing organizations to guide them toward organizational objectives.

On the other hand, Ames [1] mentions that there are factors related to the attraction of candidates and their retention, such as salary, job security, life and career plan, institutional reputation, training, and development. These last two elements, training, and development, represent a valuable factor to be evaluated by employees since they consider them an important tool to maintain and increase commitment and job satisfaction. If the employee perceives that the organization cares about improving their skills and responsibilities, their sense of belonging will increase. Of course, this must be accompanied by a salary improvement that allows them to satisfy their personal needs and achieve life quality.

Bohlander, Snell & Morris [2] have also contributed to employee development. They emphasize that the evaluation of competencies is the analysis of the set of skills and knowledge for positions whose responsibility is based on decision-making and demands high levels of knowledge due to the complexity of the function. However, it should be mentioned that the evaluation of competencies must be directed at any position to ensure high levels of productivity and development at all levels of the organization.

Werther et al. [23] ensure that the employees are responsible for defining their careers within the organization. This decision is affected by what the employee perceives in the environment, its compatibility with the organizational culture, leadership style, and growth opportunities. and development. If employees perceive these elements positively, a high sense of pride and belonging towards the organization will be reinforced.

2.1 Hypothesis of the investigation

H1. The Medical Industry Competency Certification is related to the Training processes of Organizations. H10. The Medical Industry Competency Certification is not related to the Training processes of Organizations. H2. The lack of knowledge on the part of employers about the Institutions that offer Competency Certification programs influences the planning of training programs. H20. The lack of knowledge on the part of employers about the Institutions that offer Competency Certification programs does not influence the planning of training programs. H3. The implementation of Competency-Based Certification Programs has a significant impact on job satisfaction. H30. The implementation of Competency-Based Certification Programs has a minimal impact on job satisfaction. H4. The implementation of Competency Certification Programs has a significant impact on employee motivation. H40. The implementation of Competency Certification Programs has a minimal impact on employee motivation.

3. Methodological Framework

The present research is developed using a fixed mixed method since the use of quantitative and qualitative methods was previously established during the study's planning and execution.

According to Creswell and Plano [9], the mixed-method typology that corresponds to this research is the Parallel Convergent through comparisons or relationships with a social intention in the workplace within their analysis. It is essential to mention that the research corresponds to a transversal study because it occurs at a specific moment.

The design implemented is Convergent, and the quantitative and qualitative research results are analyzed and compared to understand the problem. This describes the study with a QUAN+QUAL notation, indicating that a process is developed in which the results of both databases are compared. It involves collecting and analyzing the information obtained under the quantitative and qualitative methods; these results are mixed and compared, which allows interpreting, in this research, the situation in a medical company regarding the training of employees through

a program of labor competencies.

Regarding the convergent design variant, the parallel database variant is addressed since two sources of information are considered to analyze the same problem, and both results, although independent, are synthesized and compared during their analysis.

According to Creswell and Creswell [8], in the mixed convergent method, the researcher uses quantitative and qualitative information to provide an analysis of the problem posed; this is carried out simultaneously, and the data of the final results is integrated for the search methods they propose the use of open and closed questions.

3.1 Research Variables

The independent variables to be analyzed in this research are the actors' perceptions of the training and competencies certification processes developed by their organization, their knowledge about certification programs, and the strategies organizations use to certify.

The dependent variables are motivation and job satisfaction because the objective is to evaluate the impact that competency-based certification programs have on the employee's perception of the programs that keep them motivated and with a high level of satisfaction towards their source of employment, without a doubt, these elements benefit the organization since they allow to reduce personnel turnover.

3.2 Unit of Analysis and Study Subjects

By provision of the Human Resources and Production area, 11 employees were allowed to be interviewed: 1 HR Director, 2 Production Managers, 4 Production Supervisors, and 4 Direct Employees.

The company belongs to the medical industry and is located in Mexicali, B.C.

The analysis unit has 1,512 employees, 1,089 direct labor, 2 Production Managers, 16 Production Supervisors, and 1 Director of Human Resources.

There is a particular interest in interviewing employees related to the production process and the Human Resources area, exploring their knowledge about the internal processes of certification of competencies, as well as their understanding of the offer of the public sector regarding accreditation and the perception of the impact on motivation and job satisfaction.

A panel of experts evaluated the survey to analyze the congruence and relevance of its content and the information required.

3.3 Research Stages

Identify authors and findings related to certification programs and their benefits.

Identify a unit of analysis and their methodology of certification.

Design a survey to be applied to the employees with the authorization of the company.

Participation of a panel of experts to evaluate the survey.

Analysis of the results of the survey.

Analysis of the relation between the problem established in the investigation and the company's reality.

Analysis of the relation between the certification program, motivation, and satisfaction.

4. Results

As mentioned above, a survey and interview were conducted with 11 employees of a Medical Industry organization in Mexicali, B.C. The analysis presented below corresponds to the study, but the interview results are still being analyzed. The survey had 17 questions with a rating of 1 through 5 on a Likert scale, where one strongly disagrees, two disagree, three neither agree nor disagree, four agree, and five strongly agree. The questions are classified into five sections regarding the employee's knowledge of the certification of competencies: what labor competencies are, benefits provided by labor competencies, institutions, and certification processes offered by the government, internal procedures of the certification programs offered by your company, and if there is a positive impact on motivation and job satisfaction. This research aims to conclude that the Competency Certification of the Medical Industry has a direct relationship with the Training processes of Organizations; on the other hand, the employers' lack of knowledge about the institutions that offer Competency Certification programs influences the planning of their training programs. Verifying that implementing the Competency Certification Programs significantly impacts employees' motivation and job satisfaction is also relevant.

Robbins and Judge [19] point out that employee motivation should be associated with what they can achieve due to their performance, such as the possibility of promotion, employee development, recognition, responsibility, and achievement. They agree with Trost [21] since training processes must be present to achieve the development of employees. Both propose a model of the characteristics of the job, which establishes work dimensions that include skills, tasks, autonomy, and feedback. After analyzing the results of the surveys, it is observed that there is indeed a lack of knowledge on the part of the respondents about the institutions and processes offered by the government on the certification of competencies; this factor is rated on average with 1, that is, they are totally in disagreement because they do not know the government's offer.

They need to understand what the CONOCER is, the National System of Competencies, the National Registry of Standards of Competence, or the above as a consequence of their ignorance of the communication and promotion plan of the Certification by Competencies programs.

It is confirmed that companies in the medical industry have a direct relationship with competency certification processes because, if they are unaware of the programs offered by public institutions and do not receive economic support from the government to certify personnel, they are forced to develop their certification programs. The surveyed company is no exception.

Regarding their knowledge of the programs and procedures offered by their company for certifying competencies, they state that they have a rating of 3; that is, they say they do not agree or disagree.

This is because an internal competency certification program in critical production processes applies only to employees who perform manual assembly, extrusion, and molding operations.

The Operations, Quality, and Engineering departments determine the need to validate training effectiveness through certification in critical operations based on the results of these departments' Process Failure Mode Analyses.

The employee will be accredited for the necessary operation detected, i.e., the assembly or task carried out in the general production line or process will not be certified. As it only applies to some production employees, knowledge about the process must be generalized or clear to all interviewees.

As shown in Figure 1, the frequency in the answers to the four questions that evaluate their understanding of their company's processes is 14 answers with a value of 1-totally disagree, 10 with a value of 4-agree, and 14 with a value of 5-totally agree.

Regarding the perception of the impact on motivation and job satisfaction, the result is favorable, obtaining a value of 4, which shows that they agree with the fact that certification programs provide a positive value towards the motivation and satisfaction of employees, since they would feel more recognized and valued by their organization.

These results confirm the orientation of the CONOCER Survey [7], which establishes that 31% of its respondents are unaware of government institutions and procedures, and 56% agree that its competency model promotes employee commitment and motivation.

The result of the Chile Valora Program [5, 6] is confirmed; it states that since the beginning of this program, there has been a lack of knowledge and mistrust on this subject. By using Competency Certification programs, there is an improvement in the motivation and perception of workers since within the organization, development is promoted. Employees are recognized and motivated.

On the other hand, it confirms what the OECD [17] sustains, that, according to the reality in Mexico, collaboration between the government and the productive sector should be promoted to achieve efficiency in the implementation of public policies for the benefit of labor skills and, on the other hand, public and private financing of skills program should be improved since only .01% of GDP, of the lowest in the OECD, are intended for the activation of work skills, as shown in Table 1. In this way, the process of communication and promotion of the programs offered by the government would be improved.

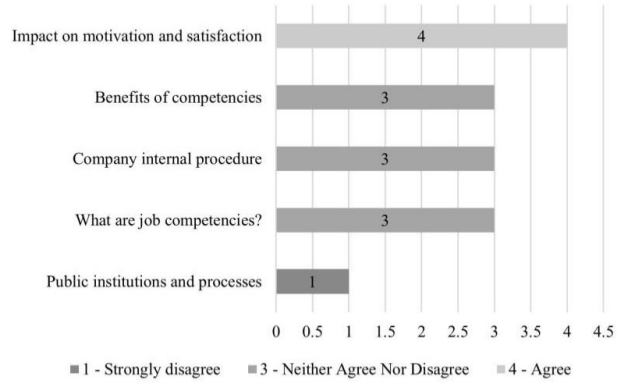

Figure 1. Competency Certification Survey Result
Source: Own elaboration.

Table 1.
Results Conocer Survey, Chile Valora, and OECD coincide with the survey results.

Source	Public Programs and Processes	Motivation and Job Satisfaction
Conocer	31%: unaware of government institutions and procedures	56%: engagement and motivation are promoted.
Chile valora	Employees and entrepreneurs had lack of knowledge and distrust of certification programs.	96%: Promote development. 92%: perceive being promoted. 89%: feel more committed to the company.
OECD	Collaboration between government and private sector should be promoted. Only .01% of GDP is allocated to competency-based certification.	Better job opportunities and better wages. Increased job satisfaction.
Present research	100%: value of 1, strongly disagrees. Unaware of the programs, institutions, and procedures offered by public institutions.	100%: value of 4, agrees competency certification has a positive impact on motivation and job satisfaction.

Source: Own elaboration.

Table 2.
Results Conocer Survey, Chile Valora, and OECD coincide with the survey results.

Source	Company and its relationship with competency certification processes (Internal Programs)
Conocer	50%: Competencies allow the achievement of business objectives and vision.
Chile valora	84% believe that certification programs have helped them decrease job turnover. 94% have allowed it to validate safety and quality standards.
OECD	Increased productivity, improved innovation. A more competitive and innovative population.
Present research	100%: value of 3, neither agree nor disagree about the internal program of CRITICAL OPERATIONS TRAINING EFFECTIVENESS, only on critical processes.

Source: Own elaboration.

Regarding the employees' perception of their internal certification program, the study subjects neither agree nor disagree about their internal program because it only applies to critical production processes, as expressed in Table 2.

Following the analysis of the results, it is important to highlight that several companies within the medical sector, particularly those involved in the manufacturing of ventilators, biomedical equipment, hospital supplies, among others, are concerned about complying with regulatory standards that guarantee the quality of their products, as well as meeting certification requirements that they are unable to fulfill through a government program. In this context, the industry has established partnerships with the education sector to develop certification programs to train their workforce and ensure compliance with required quality standards. One example is the collaboration agreement signed between the Universidad Autónoma de Baja California and the Baja California Medical Device Cluster to promote the training and ongoing development of human resources and encourage research and scientific dissemination in the field of interest.

Similarly, there is a regulatory framework that enables organizations to become a Certification and Evaluation Entity (ECE) officially registered with CONOCER. This designation authorizes them to assess and certify their employees' competencies and actively participate in developing competency standards aligned with their specific industry sector. There are 496 ECEs, including CEMEX, Bimbo, Telmex, and Tecnológico de Monterrey [7]. However, there are no registered companies in the medical products sector. This absence is corroborated by the Registro Nacional de Estándares de Competencia (RENEC) by Productive Sector [7], as no standard related to the industry of interest appears on the list of 1,119 Competency Standards by Productive Sector.

This is precisely where an opportunity arises for this industry to collaborate in designing competency standards that enable the certification of skills relevant to its operational processes. Developing a competency standard entails the establishment of a Competency Management Committee, with the collaboration of technical groups of experts, who are tasked with standardizing operational procedures under the methodology prescribed by CONOCER [7].

The ABC of Competency Standard Development [7] establishes that when a sector expresses interest in developing a Competency Standard to certify their employees, the following steps must be followed:

1. Form the Sector Technical Expert Group (GTES) and the Individual Function Technical Expert Group (GTEFI).
2. Develop the Functional Map (FM).
3. Develop the Competency Standard (CS).
4. Develop the Competency Assessment Instrument (CAI).
5. Compile the supporting documentation for the Competency Standard.

5. Conclusions

By showing evidence of these findings and coincidences with this research, it is possible to develop a model that demonstrates and explains these similarities and upholds what happens in the medical industry organization of Mexicali regarding the implementation of competency-based training programs and how they are associated with business and project management.

Regarding the knowledge entrepreneurs and employees have about the institutions and initiatives offered by the public sector, an average value of 1 is given to this indicator; they disagree because they do not know about the plans and certification processes implemented by the federal government.

This coincides with the CONOCER Survey [7], Chile Valora [5,6], and the OECD in this study, the need for knowledge and a lack of government approach towards private initiatives are evident since there are no open channels of communication and promotion of these programs.

Employers and employees agree that competency-based certification processes directly affect their organization. The company's Critical Operations Training Effectiveness program ensures quality and safety in critical production processes.

This coincides with the CONOCER Survey [7], Chile Valora [5,6], and the OECD, which state that these processes are relevant in the industry because they allow achieving objectives, validating quality and safety standards, and increasing productivity.

In this case, respondents give an average value of 3 points, they do not agree or disagree about the knowledge that employees have about their internal certification process since, as mentioned above, it only applies to specific employees who perform critical processes.

The response was overwhelming regarding the impact of certification processes on motivation and satisfaction. The respondents gave a value of 4; they agree that certification programs impact motivation and satisfaction.

This coincides with the CONOCER Survey [7], Chile Valora, [5,6], and the OECD, these studies mention that these processes impact commitment by promoting employee development and improving salary conditions.

Given the above, Human Resources Management professionals would be provided with a study validating Competency Certification Programs' positive impact on motivation and job satisfaction. This would allow organizations to improve their turnover and absenteeism rates by having more committed employees.

On the other hand, it will enable entrepreneurs to share information about the government's programs. Suppose a certification course is not part of the government's offer. In that case, the company's specialists can work with the government institution to design the program for the following certification course.

González [13] mentions that labor competencies represent today a means to achieve human development within organizations, so it is also relevant to generate a work environment and the ideal working conditions for the desired human development. This confirms that through labor skills, organizations achieve the development of their employees and the organization.

Suárez [20] confirms that work skills are essential to ensure market sustainability, continuity, and leadership.

This research provided the interviewed employees with useful information that allowed them to fill the information gap regarding the benefits of the Labor Skills Certification Program, and the institutions to request guidance and government support to implement these programs among their employees.

Based on the general objective and the expected results, it is concluded that the organization uses an internal competency-based certification program only in critical processes, leaving out other methods for which external certification processes are used through suppliers.

Employees perceive a relationship between the certification program, motivation, and job satisfaction; these programs allow them to achieve professional development in their area of expertise and improve their working conditions.

On the other hand, the interviewees are not familiar with the institutions and processes of the programs offered by the government; they consider that it would be a good practice to explore the alternative of certification in some processes or, as mentioned before, to work together with the government in the development of certifications.

As previously mentioned, various organizations have developed their strategies, such as establishing partnerships

with the education sector and registering as Certification and Evaluation Entities, however, the medical industry has not taken advantage of these opportunities, nor has it directly collaborated in developing Competency Standards.

Undoubtedly, these actions would benefit not only the organization but the entire Medical Devices Industry in the Mexican Republic; they allow the sharing of knowledge and the effectiveness of good practices, which raises the possibility of conducting future studies on programs to be developed jointly, government/private sector, for the benefit of employees and competitiveness within the industry.

It is important to mention that these actions also contribute to the scientific community, as previously mentioned, there is evidence of certification cases involving collaboration between industry and universities.

However, there is no public evidence that CONOCER has directly participated in the development of labor competency certification programs in collaboration with the medical industry. This is where the scientific community would have a role and contribution, as research projects should be promoted to highlight the need for this collaboration in the development and promotion of targeted programs for this sector. Additionally, it is important to develop research projects focused on the benefits of certification, specifically examining how certified personnel are more likely to receive higher compensation and benefit from shorter working hours. This is relevant considering that companies in Mexico that manufacture medical device products are in a key position, where competency certification through CONOCER becomes strategic to ensure regulatory standards, quality, and safety of their products.

References

[1] Ames Guerrero, R.J., Factores de atracción y retención del talento humano y su influencia en el compromiso organizacional. Económicas CUC, 43(1), pp. 139–152, 2021. DOI: https://doi.org/10.17981/econcuc.43.1.2022.Org.1

[2] Bohlander, G., Snell, S., y Morris S., Administración de recursos humanos 17va Ed., Mexico, Cengage Learning, art. 86639-0, [online]. 2018. [Date of reference November 15th of 2023]. Available at: https://repositorio.uide.edu.ec/handle/37000/4186

[3] Castillo, G., El valor central de la persona humana en las organizaciones, Claves del pensamiento de Carlos Llano, Mercurio Peruano, [en línea]. (523), art. 8135, 2010. [consulta, 3 de noviembre de 2023]. ISSN-e 0254-8135. Disponible en: https://dialnet.unirioja.es/servlet/articulo?codigo=3691168

[4] Chiavenato, I., Gestión del talento humano: el nuevo papel de los recursos humanos en las organizaciones, 5ta Edición, México, McGraw Hill, Art. 6984-5, 2020, 78 P. ISBN: 978-1-4562-6984-5

[5] Chile-Valora, La experiencia de Chile Valora: certificación de Competencias Laborales y Diálogo Social [en línea]. art. 328428-2, 2014. [consulta, 1 de noviembre de 2023]. ISBN 978-92-2-328428-2. Disponible en: https://www.ilo.org/sites/default/files/wcmsp5/groups/public/%40americas/%40ro-lima/%40sro-santiago/documents/publication/wcms_241070.pdf

[6] Chile-Valora, Estudio de la percepción del valor de la certificación de competencias laborales en empleadores, [en línea]. Chile, Pragmac, 2022. [consulta, 1 de noviembre de 2023]. Disponible en: https://www.chilevalora.cl/wp-content/uploads/2022/03/ESTUDIO-VALOR-CERTIFICACION-EMPRESAS-2021CHV.pdf

[7] CONOCER., Encuesta Anual sobre Competencias en México: informe de resultados, México, [en línea]. 2017. Disponible en: https://conocer.gob.mx/wp-content/uploads/2018/06/informe_de_resultados_encuesta_anual_de_competencias_2017.pdf

[8] Creswell, J., and Creswell, J., Research design qualitative, quantitative, and mixed methods approach. [online], Art. 8670-6, 5th Ed., Sage Publications Inc., USA, 2018. ISBN 978-1-5063-8670-6

[9] Creswell, J., and Plano, V., Designing and conducting mixed methods research. [online], Art. 4437-9, 3rd Ed., Sage Publications Inc., USA, 2018. ISBN: 978-1-4833-4437-9

[10] De la Rosa, M., Paradigmas emergentes en la educación, art. 315-2, 1ra. Ed., Pearson, Mexico, 2019. ISBN: 978-607-518-315-2

[11] Dessler, G., and Varela, R., Administración de recursos humanos: enfoque latinoamericano, art. 41014, 6ta Ed., Pearson, Mexico, 2017. ISBN 9786073241014

[12] Galleani, R., Coaching para competencias laborales: gestión en talento humano, métodos y estrategias, art. 7334-7, 1ra Ed., Olejnik Editions, Chile, 2023. ISBN: 978-956-40-7334-7.

[13] González, Y., Competencias laborales y clima organizacional como predictores del desempeño organizacional en una institución de educación superior privada. Ciencia Administrativa (2), [en linea]. art. 201902, 2019. Disponible en: https://www.uv.mx/iiesca/files/2020/02/02CA201902.pdf

[14] Hager, P., Competence-based vocational and professional education. [online]. (23), art. 41713-4, Switzerland, Springer, 2017. ISBN 978-3-319-41713-4

[15] Jones, G., and George, J., Contemporary Management, 10th Ed., Mexico, McGraw Hill, art. 6957-9, 2019, 438 P. ISBN: 978-1-45-6957-9

[16] Münch, L., Administración: gestión organizacional, enfoques y procesos administrativos, 3ra Ed., Pearson, Mexico, art. 4444-2, 2018 ISBN: 978-607-32-4444-2

[17] OECD, OECD Skills Strategy Diagnostic Report: Mexico 2017, OECD Skills Studies, OECD Publishing, Paris, 2017. DOI: https://doi.org/10.1787/9789264287679-en

[18] Robbins, S., and Coulter, M., Administration, [online]. 1st Ed., Pearson Education, Mexico, 2023. [date of reference November 11th 2023]. ISBN: 978-607-32-5932-3.

[19] Robbins, S., and Judge, T., Comportamiento Organizacional [online], 18th Ed., Pearson Education, Mexico, 2023. [date of reference November 14th, 2023]. ISBN: 978-607-32-3985-1.

[20] Suarez, S.L., Evaluación del capital humano como contribución competitiva en una empresa periodística en Xalapa, Veracruz 2019, Ciencia Administrativa [en línea], (1), pp. 70-78, 2019. Disponible en: https://www.uv.mx/iiesca/files/2019/10/11CA201901.pdf

[21] Trost, A., Human resources strategies, balancing stability and agility in times of digitization, Springer, Switzerland, 2020. ISBN 978-3-030-30592-5

[22] Vásquez, M., Factorial analysis of the elements that compose the training in the small and medium enterprises of the Industrial sector, Management, 22(2), art. 9321, 2018. DOI: https://10.2478/manment-2018-0022, ISSN 1429-9321,

[23] Werther, W., Davis, K., and Guzmán, P., Administración del Capital Humano, 8va Ed., McGraw Hill, Mexico, 2019.

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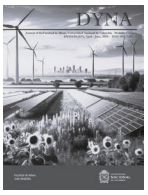

UNIVERSIDAD NACIONAL DE COLOMBIA

Advancing in Artificial Intelligence and circularity to create a sustainable ecosystem in Colombia

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Abstract
Within the search for a way to connect the circular economy and sustainability, efforts must be generated from governments to spread the importance of a route stimulated towards recent technologies, especially the implementation of artificial intelligence facilitating society a sustainable future. Therefore, the objective of this research is to identify the main enablers that allow a sustainable and circular transformation, through a theoretical review and a statistical analysis, using the principal components technique and a bivariate correlational analysis. This study shows that one of the main challenges for the future in terms of the circular economy to achieve sustainability and align with the digital transformation in Colombia, refers to the greater development of the Colombian Departments associated with the circularity of resources and the emergence of employment opportunities.

Keywords: project management; artificial intelligence; circular economy; innovation; sustainable development.

Inteligencia Artificial y economía circular para impulsar un ecosistema sostenible en Colombia

Resumen
Dentro de la búsqueda de una forma de conectar la economía circular y la sostenibilidad, se deben generar esfuerzos desde los gobiernos para difundir la importancia de una ruta dinamizada hacia tecnologías recientes, en especial la implementación de inteligencia artificial facilitando a la sociedad un futuro sostenible. Por ello, el objetivo de esta investigación es identificar los principales habilitadores que permiten una transformación sostenible y circular, a través de una revisión teórica y un análisis estadístico, utilizando la técnica de componentes principales y un análisis correlacional bivariado. Este estudio demuestra que uno de los principales retos a futuro en materia de economía circular para lograr la sostenibilidad y alinearse a la transformación digital en Colombia, se refiere al mayor desarrollo de los Departamentos colombianos asociado a la circularidad de los recursos y al surgimiento de oportunidades de empleo.

Palabras clave: gestión de proyectos; inteligencia artificial; economía circular; innovación; desarrollo sostenible.

1. Introduction

Currently, the most used economic approach is the linear economy, which refers to taking raw materials, transforming them, and finally discarding what is no longer useful. This model must be changed to an economy that generates value and is regenerative to keep the planet safe from the constant negative impacts that threaten it. In order to provide guidance to organizations to leave the linear economy behind, the BS:8001-2017 standard has been developed in the United Kingdom, which Colombia has taken as an example with its technical guide from the Colombian Institute of Technical Standards (Icontec) GTC 314:2020 [1], to implement the principles of the circular economy in companies and ensure sufficient robustness when putting it into practice.

On another hand, the circular economy requires the support of technology and under the scheme of a digital transformation, the Colombian national policy on artificial intelligence is related, framed in the National Council of Economic and Social Policy (CONPES) 3975 of the National

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Planning Department [2], whose objective is based on taking advantage of the strategic use of digital technologies to generate value at a social and economic level in different Colombian sectors. This policy seeks to reduce barriers and enable the conditions to generate innovation from the digital field, creating the necessary conditions to prepare Colombia for the economic and social changes that imply the adoption of a technology such as artificial intelligence.

Living in a world of finite resources, people must act quickly in building the necessary conditions to create a sustainable ecosystem, very different from the current one, and this is achieved by making the most of the technology that can serve as an enabler within the circular economy to achieve the sustainability that the planet requires so much. This economy empowers companies, cities, regions, and nations in sustainability [3] and it is said that there is a strong link between the circular economy and sustainability [4,5]. Many countries have been adapting their principles to achieve sustainable growth, in such a way that the use of all available resources is maximized [6,7].

Adopting strategies to achieve a circular economy requires the adoption of structural changes that go hand in hand with technological development, the fourth industrial revolution and innovation [8]. From this perspective, this revolution has the potential to generate significant changes in society [9]. It is based on the integration of different technologies and its primary objective is to increase the efficiency of production systems to obtain greater profits with their results [10]. By creating a highly flexible production model of personalized and digital products and services, a system is created that allows continuous interactions between people, products, and devices [11].

The result of these transformations is that increasingly complex processes will be seen, but at the same time they will be more sustainable within a profitable environment. On the other hand, the technologies of the fourth industrial revolution provide solutions to the environmental problems that must be faced. They are those technologies that transform the industry and carry out control and monitoring to mitigate any negative environmental impact [12]. In turn, quality and competitiveness are combined to generate such solutions [13,14] and provide a powerful framework for radical improvements in resource efficiency [15-18].

The challenging times that the world has had to face since 2020 with the arrival of the Covid 19 pandemic, and currently with Russia's invasion of Ukraine in the first quarter of 2020, completely break the traditional scheme of businesses and encourages conducting a digital transformation with sustainable models aimed at the well-being of society. Colombia has not been left behind in this transition since there has been an increase in the use of technological tools that help the transformation towards a digital world. From 2016 to today, entrepreneurs have reported an increase in their process productivity by adopting technologies that allow them to be more competitive in the market [1].

But despite this positive impulse, not all organizations are aligned in search of that path that leads to continuous improvement. The challenges that companies face, are focused on lack of knowledge about the adoption of recent technologies, lack of mentality, lack of a clear business model, lack of human capital, leadership, budget, and others. According to the digital transformation survey carried out among Colombian entrepreneurs in 2019, it is evident that there is a high percentage who claim to know emerging technologies. One of them that presents a considerable proportion is artificial intelligence [19].

This means that an important path has already begun to be established in Colombia regarding said digital transformation, but is this transformation aligned with sustainability? And what will happen in the future if the resources of industries and the entire planet are depleted faster than expected? This is where it is important to analyze whether organizations work holistically to address not only this digital transformation but also sustainability and the different paths to reach it, such as the adoption of a circular economy that is the set of regenerative strategies from the design of its processes, products, and services, allowing the closure of the different cycles that characterize it.

The following research questions are established that will be resolved in this study: How do the principles of the circular economy that lead to sustainability relate to the guidelines established by the Colombian national government related to artificial intelligence to achieve a digital transformation? What are the main enablers to establish an ecosystem where circularity and artificial intelligence converge, giving way to sustainability in Colombia?

2. Methodology

The methodological design of this research has a quantitative, descriptive, and correlational approach. The starting point is the theoretical review, which seeks to analyze the phenomena under study such as the fourteen principles of artificial intelligence contained in Conpes 3975, considered the National Council of Economic and Social Policy, which formulates a national policy focused on digital transformation. The circular economy principles of the BS-8001:2017 standard is also investigated, consisting of systemic thinking, collaboration, innovation, value optimization, responsible management, and transparency, these being the fundamental components to carry out a transition to circularity. Finally, the departmental innovation index in Colombia (IDIC) for the year 2022 is evaluated, which shows the Colombian reality according to the National Planning Department, since this secondary source contains indicators related to the main themes of the study.

From the sources consulted, a statistical analysis is carried out using the variables that have been validated by experts and by Cronbach's alpha, yielding a result of 0.967. Reason why it is determined that it is coherent and reasonable to continue with the development of the investigation. Then, the principal component variable reduction technique is applied to evaluate the essential variables that should be considered for the study. Subsequently, a bivariate Pearson correlational analysis is performed, which yields results that determine the closest associations between the variables. With the findings, a relational model is built and complemented with a set of methodological questions to know if there is a complete understanding of the research topics. The software used in this research is RStudio.

3. Results

As one of the research results, Fig. 1 presents the relationships between the variables of the principles of artificial intelligence, the components of the principles of the circular economy BS 8001:2017 and the variables of the IDIC departmental innovation index.

This model in Fig. 1, visualizes the relationship between the different variables. In each quadrant of the graph are located the principles of artificial intelligence that are associated with the IDIC indicators. All of them, regardless of the position in which they are located, are related to the concentric axes that each represent a component of the circular economy.

After reviewing the official secondary sources of the research topics, and to demonstrate the Colombian reality, the results of the official innovation indices in Colombia published by the National Planning Department, an official entity in the country, are taken and validated with Cronbach's alpha which gives a result of 0.967. This index has a group of variables that make it up. They are called pillars of innovation such as Institutions, Human Capital and Research, Infrastructure, Market Sophistication, Business Sophistication, Knowledge and Technology Production and Creative Production. Each of these pillars guides the different departmental innovation indicators in Colombia.

On the other hand, within the statistical procedure carried out in the research, the reduction of variables is carried out considering only those that are most significant according to the results obtained by the factorial technique of principal components. Regarding the correlations between the most relevant variables according to the Pearson test applied in the results of the Departmental Innovation Index in Colombia, they show that the variables Production of knowledge and technology, Creative Production, Institutions, and Infrastructure are the most influential of all due to their P value result as shown in Fig. 2.

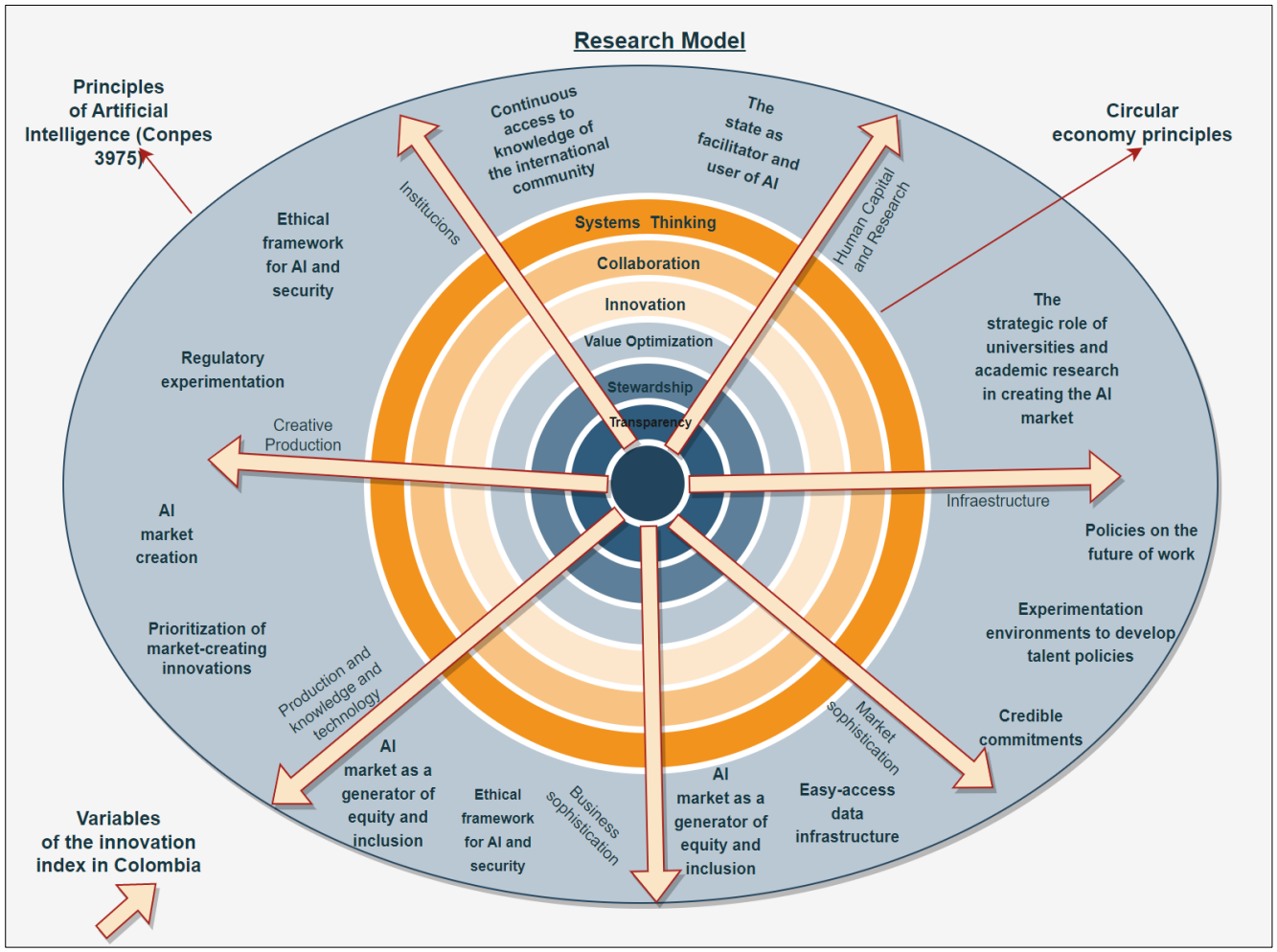

Figure 1. Research variable relationship model.
Source: Elaborated by the authors.

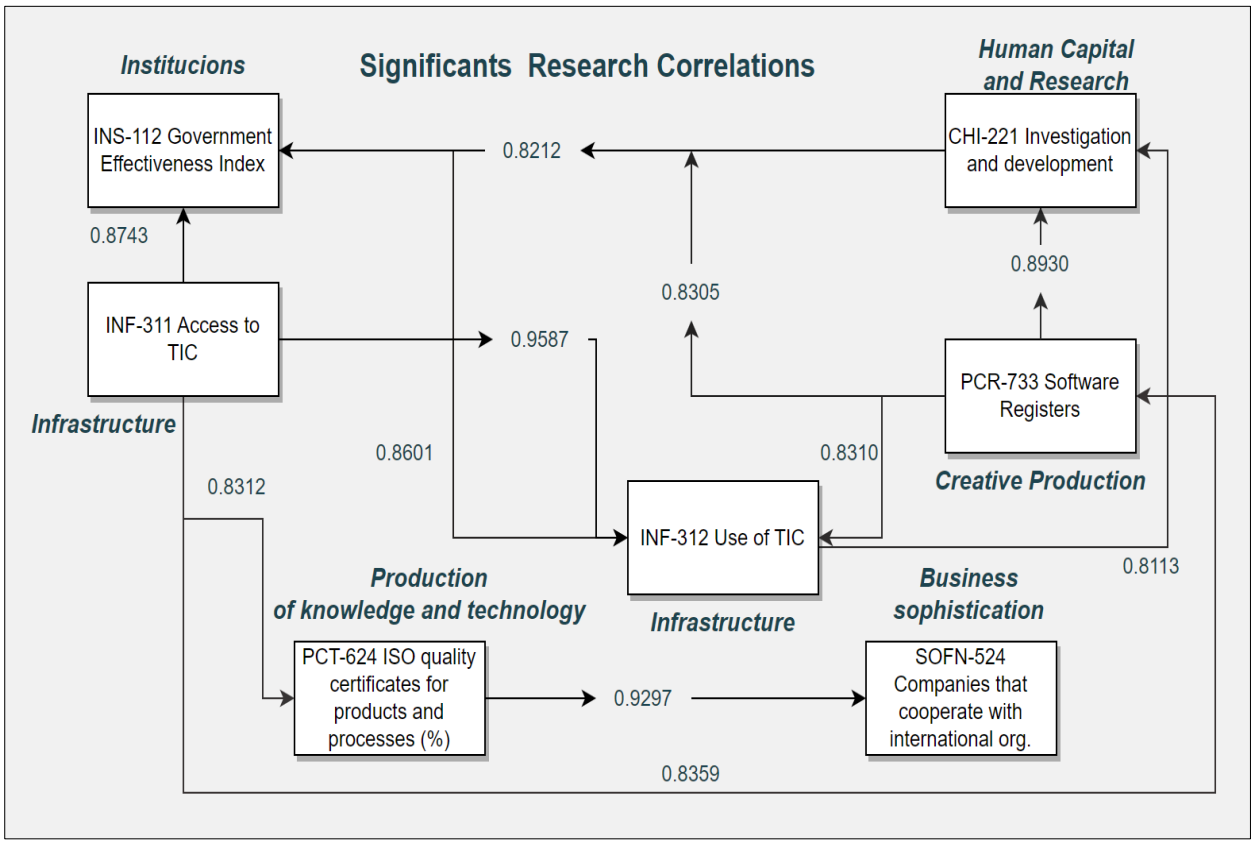

Figure 2. Correlation diagram of research variables
Source: Elaborated by the authors.

There is a strong relationship between business sophistication and the production of knowledge and technology in the study showing a p value of 0.9297. Here the importance of technological support in business is evident since it allows leverage to be enabled to obtain the expected results that the leaders of the organizations have proposed in their strategic planning. It can also be validated that research and human capital are the agents in charge of managing creative production within a business ecosystem. Their correlation shows a p value of 0.8930, a significantly high value with respect to the other binary relationships found in the statistical analysis. Technology also connects with that human capital that will focus on research and development.

Other important relationships that stand out are ICTs, referring to access to information technologies in Colombia and digital government; the Regulatory Environment, which includes policies and regulations under the framework of knowledge creation; Higher Education, referring to the coverage rate of Colombians in university institutions, graduates in engineering sciences and international mobility.

To complement the findings obtained in the research, a set of questions is presented in Fig. 3 that will guide the reader to determine what they need to know regarding the principles of artificial intelligence connected with other questions that focus on relating and validate the principles of circular economy. This figure is useful for those researchers who want to go a little deeper into the topic of study.

Reviewing the results, it is evident that the most significant elements of the statistical exercise carried out are associated with the principles of artificial intelligence highlighted by CONPES 3975, which are focused on establishing guidelines to implement artificial intelligence in Colombia, guaranteeing a ethical, innovative adoption and at the same time responsible for its execution in business and daily life. In Fig. 2, you can see all the variables considered in this research. Likewise, there are the principles of the BS 8001:2017 standard that intervene transversally in the other research variables such as systemic thinking, collaboration between actors, innovation, value optimization, responsible management, and transparency.

When considering innovation, you can think about the circular economy, since its objective is to adopt regenerative and restorative processes in a creative way, breaking traditional schemes of repetitive, routine processes that produce waste without thinking about extending the useful life of the products, inputs, and materials. This is where research and development play a fundamental role in the innovation that is proposed in a business environment. Societies urgently require human capital that is thinking about proposing alternatives to improve the quality of life, and this can happen with the circular economy. But it requires an enabler that drives it and allows it to resonate, and this enabler is technology and in particular artificial intelligence can cause this effect.

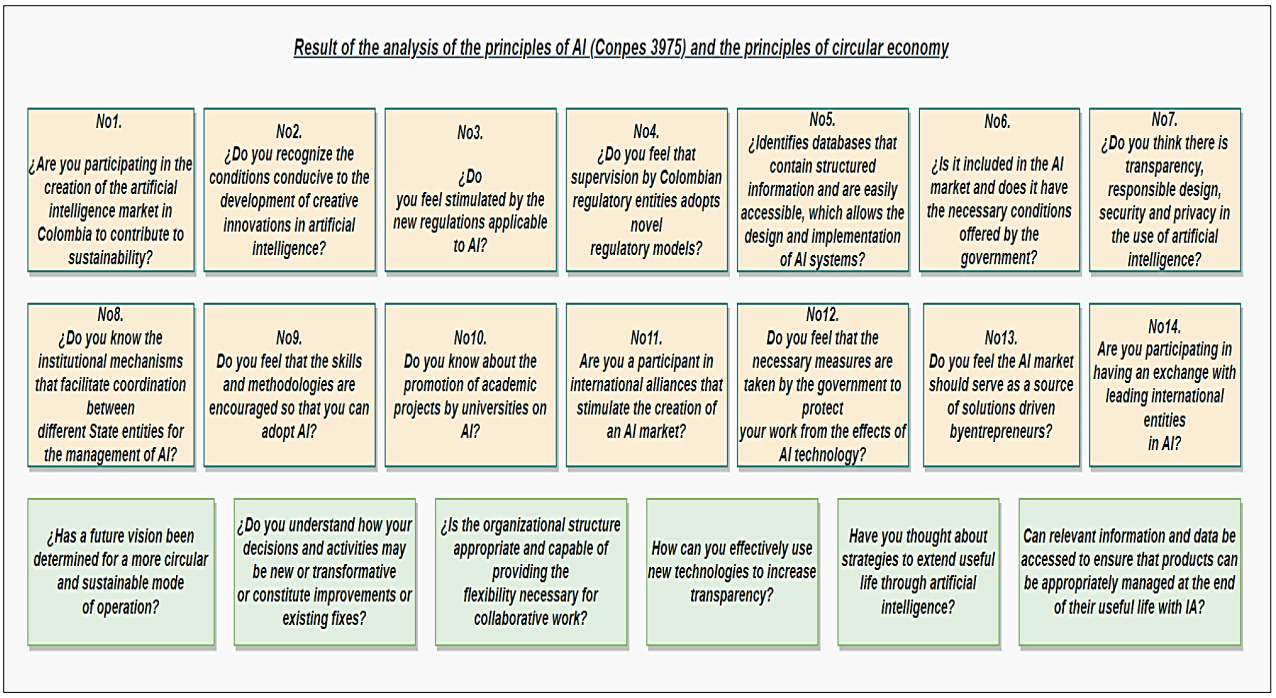

Figure 3. Results of the analysis of the principles of AI (Conpes 3975) and the principles of circular economy.
Source: Elaborated by the authors.

Furthermore, collaboration in the supply chain is not only important for economic performance but also for environmental performance [20] and must be thought and acted holistically [21,22], addressing systems thinking. This is key to understanding complex systems [23] and is part of the principles of a circular economy. It is a set of analytical skills that can help identify and understand systems and design changes to produce desired effects. It includes the ability to conceptually understand and map the structure of a system including its elements, interconnections, flows and feedback loops [24].

Another of the fundamental points in a circular economy is transparency. When all the people who are part of an organization know where they are going, they begin to work with that common goal in mind. That is why it is necessary to provide the essential information so that the guidelines of each of the processes are clear. In addition, better decisions can be made when it comes to seeing an entire panorama of the reality that is experienced from its beginning to its end. That visibility will give leaders an opportunity to establish better strategies for their organizations.

All the above must be complemented with responsible management within the community, understanding and valuing each of the axes of sustainability. Each action leads to the impact of something that contributes to the collective, therefore, it is necessary to understand that the function that each member of the community has is aimed at providing value. The circular economy also focuses on finding ways to optimize its processes and the use of all its resources. It is necessary to identify opportunities to see possibilities for improvement in what has already been established. It is necessary to continually work in search of cost reduction, higher income, adapting to the change from a transformation to a scenario that leads to the use of each of the parts of the system, including the people who are immersed in it.

On the other hand, local and global pressures from the government, the community, and consumers to achieve sustainability objectives motivate us to investigate modern technologies that can help organizations implement environmental strategies and achieve optimal corporate environmental performance [25]. The circular economy is the way to continue existing in an ecosystem with so many challenges to overcome. It is necessary that on this path systemic thinking, innovation, collaboration, value optimization, responsible management and transparency of each of the actions carried out to meet the established purposes within an organization be considered. These principles are the fundamental foundation to be able to survive on this planet, overcoming day by day the obstacles and difficulties that we must go through.

It is evident that in the respective departments of Colombia, investment is being made in Research and Development, which leads to a high percentage of innovative companies in the country. This means that Research and Development is a crucial factor for organizations to transcend the path of innovation. Likewise, by investing in activities conducive to innovation in companies, coordination with knowledge organizations will be facilitated, there will be greater industrial specialization and greater cooperation with international companies. If there is a greater percentage of innovative companies in Colombia and the number of scientific and technical publications that leads to the production of knowledge increases, then the high technological content will increase and there will be greater

quality to the extent that ISO certifications are evident. products and services in companies.

From the theoretical review regarding the principles of the circular economy nested with the Colombian public policy established on digital technologies and artificial intelligence, it is evident that to achieve sustainability in a society it is necessary to have policies agreed upon with interested parties that can be coordinated and monitored to achieve greater competitiveness. They must be supported by innovative technologies such as artificial intelligence that allow an economic result to be achieved with fewer resource inputs, waste reduction and cost savings.

The circular economy shows great promise to make this transformation towards a more sustainable and prosperous society where organizations can comprehensively rethink how to better manage their resources but in a unique way than the traditional one, to obtain financial and environmental benefits. and social. This is achieved if innovation acts as an engine to generate circularity. The innovation ecosystem presents an opportunity to establish a regenerative economic model that makes it possible to achieve behavioral change in society to appreciate and support innovations as part of the solution.

On the other hand, digital technologies and the advance in alternative materials have opened new opportunities. Regulations and economic instruments play a key role in driving innovations in a circular economy. For this to happen more smoothly, strategic partnerships are needed between entrepreneurs, universities, public and private institutions, and government to translate innovations into viable and inspiring business models.

1. Conclusions

According to the results obtained by the statistical analysis, the main enablers that allow a sustainable and circular transformation are Research and Human Capital, Creative Production, Technological Infrastructure, Institutions, Knowledge Production, and Business Sophistication. Therefore, it is detected that for a business to be innovative, it must have the support of technology to enhance the production of knowledge and in this way propose significant contributions. It is vital to be connected to the circular economy so that any new idea or one that improves processes that already exist has circularity incorporated.

The circular economy must have a series of principles that strengthen it so that it meets its objectives of being regenerative and adding value. That is why it must be accompanied by innovation, a fundamental factor to adapt to change, either by creating something new or by improving it. If you want to make a transformation from a linear economy to a circular one, you must have innovative proposals that allow this transformation. But this cannot be a reality if there is no support from an entire community. This is where it becomes evident that you cannot move forward without the collaboration of others. This is another fundamental principle that helps the circular economy create a cycle supported by the improvement and redesign of its processes, products, and services, counting on each of those involved to carry out these changes.

Responding to the research question, it is concluded that the guidelines of the principles of artificial intelligence, analyzed in the results of the study, are aligned with the circular economy to achieve a sustainable and leveraged transition hand in hand with technology, whose mission is focused in promoting novel ideas and innovative business models that contribute to the well-being of society and the competitiveness of the nation.

References

[1] ICONTEC, Marco para la implementación de los principios de la economía circular en las organizaciones, Bogotá, Colombia, 2020.

[2] CONPES 3975, Política nacional pública para la transformación digital e inteligencia artificial, Bogotá, Colombia, Departamento Nacional de Planeación, 2019.

[3] Acerbi, F., Forterre, D.A., and Taisch, M., Role of Artificial Intelligence in circular manufacturing: a systematic literature review, IFAC, 54(1), pp. 367-372, 2021. DOI: https://doi.org/10.1016/j.ifacol.2021.08.156

[4] Sauvé, S., Bernard, S., and Sloana, P., Environmental sciences, sustainable development and circular economy: alternative concepts for trans-disciplinary research, Environ. Develop., 17, pp. 48-56, 2016. DOI: https://doi.org/10.1016/j.envdev.2015.11.005

[5] Geissdoerfer, M., Savaget, P., Bocken, N.M.P., and Hultink, E.J., The circular economy: a new sustainability paradigm? J. Clean. Prod., 143, pp. 757-768, 2017. DOI: https://doi.org/10.1016/j.jclepro.2016.12.048.

[6] Geissdoerfer, M., Morioka, S.N., De Carvalho, M.M., and Evans, S., Business models, supply chains for the circular economy, J. Clean. Prod., 190, pp. 712-721, 2018. DOI: https://doi.org/10.1016/j.jclepro.2018.04.159.

[7] Young, W., and Tilley, F., Can businesses move beyond efficiency? The shift toward effectiveness and equity in the corporate sustainability debate, Bus. Strateg. Environ., 15(6), pp. 402-415, 2006. DOI: https://doi.org/10.1002/bse.538

[8] Bashtannyk, V., Buryk, Z., Kokhan, M., Vlasenko, T., and Skryl, V., Financial, economic and sustainable development of states within the conditions of industry 4.0, Int. J. Manag., 11(4), pp. 406-413, 2020.

[9] Frank, A.G., Mendes, G.H., Ayala, N.F., and Ghezzi, A., Servitization and Industry 4.0 convergence in the digital transformation of product firms: a business model innovation perspective, Technol. Forecast. Soc. Change, 141, pp. 341-351, 2019. DOI: https://doi.org/10.1016/j.techfore.2018.07.033.

[10] Lichtblau, K., Stich, V., Bertenrath, R., Blum, R., Bleider, M., Millack, A., et al., IMPULS, Industry 4.0, Readiness Impuls-Stiftung des VDMA, Aachen-Kölb, 2015.

[11] Kagermann, H., Helbig, J., Hellinger, A., and Wahlster, W., Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0: securing the future of German manufacturing industry. Final report of the Industrie 4.0, Working Group, Forschungsunion, 2013.

[12] Niehoff, S., and Beier, G., Industrie 4.0 and a sustainable development: a short study on the perception and expectations of experts in Germany, Int. J. Innovat. Sustain. Dev., 12(3), pp. 360-374, 2018. DOI: https://doi.org/10.1504/IJISD.2018.092344.

[13] Gilchrist, A., Smart Factories, Industry 4.0, Apress, Berkeley, CA, 2016, pp. 217-230.

[14] Fischer, A., and Pascucci, S., Institutional incentives in circular economy transition: the case of material use in the Dutch textile industry, J. Clean. Prod., 155, pp. 17-32, 2017. DOI: https://doi.org/10.1016/j.jclepro.2017.02.067.

[15] Ghisellini, P., Cialani, C., and Ulgiati, S., A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems, J. Clean. Prod., 114, pp. 11-32, 2016. DOI: https://doi.org/10.1016/j.jclepro.2015.09.007.

[16] Braziotis, C., Bourlakis, M., Rogers, H., and Tannock, J., Supply chains and supply networks: distinctions and overlaps, Supply Chain Manag., 18, pp. 644-652, 2013. DOI: https://doi.org/10.1108/SCM-07-2012-0260.

[17] Korhonen, J., Honkasalo, A., and Seppälä, J., Circular economy: the concept and its limitations, Ecol. Econ., 143, pp. 37-46, 2018. DOI: https://doi.org/10.1016/j.ecolecon.2017.06.041.
[18] Antikainen, M., Uusitalo, T., and Kivikytö-Reponen, P., Digitalisation as an enabler of circular economy, Procedia CIRP, 73, pp. 45-49, 2018. DOI: https://doi.org/10.1016/j.procir.2018.03.187.
[19] ANDI, Encuesta de transformación digital, Bogotá, Colombia, 2019.
[20] Vachon, S., and Klassen, R.D., Environmental management and manufacturing performance: the role of collaboration in the supply chain, Int. J. Prod. Econ., 111, pp. 299-315, 2008. DOI: https://doi.org/10.1016/j.ijpe.2006.11.030.
[21] Bressanelli, G., Perona, M., and Saccani, N., Challenges in supply chain redesign for the circular economy: a literature review and a multiple case study, Int. J. Prod. Res., 57, pp. 7395-7422, 2019. DOI: https://doi.org/10.1080/00207543.2018.1537481.
[22] Avraamidou, S., Milhorn, A., Sarwar, O., and Pistikopoulos, E.N., Towards a quantitative food-energy-water nexus metric to facilitate decision making in process systems: a case study on a dairy production plant, Comput. Aided Chem. Eng., 43, pp. 391-396, 2018. DOI: https://doi.org/10.1016/B978-0-444-64235-6.50071-1.
[23] Jaradat, R.M., Complex system governance requires systems thinking-how to find systems thinkers, Int. J. Syst. Syst. Eng., 6(1–2), pp. 53-70, 2015. DOI: https://doi.org/10.1504/IJSSE.2015.068813.
[24] Arnold, R.D., and Wade, J.P., A definition of systems thinking: a systems approach, Procedia Comput. Sci., 44, pp. 669-678, 2015. DOI: https://doi.org/10.1016/j.procs.2015.03.050.
[25] Jean, R.-J. B., Sinkovics, R.R., and Kim, D., The impact of technological, organizational and environmental characteristics on electronic collaboration and relationship performance in international customer-supplier relationships, Informat. Manag., 51(7), pp. 854-864, 2014. DOI: https://doi.org/10.1016/j.im.2014.05.002.

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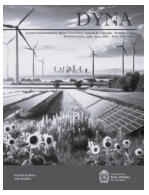

UNIVERSIDAD NACIONAL DE COLOMBIA

Contribution of an asphalt pavement modified with TiO_2 to the moderation of the Urban Heat Island (UHI)

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Abstract
Urban pavements, covering up to 40% of cities, intensify the Urban Heat Island (UHI) phenomenon by impeding rainwater infiltration and absorbing solar radiation. High pavement temperatures increase urban energy demand and pollution. One important factor affecting pavement temperature is albedo. The higher the albedo, the less solar irradiation the pavement absorbs, and the cooler it remains. This study evaluates TiO_2 incorporated into asphalt to enhance albedo. The thermal response of conventional and TiO_2-modified pavements was monitored under natural sunlight. Opto-thermal properties were measured initially and after twelve months of outdoor exposure. An energy balance quantified the heat amount released to the environment for both pavements. Results demonstrate TiO_2 effectiveness in reducing heat storage and improving radiative cooling over time. Additionally, the mechanical and rheological impacts of TiO_2 on asphalt binders were analyzed. Cool pavements with TiO_2 emerge as a viable UHI mitigation strategy, offering energy savings and enhanced urban sustainability.

Keywords: modified asphalt pavements; TiO_2; urban heat island; albedo; aging; released energy.

Contribución de un pavimento asfáltico modificado con TiO_2 a la moderación de la Isla de Calor Urbana (ICU)

Resumen
Los pavimentos urbanos, que cubren hasta el 40% de las ciudades, intensifican el fenómeno de la Isla de Calor Urbana (ICU) al impedir la infiltración de agua de lluvia y absorber la radiación solar. Las altas temperaturas del pavimento aumentan la demanda energética urbana y la contaminación. Un factor importante que afecta la temperatura del pavimento es el albedo. Cuanto mayor es el albedo, menor es la radiación solar que absorbe el pavimento y más frío se mantiene. Este estudio evalúa el TiO_2 incorporado al asfalto para mejorar el albedo. Se monitoreó la respuesta térmica de los pavimentos convencionales y modificados con TiO_2 bajo la luz solar natural. Se midieron las propiedades opto-térmicas inicialmente y después de doce meses de exposición al aire libre. Un balance energético cuantificó la cantidad de calor liberado al ambiente para ambos pavimentos. Los resultados demuestran la eficacia del TiO_2 para reducir el almacenamiento de calor y mejorar el enfriamiento radiativo con el tiempo. Además, se analizaron los impactos mecánicos y reológicos del TiO_2 en los ligantes asfálticos. Los pavimentos fríos con TiO_2 surgen como una estrategia viable de mitigación de UHI, que ofrece ahorros de energía y una mayor sostenibilidad urbana.

Palabras clave: pavimentos de asfalto modificados; TiO_2; isla de calor urbana; albedo; microclima.

1. Introduction

In recent decades, large-scale production of goods and industrial activities have caused an increase in the number of residents living in cities near production centers. The population density in cities is continuously growing and it is estimated that by 2050, nearly 70% of the world's population will live in megacities.

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To accommodate this ever-growing urban population, a housing and communication infrastructure that causes significant environmental changes has been implemented: there is an increasing replacement of natural soil with impermeable soil, and materials with inadequate opto-thermal properties are used in construction [1,2].

At present, almost half of urban land has been replaced by asphalt pavement. During the day, due to the incidence of solar irradiation, these pavements heat up and afterward release heat to the environment. Asphalt pavements are dark, so as a black body, they absorb a significant portion of the incident solar irradiation as heat, reaching surface temperatures close to 70ºC in some geographic regions during the summer. Higher pavement surface temperatures are one of the causes of the urban heat island effect, UHI, with air temperatures higher in the city than in the surrounding suburbs and rural areas [3].

A conventional asphalt pavement transfers heat to its interior, stores it during sunlight hours, and releases it into the air during the evening and night hours, causing thermal discomfort for city dwellers [4-9].

There is a huge consumption of fossil energy to cool premises and residences and air pollution occurs in large cities. In addition, due to the viscoelastic nature of asphalt, the load resistance of the pavement decreases as the temperature increases and rutting occurs on the surface, reducing the service life of the pavement. During the life of the pavement, changes occur in the composition of the asphalt binder. The laboratory-aging test reveals that the asphalt became stiffer and more prone to cracking by losing its viscous component due to temperature, humidity and the incidence of the ultraviolet (UV) component of solar radiation, among other environmental factors to which an outdoor pavement is subjected. The pavement undergoes modifications in its structure and cracks and rut appear on the surface [10-13]. Many studies have identified permanent deformation induced by high temperatures as one of the main problems in asphalt pavements in the current climate change situation.

To mitigate the UHI (Urban Heat Island) effect, among other possible solutions, it is recommended to use paving materials with higher albedo, which is defined as the ratio between reflected solar irradiation and the total solar irradiation incident on the surface [3]. The higher the albedo value is, the less solar irradiation the pavement absorbs, and the cooler it remains. The most common comparison between asphalt and concrete pavements shows that the latter has a cooler surface due to its lighter color [4,14] Various strategies have been proposed to reduce the amount of heat absorbed and stored by pavement, including the incorporation of pigments into asphalt mixtures to achieve a lighter surface color, particularly on the top layer [15]. Chen et al. affirm that incorporating TiO_2 fillers at varying percentages into a transparent resin, which is subsequently applied as a coating on different asphalt mixtures, significantly enhances the albedo value, depending on the size and concentration of the fillers [16].

Zhong has demonstrated that modifying an asphalt emulsion with varying percentages of TiO_2 and applying it as a surface coating reduces the pavement's surface temperature by approximately 5°C [17]. Cool pavements can be implemented in urban areas as a strategy to mitigate the adverse effects of urban heat islands. By preventing pavement overheating, energy savings are achieved, and the urban microclimate is improved.

It is noteworthy that asphalt pavements, initially dark in color, lighten over time, slightly increasing their albedo and reducing heat absorption as they age in service. This outdoor color variation is attributed to irreversible physicochemical modifications of the asphalt (aging), caused by a complex oxidation process of its organic compounds under the influence of environmental factors such as rainfall, temperature fluctuations, and UV component of incident solar irradiation, which photo-catalyzes the degradation [11].

This study analyzes the optothermal response of dense asphalt pavement specimens, before and after the incorporation of TiO_2 microparticles (average size 0.5 μm) as fillers in the asphalt mixture.

The surface temperature, albedo, and emissivity of the exposed samples were measured, and the effect of prolonged outdoor exposure on their thermal behavior was evaluated. Additionally, using an energy balance approach, the heat released by the samples into the environment was calculated both initially and after 12 months of outdoor exposure. The effect of TiO_2 microparticles on the physical properties of asphalt, high-temperature performance grade, and fatigue damage tolerance were also investigated using a dynamic shear rheometer (DSR).

2. Experimental

Two representative types of dense-graded asphalt mixtures were prepared. The first type utilized an asphalt binder CA-30, stone aggregates with commercial designations of 6:12 (coarse aggregate) and 0:6 (fine aggregate), and combined fillers (lime + all particles smaller than the #200 sieve from the coarse and fine aggregates). This mixture was used to fabricate reference specimens. The second asphalt mixture was prepared by removing the combined fillers, and incorporating 5% of TiO2, a powdered pigment that meets the specifications of ASTM C979. The TiO2-modified specimens analyzed in this study were fabricated with this modified asphalt mixture. All specimens were 0.3 m × 0.3 m × 0.05 m. In this paper 'specimen' denote asphalt pavement mixture, and 'sample' denote asphalt binder.

Thermal measurements were conducted by placing the specimens on a polystyrene foam (EPS) sheet 0,1 m thick, which exhibits negligible thermal conductivity (ca. 0.032 W.m-1K-1).

The albedo value of each specimen (reference and TiO_2-modified) was measured following the ASTM E1918A standard modified by Akbari et al. [18], during clear-sky days in January 2024 and January 2025, on the rooftop of the Universidad Tecnológica Nacional, Facultad Regional La Plata (National Technological University, La Plata Regional Faculty). The instrumentation included a calibrated Kipp & Zonen CMP-3 pyranometer coupled to a Campbell Scientific CR300 datalogger.

The thermal behavior of samples exposed to direct solar irradiation was evaluated using K-type thermocouples connected to Testo data-loggers. The surface temperatures of the specimens were recorded continuously every ten seconds over five consecutive days in January 2024, with the measurements repeated under similar conditions in January 2025.

Additionally, a Testo 865 thermal imaging camera was employed to estimate the emissivity (ε) of each sample, following the guidelines outlined in ASTM E1933-99a [19]. The camera, with an infrared resolution of 320 × 240 pixels and a thermal sensitivity of 0.1 °C, also enabled visual analysis of surface temperature differences between the samples, complementing the data recorded by the thermocouples.

A simplified model was employed accounting for the heat fluxes occurring between the pavement and its surrounding environment, incorporating the primary energy transfer mechanisms. The model includes: the incident solar irradiation, the portion of it absorbed by the pavement, the heat transferred to the pavement by thermal conduction, the energy released to the environment by convection (sensible heat), and the longwave radiation emitted from the hot pavement surface to the air. Using this framework, the total energy released to the environment by the two types of asphalt pavement was quantified.

To analyze the influence of TiO_2 microparticles on the asphalt binder, physical properties such as penetration (ASTM D5/D5M) [20] and softening point (ASTM D36/D36M) [21] were determined. Additionally, the high and intermediate temperature performance grades (AASHTO M320) [22] were evaluated using a dynamic shear rheometer.

The effect of TiO_2 on the physical and rheological properties of the asphalt binder was evaluated before and after subjecting the samples to thin-film oven aging (RTFOT) following AASHTO T240 [23].

3. Results

3.1 Color variation of asphalt mixtures under outdoor exposure

Fig. 1 shows images depicting the color of reference and 5% TiO_2-modified asphalt pavement specimens, both initially and after one year of outdoor exposure.

Initially, the reference specimen exhibits a characteristic black color, whereas the TiO_2-modified specimen displays a brown coloration [27]. This suggests that TiO_2 may have catalyzed a chemical transformation in the asphalt from the beginning of the experiment [24-25]. After 12 months of outdoor exposure, the reference specimen developed a dark gray coloration, while the TiO_2-modified sample exhibited a light gray tone. It can be concluded that prolonged outdoor exposure has caused surface color variations in both analyzed samples.

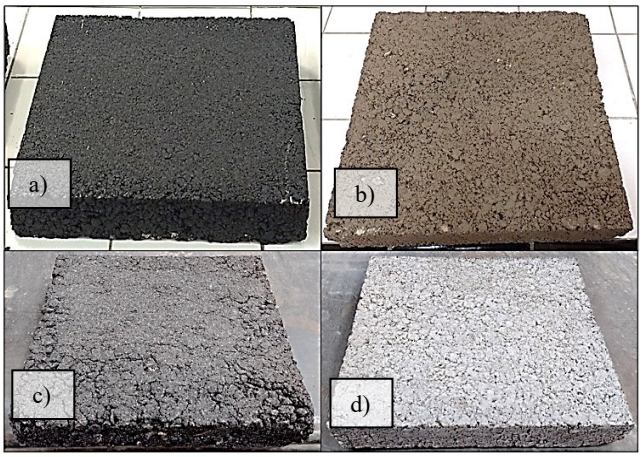

Figure 1. Images of the samples: a) reference asphalt pavement and b) TiO_2-modified asphalt pavement, at month 1; c) reference asphalt pavement and d) TiO_2-modified asphalt pavement, after 12 months of outdoor exposure.
Source: Authors' own work.

The observed color change in both specimens is attributed to the oxidation process of the asphalt due to a prolonged stay in open air (UV radiation, rainfall, oxygen, etc), a process catalyzed by TiO_2 in the modified specimen [26].

A cross-sectional cut was performed on the reference and TiO_2-modified samples exposed to outdoor conditions for 12 months to determine whether the color change was superficial or occurred throughout the whole specimen's volume. Fig. 2 shows images of the cross-sectional cuts of the (a) reference and (b) TiO_2-modified specimens. In both cases, a color difference is observed between the air-exposed surface and the sample's interior, which can be attributed to a greater aging of the surface due to UV radiation exposure. The cross-section of the TiO_2-modified specimen exhibits a marked color difference between the surface and the interior of the modified asphalt mixture. It is possible that the presence of TiO_2 catalyzes the reaction between asphalt and oxygen under UV radiation, resulting in a noticeable surface color change in the TiO_2-modified sample compared to the surface color change observed in the reference specimen for the same reaction.

3.2 Albedo values determined at solar noon on a summer day

The variation in albedo of the pavement specimens before and after being exposed to outdoor conditions for 12 months is shown in Fig. 3. The albedo measurement of each specimen was repeated six times and the standard deviation obtained was ± 0.3%.

It is confirmed that the incorporation of TiO_2 into the asphalt mixture increased the albedo at the start of the experiment.

Figure 2. Cross-sectional cut in a) the reference specimen and b) the TiO_2-modified specimen exposed to outdoor conditions for 12 months.
Source: Authors' own work.

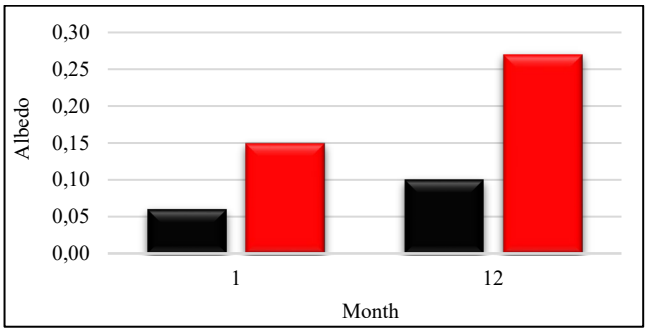

Figure 3. Albedo values for reference specimen (black) and TiO_2-modified specimen (red) at month 1 and after 12 months of outdoor exposure.
Source: Authors' own work.

After 12 months of outdoor exposure, both pavements exhibit an increase in their albedo values, with the TiO2-modified specimen showing a particularly significant rise. An increase in albedo implies a lower surface temperature of the asphalt pavement exposed to solar irradiation [28-29].

3.3 Variation in surface temperature of samples exposed to outdoor conditions

Figs. 4a and 4b illustrate the surface temperature variations of the reference and TiO_2-modified asphalt pavement specimens over a five-day period a) at the start of outdoor exposure and b) after 12 months of outdoor exposure.

Fig. 4a shows that, at the start of outdoor exposure, the TiO_2-modified asphalt pavement specimen exhibits a decrease of approximately 4°C in its surface temperature value particularly when the Sun is at its zenith. After 12 months of outdoor exposure, Fig. 4b reveals that the TiO_2-modified sample displays a more pronounced decrease in surface temperature, approximately 10°C, compared to the value recorded in the reference sample, especially during solar zenith. The observed decrease in temperature correlates with the higher albedo values measured in the specimen after 12 months of outdoor exposure. Similar behavior of the pavement superficial temperature during the solar day has been shown in [17].

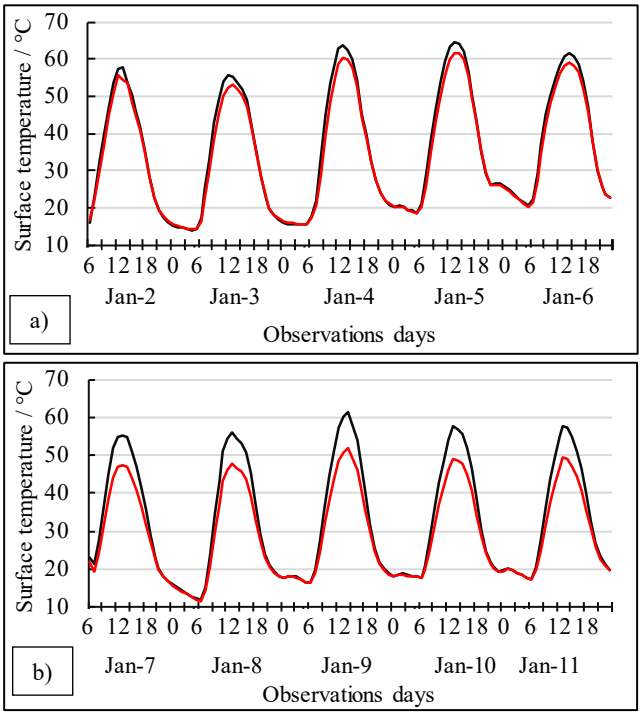

Figure 4. Surface temperature variation over five studied days, due to daily solar irradiation on the reference asphalt pavement specimen (black line) and on the TiO2-modified pavement specimen (red line): a) at month 1 and b) after 12 months of outdoor exposure.
Source: Authors' own work.

3.4 Thermographic Images

The change in surface temperature of the analyzed specimens can be qualitatively observed in the thermographic images shown in Fig. 5. The color scale illustrates that both samples (reference and TiO_2-modified asphalt pavement) at the start and after one year of outdoor exposure, exhibit lower surface temperatures, with this cooling effect being more pronounced in the TiO_2-modified specimen.

Using thermographic images and data recorded with thermocouples, the emissivity (ε) of each analyzed surface was determined. The emissivity values (ε), both at month 1 and month 12, were 0.91 for the reference specimen and 0.97 for the TiO_2-modified specimen.

3.5 Variation of Heat Released to the Environment for Each Analyzed Pavement

The thermal balance of a pavement exposed to solar irradiation must account for:

- The amount of solar irradiation absorbed by the pavement,
- The heat flux transferred by conduction (Qcond) into the pavement's interior,
- The infrared radiation (Qrad) emitted by the surface of the heated body,
- The heat flux, transferred by convection (Qconv), from the hot surface to the air.

According to the Bentz model [30] and following the analyses by Asaeda [31] Qin et al and Xu et al. [32,33], the energy balance at the surface of a dry pavement is:

$$I.(1-albedo) = h_c.(T_S - T_{amb}) + \varepsilon.\sigma.(T_S^4 - T_C^4) - k.(dT/dz) \quad (1)$$

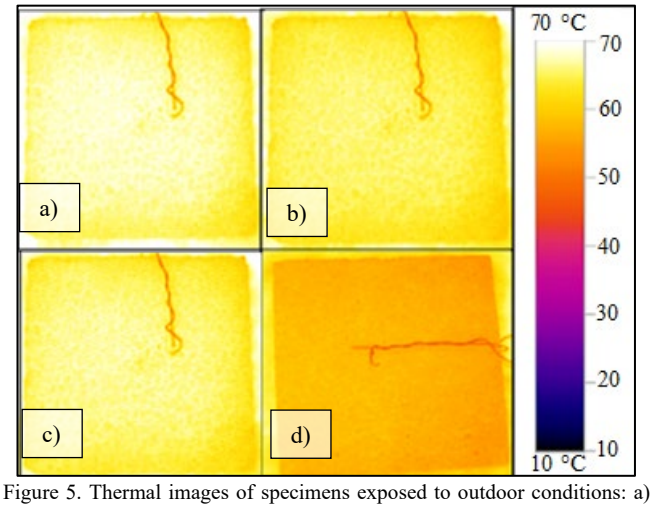

Figure 5. Thermal images of specimens exposed to outdoor conditions: a) and b) reference asphalt pavement and TiO_2-modified asphalt pavement at month 1, respectively; c) and d) reference asphalt pavement and TiO_2-modified asphalt pavement after 12 months of outdoor exposure, respectively.
Source: Authors' own work.

where I is the incident solar irradiation on the sample surfaces; h_c [$W.m^{-2}.K^{-1}$] is the convective coefficient, dependent on wind speed; T_S [K] is the pavement surface temperature; T_{amb} is the ambient temperature [K]; σ is the Stefan-Boltzmann constant (5.67×10^{-8} [$W.m^{-2}.K^{-4}$]); ε is the emissivity of the pavement (dimensionless, ranging between 0 and 1); T_C[1] [K] is the sky temperature; k [$W.m^{-1}.K^{-1}$] is the material's thermal conductivity; and dT/dz [$K.m^{-1}$] is the thermal gradient into the pavement's interior.

The portion of solar energy that is not reflected by the surface is absorbed by the pavement. The absorbed energy is partially transferred throughout the pavement's volume via conduction, increasing its temperature. Additionally, a heated body emits radiation in the infrared (IR) region of the electromagnetic spectrum. This radiative heat transfer depends on the surface temperature value and the emissivity of the composite material. Furthermore, when the pavement's surface temperature exceeds the temperature of the air above it, part of the absorbed energy begins to be transferred from the pavement surface to the air via convection (sensible heat). Convective heat transfer to the environment depends on the surface temperature of the heated sample, the surrounding air temperature, and the wind speed over the analyzed surface.

Using the surface temperature data shown in Fig. 4a and 4b, considering the thermal balance, and accounting for the variation in the optical properties that the samples undergo after being exposed to the outdoors for 12 months, the energy released into the environment as sensible heat and longwave radiation is calculated over a five-day period using eq (1).

Fig. 6 shows the behavior of each component of the energy balance (at month 1 and after 12 months) for the reference sample and the TiO2-modified sample of outdoor exposure, both over five consecutive days.

It is confirmed that the TiO2-modified sample absorbs less energy than the reference sample, which is directly reflected in the amount of energy the sample releases to the air adjacent to the surface. This effect is more pronounced when the samples have been exposed to outdoor conditions for 12 months. The amounts of energy flux released to the environment by the samples over the five studied days during both daytime and nighttime periods were calculated.

Table 1 presents the energy flux released to the environment (Q_{rel}) between 06:00 and 20:00 hours, calculated as the sum of sensible and radiative heat, for reference and the TiO_2-modified samples, both over the five studied days, at month 1 and after 12 months of exposure to outdoor conditions.

Table 1 demonstrates that, during daytime hours, the majority of energy flux released to the environment by both specimens occurs as sensible heat (Q_{conv}), with the reference sample exhibiting a higher Q_{conv} value than the TiO_2-modified specimen.

In contrast, during nighttime (Table 2), the total amount of energy released is lower than the one released during the daytime, and it is primarily attributed to long-wave radiation, Q_{rad}, the lower emission value is again for the TiO_2- modified specimen.

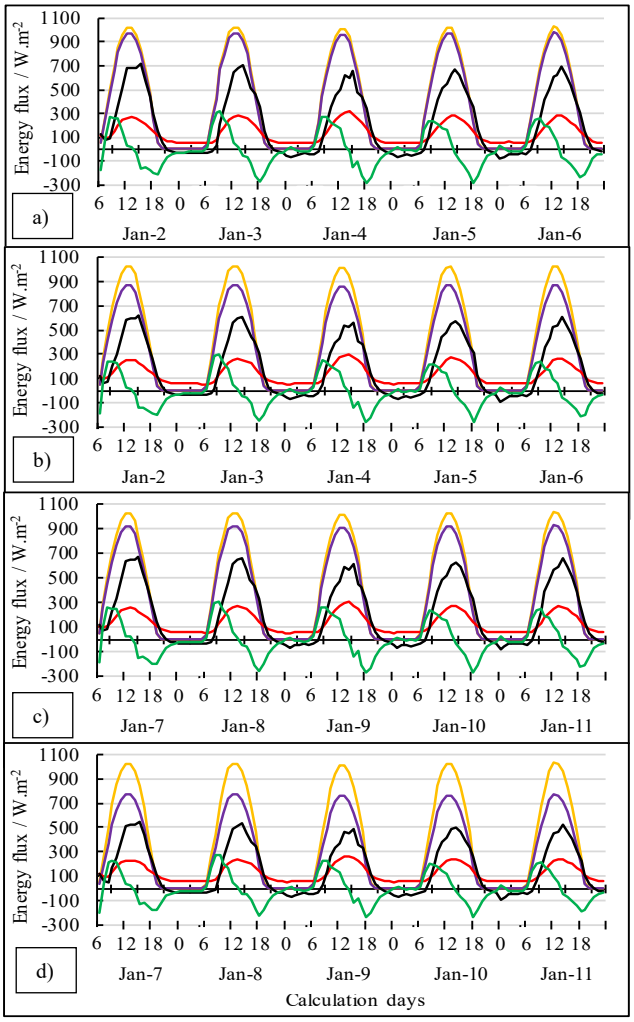

Figure 6. Energy flux components calculated over five days period of: a) reference specimen and b) TiO_2-modified specimen with optical properties of month 1; c) reference asphalt specimen and d) TiO_2-modified asphalt specimen with optical properties of month 12. Lines: *yellow*: incident solar irradiation; *purple*: absorbed solar energy; *black*: energy transferred to the environment via convection; *green*: long-wave IR energy emitted to the environment; *red*: heat flux between the pavement surface and its interior. Source: Authors' own work.

Table 1.
Energy flux released to the environment (Qrel) over the five studied days, by the reference and TiO_2-modified asphalt pavement specimens, between 06:00 and 20:00 hours, before and after 12 months of outdoor exposure.

Month	Reference Specimen		TiO_2 Modified Specimen	
	Q_{Rel} / $Wh.m^{-2}$		Q_{Rel} / $Wh.m^{-2}$	
1	Q_{Rad} / $Wh.m^{-2}$	Q_{Conv} / $Wh.m^{-2}$	Q_{Rad} / $Wh.m^{-2}$	Q_{Conv} / $Wh.m^{-2}$
	12008.8	26443.4	11503.5	22807.3
	38452.2		34310.9	
	Q_{Rel} / $Wh.m^{-2}$		Q_{Rel} / $Wh.m^{-2}$	
12	Q_{Rad} / $Wh.m^{-2}$	Q_{Conv} / $Wh.m^{-2}$	Q_{Rad} / $Wh.m^{-2}$	Q_{Conv} / $Wh.m^{-2}$
	11483.1	24889.1	10430.7	19718.4
	36372.2		30149.1	

Source: Authors' own work.

[1] The sky temperature, T_C, is the average temperature derived from the ground surface under study and the temperature in the upper troposphere, where water vapor content is minimal.

Table 2.
Energy flux released to the environment (Q_{rel}) by the reference and TiO_2-modified asphalt pavement specimens, over the five studied days, between 20:00 and 06:00 hours, before and after 12 months of outdoor exposure.

Month	Reference Specimen		TiO_2 Modified Specimen	
	Q_{Rel} / Wh.m^{-2}		Q_{Rel} / Wh.m^{-2}	
1	Q_{Rad} / Wh.m^{-2}	Q_{Conv} / Wh.m^{-2}	Q_{Rad} / Wh.m^{-2}	Q_{Conv} / Wh.m^{-2}
	2859.2	-740.7	2978.2	-958.5
	2118.5		2019.8	
	Q_{Rel} / Wh.m^{-2}		Q_{Rel} / Wh.m^{-2}	
12	Q_{Rad} / Wh.m^{-2}	Q_{Conv} / Wh.m^{-2}	Q_{Rad} / Wh.m^{-2}	Q_{Conv} / Wh.m^{-2}
	2848.9	-773.4	2957.1	-1021.1
	2075.5		1936.1	

Source: Authors' own work.

In contrast, during nighttime (Table 2), the total amount of energy released is lower than the one released during the daytime, and it is primarily attributed to long-wave radiation, Q_{rad}, the lower emission value is again for the TiO_2- modified specimen.

It is observed that the greatest energy flux released from the samples to the environment occurs during the sunlight period. Notably, when comparing the TiO_2-modified sample energy flux released with that of the reference sample, it is noticed a reduction in the energy flux transferred to the environment by the TiO_2-modified sample, both initially and after 12 months of outdoor exposure. The TiO_2-modified pavement, being lighter in color, absorbs less solar heat and lowers its surface temperature, thereby contributing to an improved urban microclimate [5,7].

3.6 Influence of TiO_2 on the physical properties of asphalt CA-30

The effect of TiO_2 on the physical properties of the asphalt binder was evaluated before (virgin) and after subjecting the samples to thin-film oven aging (aged) (RTFOT) following AASHTO T240.

In Table 3, the penetration and softening point values before and after subjecting the samples to thin-film oven aging (RTFOT): i) asphalt CA-30, ii) asphalt CA-30 + combined fillers, and iii) asphalt CA-30 + TiO_2 filler, at the proportions used in the mixture.

Table 3 shows that asphalt with combined fillers has the lowest penetration value and the highest softening point, a behavior like to that of asphalt with only TiO_2 as a filler, both, before and after aging. This behavior derives from the filler/asphalt weight ratios, being 1.1 for CA-30 asphalt with combined fillers and 1 for CA-30 with TiO_2 filler.

Table 3.
Properties of asphalt CA-30 and fillers modified asphalt CA-30 before and after subjecting the samples to thin-film oven aging (RTFOT).

Samples	Properties	
	Penetration	Softening Point
Virgin asphalt	46 x 10^{-1} mm	54 °C
Aged asphalt (RTFOT)	29 x 10^{-1} mm	59 °C
Virgin Asphalt + combined fillers	20 x 10^{-1} mm	63 °C
Aged Asphalt + combined fillers (RTFOT)	15 x 10^{-1} mm	68 °C
Virgin Asphalt + TiO_2 filler	27 x 10^{-1} mm	60 °C
Aged Asphalt + TiO_2 filler (RTFOT)	17 x 10^{-1}mm	65 °C

Source: Authors' own work.

This indicates that asphalts with fillers (combined or with only TiO_2) have low thermal susceptibility, and therefore, in both cases, the viscosity resists creep changes with increasing temperature [34,35].

3.7 High-Temperature Performance Grade (PG)

To evaluate the high-temperature performance grade of the analyzed asphalt binder (virgin and RTFO-aged) according to AASHTO M320, the rutting parameter (G*/sinδ) was determined for asphalt CA-30, asphalt CA-30 + combined fillers, and asphalt CA-30 + TiO_2 filler. Here, G* (complex modulus) represents a measure of the material's dynamic mechanical properties, and δ (phase angle) corresponds to a measure of its elastic and viscous properties [36,37].

From the G*/sinδ vs. temperature relationship, it was determined that by incorporating TiO_2 into CA-30 asphalt, the rutting failure temperature changed from 64°C for CA-30 asphalt to 76°C for CA-30 asphalt + TiO_2 filler, and 82°C for CA-30 asphalt + combined fillers.

The data reveals an improved performance grade in the asphalt CA-30 modified with combined fillers concerning rutting resistance (G*/sinδ) compared to the sample asphalt CA-30 + TiO_2 filler.

However, regarding surface temperatures recorded in specimens shown in Fig. 4a, a contrasting performance is noticed: the TiO_2-modified specimen exhibits higher albedo, which reduces its surface temperature under the same solar irradiation conditions as those experimented by the reference specimen.

This behavior suggests that, under real-world exposure conditions, the sample prepared with CA-30 asphalt + TiO_2 filler could compensate for its lower intrinsic rutting resistance through its enhanced heat-reflective capacity. Studies by Saleh and Trad, as well by Hashema et al. [38,39], show that, according to the SUPERPAVE and LTPP programs (integrated in the AASHTO M 320 standard), the geographic PG (Performance Grade) predicts the surface temperature of black pavements based on regional climatic conditions. Thus, the determination of the geographic PG is affected not only by climatic data but also by the pavement albedo value, an optical property of the pavement surface nature.

The maximum surface temperatures, shown in Fig. 4a, reached 64 °C for the reference specimen, compared to 61 °C for the TiO_2-modified specimen. Indicating that the TiO_2 modified pavement will be under lower thermal loads. Consequently, by operating at a lower surface temperature, the TiO_2-modified sample exhibits a mechanical response to rutting that could match or surpass that of the CA-30 asphalt + conventional fillers. To validate this hypothesis, we quantified the rutting rheological parameters (G*/sinδ) at the specific temperatures attained by each sample under real environmental conditions (Table 4), derived from temperature sweeps conducted via DSR rheometer.

The values shown in Table 4 indicate that the specimen incorporating CA-30 + TiO_2 asphalt filler, which has the highest albedo and lowest surface temperature, shows improved rutting resistance under these conditions.

Table 4.
G*/sinδ values obtained with samples, at the surface temperatures reached by the respective specimens under identical solar irradiation conditions.

Sample	G*/sinδ	Surface temperature / °C
Asphalt CA-30 + combined fillers	9.1	64
Asphalt CA-30 + TiO_2 filler	9.9	61

Source: Authors' own work.

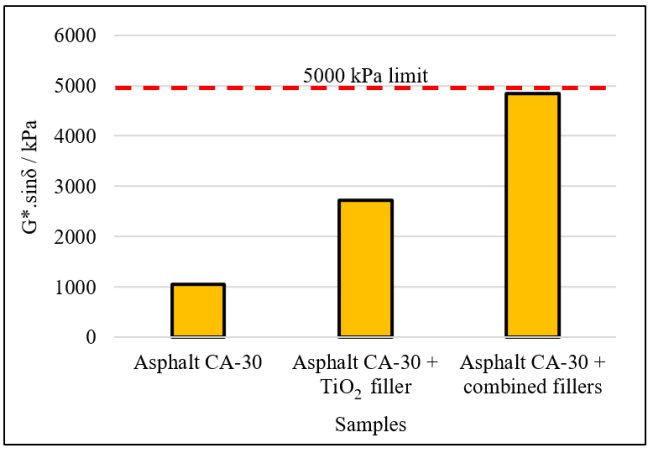

Figure 7. Fatigue parameters obtained at 30°C for the three analyzed samples: a) asphalt CA-30, b) asphalt CA-30 + TiO_2 filler, and c) asphalt CA-30 + combined fillers.
Source: Authors' own work.

3.8 Fatigue damage tolerance

The fatigue parameter G*.sin δ was assessed following the SHRP SUPERPAVE methodology [34], with the limiting value of G*.sin δ defined as 5000 kPa. The values obtained at an intermediate temperature (30°C) for the asphalt CA-30, asphalt CA-30 + combined fillers, and asphalt CA-30 + TiO_2 fillers (shown in Fig. 7) illustrate that the asphalt CA-30 + combined fillers will be the first to fail under fatigue conditions. Therefore, the asphalt CA-30 + TiO_2-filler presents a superior intermediate-temperature performance.

4. Conclusions

a
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It was possible to prepare two different specimens employing CA-30 binder: reference specimen with combined fillers and a modified specimen with TiO_2 filler. To evaluate the physical and rheological properties, samples of the CA-30 asphalt + combined fillers and CA-30 asphalt + TiO_2 fillers were studied. The thermal behaviors of the specimens were also evaluated before and after outdoor exposure for twelve months.

The most relevant conclusions are:

1. **Initial Albedo:** The TiO_2-modified asphalt mixture pavement exhibits a higher initial albedo compared to the reference pavement.
2. **Albedo Increase Over Time**: After 12 months of outdoor exposure, both the reference and TiO_2-modified asphalt pavements showed increased albedo values, with their coloration becoming lighter compared to the experiment's initial state.
3. **Photocatalytic Effect**: TiO_2 acts as a photocatalyst of a process which explains its more effective bleaching (decolorizing) action.
4. **Thermal Impact Reduction**: The addition of TiO_2 into the asphalt mixture helps to reduce heat transfer from the pavement surface to the surrounding air.
5. **High-Temperature Performance Enhancement**: Although the asphalt CA-30 + combined fillers exhibit the highest rutting resistance, the superior albedo of the asphalt CA-30 + TiO_2 filler specimen, which results in lower surface temperatures under equivalent solar irradiation, enhances the high-temperature performance grade of the latter.
6. **Fatigue Damage Tolerance**: At intermediate temperatures, the asphalt CA-30 + TiO_2 filler exhibits higher fatigue damage tolerance.

References

[1] Akbari, H., Cartalis, C., Kolokotsa, D., Muscio, A., Pisello, A.L., Rossi, F., Santamouris, M., Synnefa, A., Wong, N.H., and Zinzi, M., Local climate change and urban heat island mitigation techniques – The state of the art. Journal of Civil Engineering and Management, 22 (1), pp. 1–16, 2016. DOI: https://doi.org/10.3846/13923730.2015.1111934

[2] Beltran-Hernandez, R.I., Martinez-Ortiz, J.A., Lucho-Constantino, C.A., Lazarraga-Mendiola, L.G., and Bigurra-Alzati, C.A., Alternatives to counteract the effects of anthropogenic soil sealing. Pädi Boletín Científico de Ciencias Básicas e Ingenierías del ICBI, [online]. 8(15), art. 115020, 2020. Available at: https://portal.amelica.org/ameli/journal/595/5953115020/

[3] Santamouris, M., Using cool pavements as a mitigation strategy to fight urban heat island. A review of the actual developments. Renewable and Sustainable Energy Reviews, 26, pp. 224-240, 2013. DOI: https://doi.org/10.1016/j.rser.2013.05.047

[4] Alchapar, M.L., Correa, E.N., and Cantón, A., Solar reflectance index of pedestrian pavements and their response to aging. Journal of Clean Energy Technologies, 1(4), pp. 281-285, 2013. DOI: https://doi.org/10.7763/JOCET.2013.V1.64

[5] Wang, Z., Xie, Y., Mu, M., Feng, L., Xie, N., and Cui, N., Materials to mitigate the urban heat island effect for cool pavement: a brief review. Buildings, 12(8), art. 1221, 2022. DOI: https://doi.org/10.3390/buildings12081221

[6] Nwakaire, C., Onn, C.C., Poh, Y.S., Yuen, C.W., and Onodagu, P.D., Urban heat island studies with emphasis on urban pavements: a review. Sustainable Cities and Society 63, art. 102476, 2020. DOI: https://doi.org/10.1016/j.scs.2020.102476

[7] Zhu, S., and Mai, X., A review of using reflective pavement materials as mitigation tactics to counter the effects of urban heat island. Advanced Composites and Hybrid Materials, [online]. 2(3), pp. 381–388, 2019. Available at: https://link.springer.com/article/10.1007/s42114-019-00104-9

[8] Sophia, K., Souliotis, M., Papaefthimiou, S., Panaras, G., Paravantis, J., Michalena, E., Hills, J., Vouros, A.P., Dymenou, K., and Mihalakakou, G., Cool pavements: state of the art and new technologies. Sustainability, 14(9), art. 5159, 2022. DOI: https://doi.org/10.3390/su14095159

[9] Gong, Z., Zhang, L., Wu, J., Xiu, Z., Wang, L., and Miao, Y., Review of regulation techniques of asphalt pavement high temperature for climate change adaptation. Journal of Infrastructure Preservation and Resilience, 3, art. 9, 2022. DOI: https://doi.org/10.1186/s43065-022-00054-5

[10] Fernandez-Gomez, W.D., Rondón-Quintana, H.A., and Reyez Lizcano, F., A review of asphalt and asphalt mixture aging. Ingeniería e Investigación, 33(1), pp. 5-12, 2013. DOI: https://doi.org/10.15446/ing.investig.v33n1.37659

[11] Xie, N., Li, H., Zhang, H., Zhang, X., and Jia, M., Effects of accelerated weathering on the optical characteristics of reflective coatings for cool pavement. Solar Energy Materials and Solar Cells, 215, art. 110698, 2020. DOI: https://doi.org/10.1016/j.solmat.2020.110698
[12] Hossain, K., Sertac, A., and Das, P., Effect of ultraviolet aging on rheological properties of asphalt cement. Proceedings of Canadian Technical Asphalt Association (CTAA), 2018.
[13] Lu, X., Talon, Y., and Redelius, P., Aging of bituminous binders – laboratory tests and field data. Proceedings of E&E Congress, 2008.
[14] Badin, G., Ahmad, N., Ali, H.M., Ahmad, T., and Jameel, M.S., Effect of addition of pigments on thermal characteristics and the resulting performance enhancement of asphalt. Construction and Building Materials, 302, art. 124212, 2021. DOI: https://doi.org/10.1016/j.conbuildmat.2021.124212
[15] Ayar, P., Ruhi, A., Baibordy, A., Azadgoleh, M.A., Mohammadi, M.M., and Abdipour, S., Toward sustainable roads: a critical review on nano-TiO2 application in asphalt pavement. Innovative Infrastructure Solutions, 9, art. 148, 2024. DOI: https://doi.org/10.1007/s41062-024-01450-4
[16] Chen, J., Zhou, Z., Wu, J., Hou, S., and Liu, M., Field and laboratory measurement of albedo and heat transfer for pavement materials. Construction and Building Materials, 202(4), pp. 46–57, 2019. DOI: https://doi.org/10.1016/j.conbuildmat.2019.01.028
[17] Zhong, Y., Research on thermal reflection and cooling curing coating material of nano modified emulsified asphalt for urban road pavement. E3S Web of Conferences 261, art. 02051, 2021. DOI: https://doi.org/10.1051/e3sconf/202126102051
[18] Akbari, H., Levinson, R., and Stern, S., Procedure for measuring the solar reflectance of flat or curved roofing assemblies. Solar Energy, 82(7), pp. 648-655, 2008. DOI: https://doi.org/10.1016/j.solener.2008.01.001
[19] ASTM (2006). ASTM E1933-99ª: American Society for Testing and Materials, Standard Test Methods for measuring and compensating for emissivity using infrared imaging radiometers. ASTM
[20] ASTM D5/D5M. Standard Test Method for Penetration of Bituminous Materials, ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA., United States, 2020.
[21] ASTM D36/D36M. Standard Test Method for Softening Point of Bitumen (Ringand-Ball Apparatus), ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA., United States, 2020.
[22] AASHTO M320. Standard Specification for Performance-Grade Asphalt Binder.
[23] AASHTO T240. Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test).
[24] Dell'Antonio-Cadorin, N., Staub-de Melo, J.V., Borba-Broering, W., Manfro, A.L., and Salgado-Barra, B., Asphalt nanocomposite with titanium dioxide: Mechanical, rheological and photoactivity performance. Construction and Building Materials, 289, art. 123178, 2021. DOI: https://doi.org/10.1016/j.conbuildmat.2021.123178
[25] Villegas-Villegas, R.E., Baldi-Sevilla, A., Aguiar-Moya, J.P., and Loria-Salazar, L., Analysis of asphalt oxidation by means of accelerated testing and environmental conditions. Transportation Research Record, 2672(28), pp. 244-255, 2018. DOI: https://doi.org/10.1177/0361198118777630
[26] Ramadhansyah, P.J., Masri, K.A., Norhidayah, A.H., Hainin, M.R., Muhammad Naqiuddin, M.W., Haryati, Mohd, K.I., Juraidah, A., Nanoparticle in asphalt binder: a state-of-the-art review. IOP Conference Series Materials Science and Engineering, 712, art. 012023, 2020. DOI: https://doi.org/10.1088/1757-899X/712/1/012023
[27] Huang, M, and Wen, X., Experimental study on photocatalytic effect of Nano TiO_2 epoxy emulsified asphalt mixture. Applied Sciences, 9(12), art. 2464, 2019. DOI: https://doi.org/10.3390/app9122464
[28] Pasetto, M., Baliello, A., Pasquini, E., and Giacomello, G., High albedo pavement materials. Eco-efficient Materials for Reducing Cooling Needs in Buildings and Construction, 2020. DOI: https://doi.org/10.1016/B978-0-12-820791-8.00002-X
[29] Li, H., Harvey, J., and Kendall, A., Field measurement of albedo for different land cover materials and effects on thermal performance. Building and Environment, 59, pp. 536–546, 2013. DOI: https://doi.org/10.1016/j.buildenv.2012.10.014
[30] Bentz, D.P., A Computer model to predict the surface temperature and time-of-wetness of concrete pavements and bridge decks building and fire research laboratory. August 2020 National Institute of Standards and Technology Administration, U.S. Department of Commerce.
[31] Asaeda, T., Vu, C., and Wake, A., Heat storage of pavement and its effect on the lower atmosphere. Atmospheric Environment, 30(3), pp. 413-427, 1996. DOI: https://doi.org/10.1016/1352-2310(94)00140-5
[32] Qin, Y., Hiller, J.E., and Meng, D., Linearity between pavement thermophysical properties and surface temperatures. Journal of Materials in Civil Engineering, 31(11), art. 2890, 2019. DOI: https://doi.org/10.1061/(ASCE)MT.1943-5533.0002890
[33] Xu, L., Wang, J., Xiao, F., EI-Badawy, S., and Awed, A.M. Potential strategies to mitigate the heat island impacts of highway pavement on megacities with considerations of energy uses. Applied Energy, 281, art. 116077, 2021. DOI: https://doi.org/10.1016/j.apenergy.2020.116077
[34] Sadeghnejad, M., and Shafabakhsh, G., Use of Nano SiO_2 and Nano TiO_2 to improve the mechanical behaviour of stone mastic asphalt mixtures. Construction and Building Materials, 157, pp. 965-974. DOI: https://doi.org/10.1016/j.conbuildmat.2017.09.163
[35] Li, R., Xiao, F., Amirkhanian, S., You, Z., and Huang, J., Developments of nano materials and technologies on asphalt materials–A review. Construction and Building Materials, 143, pp. 633-648, 2017. DOI: https://doi.org/10.1016/j.conbuildmat.2017.03.158
[36] Miranda-Argüello, F., Loria-Salazar, L., Aguiar-Moya, J.P., and Leiva-Padilla, P., Measurement of G* in fine asphalt mixes: dynamic mechanical analyzer shear test implementation. Transportation Research Record, 2507(1), pp. 39-49, 2019. DOI: https://doi.org/10.3141/2507-05
[37] Mohammed, A.M., and Abed, A., Effect of nano-TiO_2 on physical and rheological properties of asphalt cement. Open Engineering, 14(1), art. 20220520, 2024. DOI: https://doi.org/10.1515/eng-2022-0520
[38] Saleh, A.M.M., and Trad, M.A., Generation of asphalt performance grading map for Egypt based on the SUPERPAVETM program. Construction and Building Materials, 25, pp. 2248-2253, 2011. DOI: https://doi.org/10.1016/j.conbuildmat.2010.11.009
[39] Abo-Hashema, M.A., Mousa, R.M., Al-Zedjali, S.A., Al Balushi, Q.A., Metwally, M., and Al-Rashdi, M.H., Development of oman performance grade paving map for superpave asphalt mix design. In: The 19th Annual International Conference on Highway, Airports Pavement Engineering, Infrastructures & Asphalt Technology. Liverpool, United Kingdom, [online]. 2020. Available at: https://www.ljmu.ac.uk/%7E/media/files/ljmu/about-us/faculties-and-schools/asphalt-conference/papers/asphalt/asphalt/doi-10,-d-,1515ijpeat20160033.pdf?la=en

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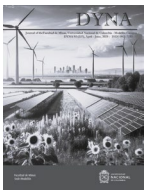

UNIVERSIDAD NACIONAL DE COLOMBIA

Enhancing road safety: a comprehensive examination of critical factors

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Abstract
The global road traffic safety situation is alarming, with millions of fatalities and injuries annually, underscoring the urgent need for improved safety measures. This study examines factors influencing highway safety, prioritizing them using the Relative Importance Index (RII). Through case evaluations, expert interviews, and a 29-criteria questionnaire grouped into road, vehicle, driver, and environmental factors, key issues were identified. The most critical factors include poorly designed roads (84.2%), malfunctioning brakes (83.4%), distracted driving (82.8%), and adverse weather (80.6%). These findings highlight the necessity of addressing fundamental road safety challenges to reduce accidents and their economic impacts. Proactive measures targeting infrastructure, vehicle maintenance, driver behavior, and environmental adaptability are essential for enhancing traffic safety worldwide.

Keywords: road safety; traffic accidents; human factors; highway design; vehicle maintenance; environmental factors; safety management; risk assessment.

Mejorar la seguridad vial: un análisis exhaustivo de los factores críticos

Resumen
La situación global de seguridad vial es alarmante, con millones de muertes y lesiones anuales, lo que subraya la necesidad urgente de mejorar las medidas de seguridad. Este estudio analiza los factores que influyen en la seguridad vial, priorizándolos mediante el Índice de Importancia Relativa (RII). Mediante evaluaciones de casos, entrevistas a expertos y un cuestionario de 29 criterios—agrupados en factores viales, vehiculares, humanos y ambientales—se identificaron problemas clave. Los factores más críticos incluyen diseño inadecuado de carreteras (84.2%), fallas en los frenos (83.4%), conducción distraída (82.8%) y condiciones climáticas adversas (80.6%). Estos hallazgos resaltan la necesidad de abordar desafíos fundamentales en seguridad vial para reducir accidentes y sus impactos económicos. Medidas proactivas enfocadas en infraestructura, mantenimiento vehicular, comportamiento del conductor y adaptación ambiental son esenciales para mejorar la seguridad vial a nivel global.

Palabras clave: seguridad vial; accidentes de tráfico; factores humanos; diseño de carreteras; mantenimiento de vehículos; factores ambientales; gestión de la seguridad; evaluación de riesgos

1. Introduction

Every year, approximately one million people lose their lives in automobile accidents, with up to fifty million sustaining injuries. The global economic impact is estimated at $518 billion, representing 1% to 3% of the world's GDP [1]. Traffic accidents continue to increase annually, causing severe injuries and property damage [2]. Consequently, numerous researchers have studied the factors contributing to different types of road traffic accidents to enhance safety. However, road collisions are primarily caused by interactions involving motorized and non-motorized vehicles, pedestrians, and passengers, excluding incidents solely between individuals. Current research often focuses on specific accident types while neglecting others, underscoring the urgent need for a comprehensive analysis of contributing

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factors. According to findings, for children and individuals aged 5 to 29, road traffic accidents rank as the ninth leading cause of death across all age groups. In the United States, recent reports highlight similar concerns [3].

The highway traffic system primarily consists of individuals, vehicles, roads, and traffic environments. For this dynamic system to operate effectively, all components must work in harmony.

The current study identifies human-related factors like driver behavior, age, and experience as major contributors to accidents, with research showing that distractions, impaired driving, and speeding significantly increase crash risks. Vehicle-related factors such as tire blowouts, brake failures, and mechanical defects, particularly in commercial trucks, contribute to accidents, while poor road design, including sharp curves and inadequate markings, further elevates risks. Additionally, adverse weather conditions like rain, fog, and snow heighten accident severity, emphasizing the need for comprehensive safety measures addressing human, vehicle, road, and environmental factors. While other studies. The response mechanism of drivers to warnings was studied by Shao et al. [4] by taking into account the characteristics of the driver along with the real-time risk level of driving, so as to compare normal and conservative drivers with impulsive drivers who tend to follow another car much closer ahead of them with a lower probability to slow down. And Haq et al [5]. studied severity regarding crashes and injuries pertaining to brake failure in steep mountainous roads in Wyoming. Some scholars have thus described the impact of vehicle safety hazards on traffic accidents. Excessive speed is the leading cause of traffic accidents. Uddin et al. [6] indicated that on rainy days, variable speed limit signs should be placed in order to restrain the speed of trucks. The studies Any imbalance or inconsistency can disrupt the system, leading to accidents. Factors contributing to such issues include:

- Human-Related Factors: Driver behavior significantly affects accidents. Inadequate driving skills and driver age are major contributors [4,5]Inexperienced drivers are more likely to be involved in crashes, emphasizing the need for additional training and education. Risky driving behaviors remain one of the leading causes of fatal accidents [6-8].
- Vehicle-Related Factors: Research has examined the effects of vehicle defects, including tire blowouts, steering malfunctions, and brake failures, on traffic accidents [9]These flaws, particularly tire blowouts and braking failures, are significant contributors to accidents [10]. Speed is another major factor influencing road accidents [11-13].
- Road-Related Factors: Research has examined how certain road features, like steep climbs, sweeping curves, and points of intersection, affect auto accidents. Reducing accidents requires careful consideration of roadway geometry. For instance, the likelihood of collisions increases when the radius of horizontal curves is less than 200 meters [14].
- Environment-Related Factors: Beyond human and vehicular components, environmental conditions significantly impact highway safety. Poor weather and high traffic volume are closely associated with accident rates. Adverse weather, such as rain, fog, snow, and wind, poses serious [15,16]. In such conditions, limited visibility, impaired judgment, and slippery roads increase the likelihood of errors and accidents [17]. This paper aims to identify the factors influencing highway safety and their overall impact.

2. Methodology

The initial step comprises a questionnaire and how the author gathers and prepares the questionnaire from the ministry of transportation in Iraq which spate into open and closed questionnaires. The second step consists of two steps including the selection of the use of case studies for road.

projects. Then, list the elements that influence roadway safety. Finally, the research ranks these aspects using the Relative Importance Index (RII). Fig. 1

2.1 The first part: general information

The following part contains general information about the participant as well as information on the people who completed the questionnaire from the study's target community (specialty, educational background, current field, and years of experience).

2.2 Part two: the factors affecting on highway safety

This section of the questionnaire contains a list of variables that are likely to have a negative influence on highway safety in (Appendix (A).

2.2.1 Design questionnaire

Based on the study's goals, a questionnaire survey was created to assess the causes and impacts of building delays. The questionnaire was divided into two sections. The first segment collected essential data regarding the people who participated. The second section contained a list of identified significant failure variables impacting highway safety.

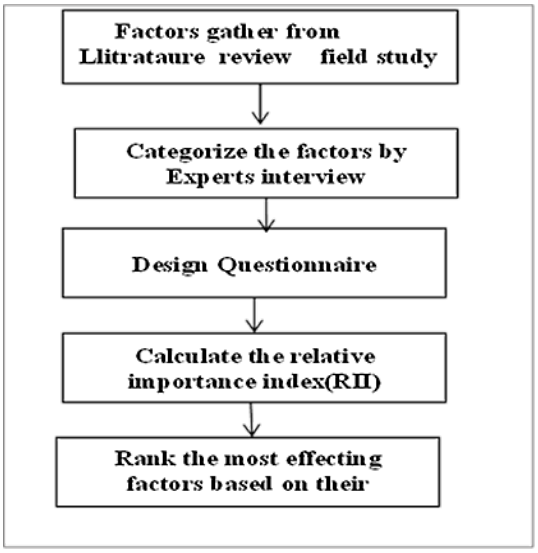

Figure 1. Research Methodology
Source: own work

The factors were divided into four categories: driver, road, vehicle, and environment. The significance of each element was assessed on a five-point scale: strongly agree, agree, neutral, disagree, and strongly disagree (scoring from five to one). This section contains 29 closed questions geared up with a five-point Likert scale [18]**.** this study aims to enhance road safety using relative important index

2.2.2 Questionnaire distribution

The questionnaire was delivered to the 82 persons who comprised who intended sample. Professionals working on Iraqi construction projects in Diyala province (Architects, Civil Engineers, Mechanical Engineers, Electrical Engineers, and any other professional with associated specialty) are included in the research population Using this strategy, the researcher presented a clear summary of the research project's aims and provided any further clarifications that were required.

This approach ensures higher levels of precision and realism since it allows for direct engagement and follow-up with participants. Direct meetings enabled the involvement of seventy people.

Only 75 surveys have been received by participants. Fig. 1 presents a summary of the research sample, containing the total quantity of surveys that were sent and received. Additionally, it displays the distribution process and response rate.

The findings show that 91% of respondents are happy, indicating a high level of engagement according to the size of the sample (72 ÷ 82 =91%)

2.2.3 Reliability of Questionnaires

One of among the most important methods for determining dependability is the Alpha Cronbach constant, which has a value between 0 and 1; the closer to 1, the better the degree of reliability [20].

The degree of reliability is categorized in Table1.

The process of assessing whether questionnaire findings remain consistent by delivering the same responses while applying again (twice) to the same group of people at different periods. It refers to the degree to which a measuring process produces comparable findings when repeated.

Cranach's Alpha is used to assess reliability, and it has to be at least 0.7 representing the values of Alpha Cronbach.

Table 1.
Reliability Cutoff Values

Cronbach's alpha	Degree of Reliability
$\alpha \geq 0.9$	Excellent
$0.9 > \alpha \geq 0.8$	Good
$0.8 > \alpha \geq 0.7$	Acceptable
$0.7 > \alpha \geq 0.6$	Questionable
$0.6 > \alpha \geq 0.5$	Poor
$0.5 > \alpha$	Unacceptable

Source: Adapted from P. N. Vijayamohanan and A. Rjumohan, 2020.

3. Results and Discussion

3.1 Statistical analysis

Part one: General Information

The characteristics of the target sample for the survey are shown in the following figures.

The x-axis represents the (Experience Years, Academic Degree, Working Sector, and Field of Specialization

The y-axis represents the percentage of respondents

Experience Years

Fig. 2 shows the years of experience in the sample where the percentages are as follows: (0-5) equal to 26%, (5-10) equal to 40%, (10-25) equal to 18%, and 25-30 equal to 12%

Academic Degree

Fig.3, represented the distribution of academic degrees. The findings show that 50% of those surveyed hold a bachelor's degree; 22% have a master's degree and 23% a PhD.

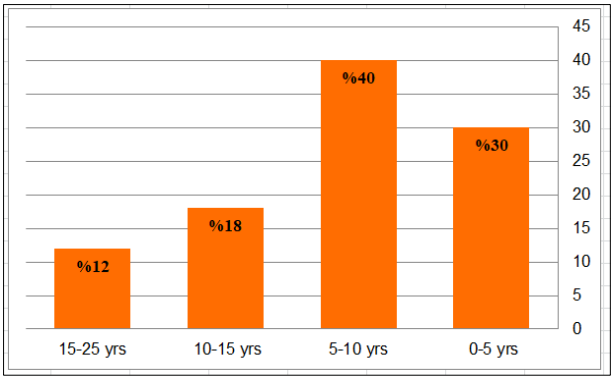

Figure 2. Experience years of responding
Source: own work

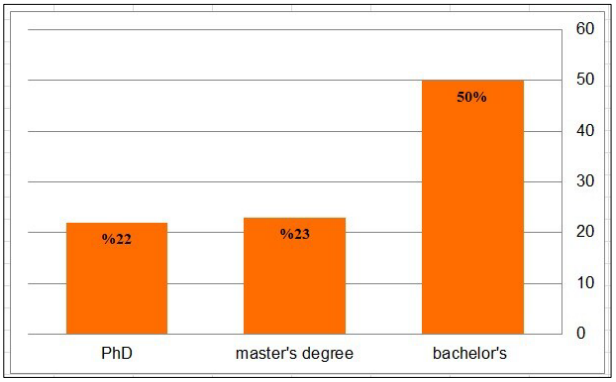

Figure 3. Academic Degree
Source: own work

Working Sector

As shown in Fig. 4, this part focuses on the working sectors of the respondents. According to the data in the figure, 67% of participants are from the public sector, and 33% are from the private sector.

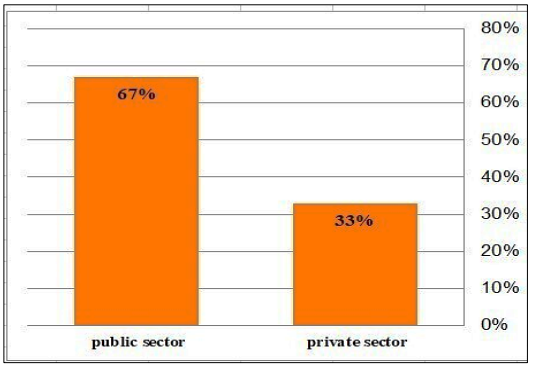

Figure 4. Working Sector
Source: own work

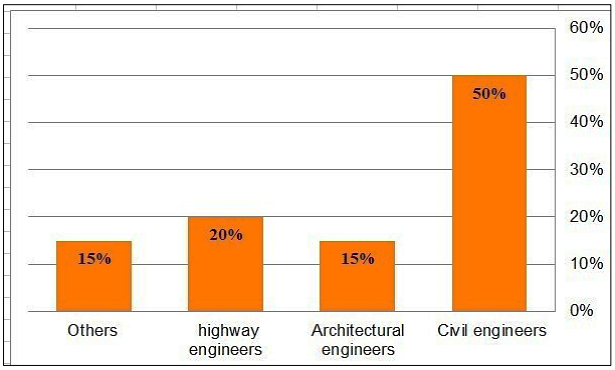

Figure 5. Field of Specialization
Source: own work

Field of Specialization

With 40% going to civil engineers, 17% to architects, 20% to mechanical engineers, and 8% to electrical engineers, there is a notable diversity of specializations. According to Fig. 5, 15% of responders have a variety of expertise.

3.2 Descriptive statistics

The numerical, graphical, and tabular approaches for organizing, analyzing, and presenting data are known as descriptive statistics and the most significant benefit of descriptive statistics is that they make a large amount of study material easier to 'read.' The results of the study can be conveyed clearly and concisely by condensing a big set of data into a few statistics or a graphic such as a graph or table (Argyrous, 2011). The following descriptive statistics were used.

Data Analysis The forms were gathered and organized in tables to compute the statistical analysis by using the statistical program SPSS version 26

3.2.1 Relative Importance Index (RII)

The relative importance index (RII) approach was used to calculate responders' rankings of items/variables. RII is determined using a specific equation [19]

$$RII = \frac{\sum W}{(A * N)} \quad (1)$$

When:
W: The weight given by respondents for each component (ranging from 1 to 5)
A: Represents the highest weight (which equals 5)
N: Represents the total number of respondents

3.2.2 Mean score ranking technique

One of the most important indicators of central tendency is the mean. The following formula was used to determine the mean score for each element or option. [20].

$$Ms = \sum_{K=1}^{K=N} \frac{X_1 * S_1 + X_2 * S_2 + X_3 * S_3 + X_4 * S_4 + X_5 * S_5}{N} \quad (2)$$

Were
Ms= mean score (1≤Ms≤5)

3.2.3 Measure of variation

The most important measure of variation is the standard deviation. It is quantitative measurement, which indicates the variability among the numbers in any distribution; and tells as to whether it is centered or dispersed-about-the-mean (SD) (Gravetter and Wallnau, 2016).

The standard deviation(SD) for respondents based on the equation given below is: [20]:

$$SD = \sqrt{\sum_{k=0}^{n} (xi - x)^2 * \frac{fi}{\sum_{k=0}^{n} fi}} \quad (3)$$

Were
SD = standard deviation
x= mean score
xi= degree of the criterion importance
fi= frequency

4. Results and discussion

The primary goal of employing a closed questionnaire is to evaluate the relative relevance of the elements influencing highway safety. The tables of information below present the data evaluation for the twenty-nine factors.

Table 2 highlights key factors related to vehicle influencing highway safety, assessed through their mean, relative importance index, and rank. The analysis reveals that Poorly Designed Roads (RII: 84.2%) are the most critical factor, significantly contributing to unsafe driving conditions. Roadway Design Flaws (RII: 80.6%) also rank highly, underscoring the impact of improper alignment and

Table 2
Factors related to Vehicle[21]

No.	Factors	Mean	Std. Deviation	RII	Rank
1	Poor Vehicle Maintenance	3.24	1.662	0.648	7
2	Malfunctioning brake systems	4.17	1.167	0.834	1
3	Defective Lights	3.83	1.537	0.766	3
4	Improperly Adjusted Mirrors	3.66	1.61	0.732	6
5	Missing Safety Features	3.72	1.486	0.744	5
6	Overloaded Vehicles	4.07	1.557	0.814	2
7	Vehicle Design Flaws	3.79	1.521	0.758	4

Source: Adapted from R. A. Rahman, A. R. Radzi, M. S. H. Saad, and S. I. Doh, 2020

Table 3.
Factors related to roads[22]

No.	Factor	Mean	Std. Deviation	RII	Rank
1	Poorly Design Roads	4.21	1.236	0.842	1
2	Inadequate Road Signage	3.69	1.339	0.738	6
3	Inadequate Lighting	3.9	1.472	0.78	3
4	Roadway Design Flaws	4.03	1.375	0.806	2
5	Lack of Cycling Infrastructure	3.1	1.633	0.62	9
6	Road Hazards	3.79	1.449	0.758	4
7	Obsolete Infrastructure	3.61	1.721	0.722	8
8	Inadequate Road Maintenance	3.69	1.514	0.738	5
9	Inadequate Road Markings	3.66	1.565	0.732	7

Source: Adapted from S. Deep, S. Banerjee, S. Dixit, and N. I. Vatin,2022

design elements on accident rates. Inadequate Lighting (RII: 78%) is equally significant, as insufficient visibility, particularly at night, increases the likelihood of traffic accidents.

These high RII values emphasize the need for immediate interventions to address these pressing safety issues[21].

Table 3 identifies critical road-related factors significantly affecting traffic safety, as reflected by their high relative importance index values and top rankings. Malfunctioning brake systems rank as the most impactful factor with RII (88%), highlighting their essential role in preventing accidents. Overloaded Vehicles follow closely with RII (87.6%), as excessive

weight compromises vehicle stability and control. Defective Lights with RII (80.2%) are another key concern, as poor lighting reduces visibility and increases the risk of collisions. Addressing these issues through regular maintenance, strict weight regulations, and proper vehicle inspections is crucial for enhancing road safety[22]

Table 4 highlights critical driver-related factors that significantly impact traffic safety. Distracted Driving ranks as the most influential factor (RII: 87.2%), emphasizing the dangers of losing focus while driving. Exceeding speed limits (RII: 86.6%) is equally critical, as it increases the likelihood and severity of accidents.

Aggressive Driving (RII: 82.6%) also poses a significant risk, as it often leads to reckless behavior and reduced reaction times. Addressing these behaviors through awareness campaigns, strict enforcement of traffic laws, and driver education programs is essential to improving road safety[23].

Table 4.
Factors related to Driver[23].

No.	Factors	Mean	Std. Deviation	RII	Rank
1	Distracted Driving.	4.14	1.407	0.828	1
2	exceeding speed limits	4.1	1.472	0.82	2
3	Aggressive Driving	3.72	1.437	0.744	3
4	Lack of driving knowledge and skills	3.66	1.653	0.732	5
5	Failure to follow traffic rules	3.66	1.696	0.732	4
6	Lack of Proper Training	3.28	1.623	0.656	7
7	Misinterpretation of Road Signs and Signals	3.31	1.442	0.662	6
8	Failure to Adapt to Changing Conditions	3.24	1.573	0.648	8

Source: Adapted from N. Maelissa, M. Arif Rohman, and I. Putu Artama Wiguna,, 2023.

Table 5:
Factors related to Environment [24]

No.	Factors	Mean	Std. Deviation	RII	Rank
1	Adverse Weather Conditions	4.03	1.239	0.806	1
2	Poor Visibility	3.97	1.451	0.794	2
3	Wildlife Crossings	3.55	1.549	0.71	4
4	Pollution	3.38	1.59	0.676	5
5	Natural Disasters	3.93	1.646	0.786	3

Source: Adapted from Z. Zhou, Y. Su, Z. Zheng, and Y. Wang,2023

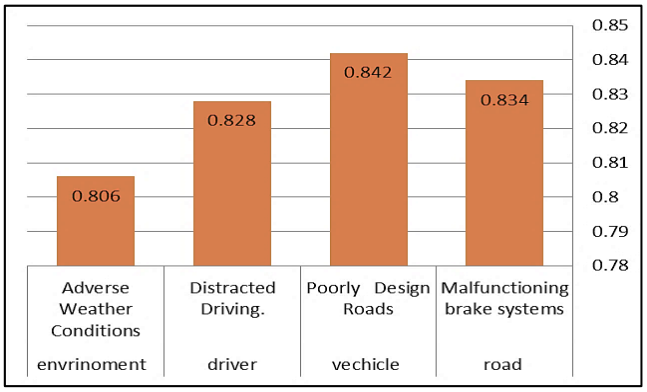

Figure 6. Factors affecting on highway safety
Source: on work

Table 5 emphasizes key environmental factors that significantly impact traffic safety. Adverse Weather Conditions rank as the most critical factor with RII(80.6%), highlighting the risks posed by rain, snow, and fog, which reduce visibility and increase the likelihood of accidents. Poor Visibility with RII (79.4%) further compounds these dangers, especially during nighttime or in areas with inadequate lighting.

Natural Disasters with RII (78.6%) also play a notable role, as events like floods and earthquakes disrupt road conditions and driver safety.

Addressing these factors requires improved infrastructure, such as better drainage systems and lighting, and robust emergency response strategies to mitigate risks during extreme conditions [24].

This Fig. 6 represents the relative importance of four factors contributing to certain outcomes (likely road safety or accident-related issues).

The x-axis lists the factors categorized into groups (environment, driver, vehicle, and road), while the y-axis shows their importance score, likely based on a normalized value ranging from 0.78 to 0.85.

1. Conclusion

This research focuses on assessing the essential role aspects in highway safety. Twenty-nine indicators were identified through cases and interviews with experts. These variables were divided into four major categories: road factors, vehicle-related concerns, driving factors, and environmental factors. Seventy-five of the eighty questionnaire forms were returned.

The outcomes demonstrated a high level of consistency amongst responders when rating the criteria. Cronbach's alpha test has a high coefficient and is valid, demonstrating this. These variables are ranked using the relative significance index. Additionally, the results showed that the factors' RIIs varied from 62% to 84%.

and these factors Driver-related RII was (0.828) from Distracted Driving. Malfunctioning brake systems from Road related factors the RII was (0.834),.while Vehicle-related issues, the problem the Poorly Design Roads the RII was (0.842). Adverse Weather Conditions from Environmental factors the RII was 0.806. Addressing these issues requires a multidisciplinary approach involving enhanced training, better road and vehicle design, and improved management of environmental risks.

References

[1] Bochen et al.,WHO methods and data sources for country-level causes of death,World Heal, 2020.

[2] Zhang, H., et al. The effect of fatigue driving on car following behavior. Transportation research part F: Traffic psychology and behaviour, 43, pp. 80-89, 2016. DOI: https://doi.org/10.1016/j.trf.2016.06.017

[3] Rodwell, D., Watson-Brown, N., and Bates, L., Perceptions of novice driver education needs, development of a scale based on the goals for driver education using young driver and parent samples. Accident Analysis & Prevention, 191, art. 107190., 2023. DOI: https://doi.org/10.1016/j.aap.2023.107190

[4] Abdel-Aty, M.A., and Abdelwahab, H.T., Exploring the relationship between alcohol and the driver characteristics in motor vehicle accidents. Accident Analysis & Prevention, 32(4), art. 473482, 2000. DOI: https://doi.org/10.1016/S0001-4575(99)00062-7

[5] Escamilla-Robla, C., Beleña-Mateo, M.Á., and Mateu-Mollá, J., Influence of alcohol consumption, personality and attention deficit hyperactivity disorder on traffic offenders. Psicothema, 34(3), art. 410, 2022. DOI: https://doi.org/10.7334/psicothema2022.38

[6] Watling, C.N., and Home, M., Hazard perception performance and visual scanning behaviours: the effect of sleepiness. Transportation research part F: traffic psychology and behaviour, 90, pp. 243-251, 2022. DOI: https://doi.org/10.1016/j.trf.2022.08.020

[7] Dinges, D., D rowsy D riving and Automobile C rashes. Sleep (Rochester), 10(4), pp. 313-329, 1987.

[8] Wright, L., Brown, A., and Davidson-Mundt, A., Newborn screening: the miracle and the challenge. Journal of Pediatric Nursing, 7(1), pp. 26-42, 1992.

[9] Blower, D., Green, P.E., and Matteson, A., Condition of trucks and truck crash involvement: evidence from the large truck crash causation study. Transportation Research Record, 2194(1), pp. 21-28, 2010. DOI: https://doi.org/10.3141/2194-03

[10] Solah, M.S., Hamzah, A., Ariffin, A.H., Paiman, N.F., Hamid, I.A., Wahab, M.A., and Osman, M.R., Private vehicle roadworthiness in Malaysia from the vehicle inspection perspective. Journal of the Society of Automotive Engineers Malaysia, 1(3), pp. 262-271, 2017. DOI: https://doi.org/10.56381/jsaem.v1i3.67

[11] Fondzenyuy, S.K., Fowo-Fotso, C.S., Feudjio, S.L.T., Usami, D.S., and Persia, L., Self-Reported speed compliance and drivers speeding behaviour in Cameroon. Future Transportation, 4(2), pp. 659-680, 2024. DOI: https://doi.org/10.3390/futuretransp4020031

[12] Varet, F., Apostolidis, T., and Granié, M.A., Social value, normative features and gender differences associated with speeding and compliance with speed limits. Journal of Safety Research, 84, pp. 182-191, 2023. DOI: https://doi.org/10.1016/j.jsr.2022.10.018

[13] Raju, N., Arkatkar, S.S., Easa, S., and Joshi, G., Investigating performance of a novel safety measure for assessing potential rear-end collisions: an insight representing a scenario in developing nation. IATSS research, 46(1), 138-146, 2022. DOI: https://doi.org/10.1016/j.iatssr.2021.09.002

[14] Elvik, R., International transferability of accident modification functions for horizontal curves. Accident Analysis & Prevention, 59, pp. 487-496, 2013. DOI: https://doi.org/10.1016/j.aap.2013.07.010

[15] Uddin, M., and Huynh, N., Injury severity analysis of truck-involved crashes under different weather conditions. Accident Analysis & Prevention, 141, art.

105529, 2020. DOI: https://doi.org/10.1016/j.aap.2020.105529
[16] Yasanthi, R.G., Mehran, B., and Alhajyaseen, W.K., Modelling speed behaviour in rural highways: safety analysis of driving under adverse road-weather conditions. PLoSone, 16(8), e0256322, 2021. DOI: https://doi.org/10.1371/journal.pone.0256322
[17] Abdel-Aty, M., Ekram, A.A., Huang, H., and Choi, K., A study on crashes related to visibility obstruction due to fog and smoke. Accident Analysis & Prevention, 43(5), pp. 1730-1737, 2011. DOI: https://doi.org/10.1016/j.aap.2011.04.003
[18] Romeo, I., and Riconscente, M., Technique for the measurement of attitudes. In Encyclopedia of Research Design. Sage Publications, 2010, pp. 1490-1493. DOI: https://doi.org/10.4135/9781412961288.n454
[19] Rajgor, M., Paresh, C., Dhruv, P., Chirag, P., and Dhrmesh, B., RII & IMPI: Effective techniques for finding delay in construction project. International Research Journal of Engineering and Technology, 3(1), pp. 1173-1177, 2016.
[20] Hinton, P., RStatistics explained. Routledge, 2024.
[21] Rahman, R.A., Radzi, A.R., Saad, M.S.H., and Doh, S.I., Factors affecting the success of highway construction projects: the case of Malaysia. In: IOP Conference Series: Materials Science and Engineering, 712(1), art. 012030). IOP Publishing, 2020.
[22] Deep, S., Banerjee, S., Dixit, S., and Vatin, N.I., Critical factors influencing the performance of highway projects: an empirical evaluation. Buildings, 12(6), art. 849, 2022. DOI: https://doi.org/10.3390/buildings12060849
[23] Maelissa, N., Rohman, M.A., and Wiguna, I.P.A., Influencing factors of sustainable highway construction. In: E3S Web of Conferences, 429, art. 03002, 2023. DOI: https://doi.org/10.1051/e3sconf/202342903002
[24] Zhou, Z., Su, Y., Zheng, Z., and Wang, Y., Analysis of the drivers of highway construction companies adopting smart construction technology. Sustainability, 15(1), art. 703, 2022. DOI: https://doi.org/10.3390/su15010703

Appendix (A) questionnaire

Part I: general information

	Name (Optional):	
	Name of Ministry	
	Age :	
		Field of Specialization
	Gender:	Architect
	Male	Civil Engineer
	Female	Electrical Engineer
		Mechanical engineer
		Other (specify Please)
	Academic Degree:	
	Bachelor	
	Master	
	Ph.D.	
	Experience Years:	
	From 0 to 5 years	**Work sector:**
	From 5 to 10 years	Public
	From 10to 15 years	Private
	More than 20 years	

Part 2: The factors affecting on highway safety

Number	Item	Strongly Agree	Agree	Moderate	Disagree	Strongly Disagree
	Factors related to roads					
1	Poor Vehicle Maintenance					
2	Malfunctioning brake systems					
3	Defective Lights					
4	Improperly Adjusted Mirrors					
5	Missing Safety Features					
6	Overloaded Vehicles					
7	Vehicle Design Flaws					
	Factors related to Vehicle					
8	Poorly Design Roads					
9	Inadequate Road Signage					
10	Inadequate Lighting					
11	Roadway Design Flaws					
12	Lack of Cycling Infrastructure					
13	Road Hazards					
14	Obsolete Infrastructure					
15	Inadequate Road Maintenance					
16	Inadequate Road Markings					
	Factors related to Driver					
17	Distracted Driving.					
18	exceeding speed limits					
19	Aggressive Driving					
20	Lack of driving knowledge and skills					
21	Failure to follow traffic rules					
22	Lack of Proper Training					
23	Misinterpretation of Road Signs and Signals					
24	Failure to Adapt to Changing Conditions					
	Factors related to Environment					
25	Adverse Weather Conditions					
26	Poor Visibility					
27	Wildlife Crossings					
28	Pollution					
29	Natural Disasters					

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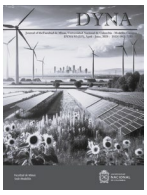

UNIVERSIDAD NACIONAL DE COLOMBIA

A low-cost upper limb exoskeleton assistive device based on elbow torque feedback

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Abstract
To alleviate upper limb movement impairment in specific groups, reduce the heavy workload of laborers, and assist patients with elbow joint injuries in post-rehabilitation training, we designed a wearable upper limb exoskeleton. A dual-motor system based on elbow torque feedback can realize the smooth rotation and motion assistance of elbow joints by motor driving. To evaluate the performance of the upper limb exoskeleton, we conducted a loaded elbow flexion comparative test while collecting and evaluating electromyographic (EMG) signals. The test demonstrates that the upper limb exoskeleton effectively abates muscle workload. This low-cost upper limb exoskeleton effectively assists movement and enhances upper limb endurance for rehabilitation training or tasks like lifting and carrying. It offers an opportunity to enhance the quality of life for users by aiding in the recovery or improvement of upper limb function.

Keywords: upper limb exoskeleton; torque feedback; loaded elbow flexion; EMG signals; performance evaluation.

Un dispositivo de asistencia del exoesqueleto de las extremidades superiores de bajo costo basado en la retroalimentación del torque del codo

Resumen
Para aliviar el deterioro del movimiento de las extremidades superiores en grupos específicos, reducir la gran carga de trabajo de los trabajadores, y ayudar a los pacientes con lesiones en las articulaciones del codo en el entrenamiento post-rehabilitación, hemos diseñado un exoesqueleto vestible de las extremidades superiores. Un sistema de doble motor basado en la retroalimentación del par del codo puede realizar la rotación suave y la asistencia de movimiento de las articulaciones del codo por motor de conducción. Para evaluar el desempeño del exoesqueleto del miembro superior, se realizó un test comparativo de flexión del codo cargado mientras se recogían y evaluaban las señales electromiográficas (EMG). La prueba demuestra que el exoesqueleto del miembro superior disminuye con eficacia la carga de trabajo muscular. Este exoesqueleto de las extremidades superiores de bajo costo ayuda eficazmente al movimiento y mejora la resistencia de las extremidades superiores para el entrenamiento de rehabilitación o tareas como levantar y llevar. Ofrece una oportunidad para mejorar la calidad de vida de los usuarios al ayudar en la recuperación o mejora de la función de las extremidades superiores.

Palabras clave: exoesqueleto del miembro superior; retroalimentación de par; flexión del codo con carga; las señales EMG; evaluación del desempeño.

1. Introduction

With the progress of population aging, the number of the elderly suffering from upper limb functional impairments is increasing, driving higher demand for corresponding social security and medical resources. In recent years, assistive

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exoskeletons have been extensively studied as a viable rehabilitation solution. By providing targeted assistance and movement control, exoskeleton systems facilitate the restoration and enhancement of upper limb motor functions in patients, demonstrating significant potential for clinical application and cost-effectiveness [1]. Although industries are undergoing digital and intelligent upgrades, with the widespread adoption of intelligent manufacturing, digital workshops, unmanned production lines and intelligent equipment, frontline workers are still responsible for a significant amount of high-intensity physical labor due to the increasing specificity of industrial demands. Exoskeleton can significantly mitigate the health risks of such labor, effectively alleviating muscle and cardiac fatigue, and ultimately helping to prevent occupational diseases. Additionally, these devices enhance efficiency and quality in repetitive tasks, leading to a more optimized work environment in factories.

The high demand for exoskeleton robots has garnered the attention of researchers worldwide. For example, the Swiss Federal Institute of Technology Zurich developed the fully actuated upper limb exoskeleton ANYexo 2.0 [2], designed for joint-oriented training across all stages of rehabilitation. This exoskeleton is equipped with 9 degrees of freedom (DoF) under active control and 3 six-DoF force/torque sensors, enabling it to seamlessly track the upper limb's movements. It is designed as a highly adaptable therapeutic robot, capable of serving a broad range of users and exercises. However, its high energy consumption and cost limit its widespread use. Similarly, the "Carry" pneumatic elbow exoskeleton, designed by the Technical University of Munich [3], is a lightweight, active device primarily designed to assist with carrying tasks. It can relieve localized muscle fatigue; however, its complex pneumatic components may make maintenance challenging and time-consuming.Exoskeletons with flexible assistance can also be driven by tendons, such as the Myoshirt textile exomuscle from the Swiss Federal Institute of Technology Zurich [4], which helped testers delay muscle fatigue onset by 51.5 seconds and reduce muscle activity by 49.1%. Moreover, the Series Elastic Actuator (SEA) is a widely used type of joint actuator for exoskeletons [5,6]. To ensure ease of use, exoskeleton actuators need to be lightweight and compact while still meeting performance requirements. In addition to active assistance methods, passive exoskeletons also exist. One example is the unpowered ankle exoskeleton developed by Carnegie Mellon University [7]. It uses ratchets and springs to passively support human movement.

Improving the comfort and portability of exoskeletons is a challenge in human motion assistance [8], requiring solutions to technical problems like motion compatibility and the development of effective human-machine interaction [9]. The choice of actuation method is crucial. In this study, we adopt direct motor drive assistance, which offers high efficiency, rapid response, low maintenance requirements and precise control. In the design of upper limb exoskeletons, torque feedback [10,11] is a key technology that detects the user's motion intent and provides torque compensation, facilitating more precise replication and enhancement of upper limb functions through personalized assistance. The elbow joint is among the most complex joints in the upper limb, characterized by a broad range of motion and diverse functions [12]. Through elbow torque feedback, the exoskeleton can more accurately mimic and enhance the user's elbow function, allowing them to carry out more daily activities and work tasks [13]. However, research on elbow torque feedback remains relatively limited, primarily concentrating on algorithms and control strategies while often overlooking user experience and adaptability. Therefore, this paper seeks to enhance the design and performance of upper limb exoskeleton assistive devices by investigating elbow torque feedback technology. The goal is to deliver improved assistance and user experience while designing a low-cost upper limb exoskeleton. This paper outlines the principles and mechanisms of upper limb exoskeleton robots, covering structural design, torque computation and torque feedback control. The experimental procedures and performance evaluations are thoroughly presented to assess the efficacy and functionality of the exoskeleton device. This work aims to guide and inspire the design and implementation of upper limb exoskeleton assistive devices while encouraging further research and advancement in elbow torque feedback technology. This will enhance the rehabilitation experience and work quality for individuals undergoing rehabilitation training or performing heavy-lifting tasks, aiding in the recovery or improvement of their upper limb motor function. We created the exoskeleton Project Website: https://exoskeleton-club.github.io/ULETF/.

2. Mechanical design of the upper limb exoskeleton

2.1 Structural design

This section introduces the bionic design of the upper limb exoskeleton structure, replicates the freedom of the human upper limb, and provides flexible rotational freedom for each joint and controllable auxiliary torque for the elbow joint. The exoskeleton is composed of three sub-modules: the back, shoulders and elbows. The main degrees of freedom in the upper limbs come from the shoulder, elbow and wrist joints, which exert force on the shoulder and elbow muscles when carrying objects or lifting heavy objects, especially during flexion/extension. To reduce weight and improve control, the shoulder joint features passive support, while the elbow joint is driven by a direct motor. We replaced the traditional reducer with a direct-drive system, allowing the exoskeleton joints to be controlled by the user's movements [11] and eliminating the need for complex trajectory planning.

When the exoskeleton system's degrees of freedom match those of the human body, it offers maximum comfort and unrestricted movement. However, from a control perspective, fewer degrees of freedom make the system easier to manage, creating a trade-off between control feasibility and comfort. To balance both control and comfort, this exoskeleton is primarily designed to support the shoulder and elbow joints. Considering both control ease and freedom matching, the shoulder joint was assigned 3 degrees of freedom, the elbow joint 1 degree of freedom, while the wrist joint was omitted, resulting in a total of 4 degrees of freedom for the right upper limb.

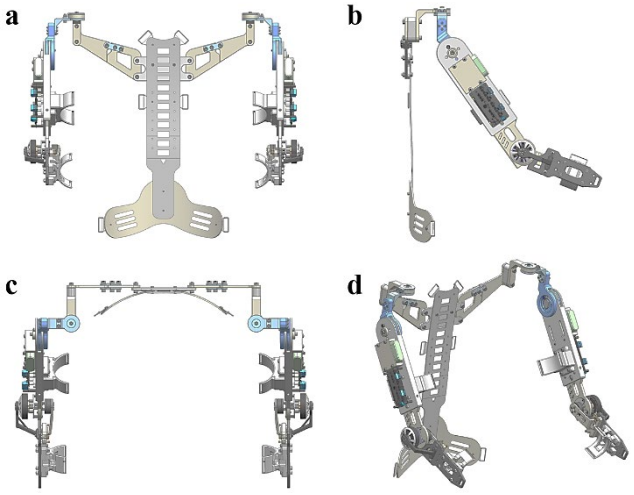

Figure 1. Structural design of upper limb exoskeleton. (a) The front view of the exoskeleton. (b) The left view of the exoskeleton. (c) The top view of the exoskeleton. (d) The axonometric diagram of the exoskeleton.
Source: authors

This setup is sufficient to meet the needs of most activities of daily living (ADLs) [14], while maintaining workspace integrity and simplifying both structure and control. The exoskeleton's weight is distributed through the back plate, and when integrated with a lower limb exoskeleton, it can be further transferred to the ground. The 3D structural design is illustrated in Fig. 1.

Fig. 1 shows the three orthographic views and an axonometric projection of the upper limb exoskeleton robot. The backplate features buckles, while the ring supports on the upper and lower arm panels include slots for securing them to the body with straps, elastic bands and Velcro. The length of the upper arm panel is adjustable to accommodate users of different heights. The elbow joint incorporates a dual-motor coaxial design, while the back panel is constructed from rigid aluminum alloy to provide support. The exoskeleton joint axis must align with the user's joint axis to ensure movement coordination. To lower manufacturing costs and simplify production, most exoskeleton components are fabricated from 3D-printed white resin.

2.2 Range of motion of the upper limb joints

The design of the exoskeleton structure must ensure that the dimensions of the parts and the joint constraints align with the range of motion of the human upper limb. The motion range of the exoskeleton joints should be defined according to the normal range of human joint motion. The shoulder joint is the most complex joint in the upper limb, with three orthogonal rotational degrees of freedom: abduction/adduction about axis-1, external/internal rotation about axis-2 and flexion/extension about axis-3. The elbow joint rotates about axis-4 and is considered to have one degree of freedom: flexion and extension. The wrist joint is the most complex joint in the upper limb, which can also be simplified into three rotational DOFs [14]. As the exoskeleton design excludes the wrist joint, the human wrist's range of motion is not considered. After analyzing the DOF of the upper limb, the motion angles of each joint need to be studied to design appropriate joint motion ranges and limits. Aligning the exoskeleton design with the range of motion of the human upper limb enhances both practicality and comfort. The specific joint limits, detailed structural information, and simplified diagram of human joint freedom corresponding to the exoskeleton are shown in Fig. 2.

The elbow joint of the upper limb exoskeleton incorporates a mechanical limiter, restricting the motion angle to 0°–130° (Fig. 2a). Fig. 2b illustrates the adjustable mechanism of the upper arm plate, where the length can be modified by changing the hole position and bolt connection. The forearm plate measures 200 mm, while the upper arm

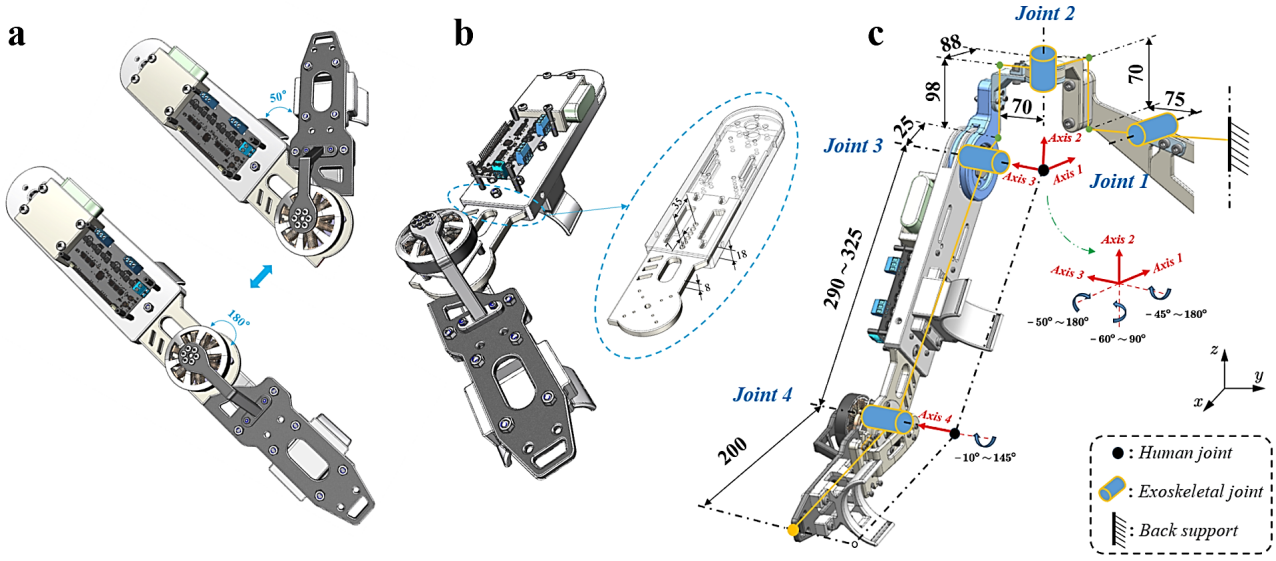

Figure 2. Joint limitations in upper limb exoskeleton with partial details and diagrammatic diagram of human joint freedom. (a) Variation of the joint limiting angle at the elbow joint of the exoskeleton. (b) Detail of the assembly of the adjustable plate of the exoskeleton with the big arm plate. (c) Diagram of the degrees of freedom of the human body joints in the positions corresponding to the joints of the exoskeleton.
Source: authors

Table 1.
The range of joint movement restrictions of the exoskeleton.

Axis	Angle Range	Joint/Assistance Type
Axis-1	0° ~ 180°	Shoulder [Abduction/Adduction] (Passive Support)
Axis-3	-55° ~ 30°	Shoulder [External/Internal Rotation] (Passive Support)
Axis-3	-40° ~ 140°	Shoulder [Flexion/Extension] (Passive Support)
Axis-4	0° ~ 130°	Elbow [Flexion/Extension] (Direct Motor Drive)

Source: authors

plate is adjustable between 290 mm and 325 mm. The simplified DOF of human joints include 3-DOF for the shoulder and 1-DOF for the elbow, corresponding to upper limb shoulder abduction/adduction (axis-1), external/internal rotation (axis-2), flexion/extension (axis-3) and elbow flexion/extension (axis-4) [14]. The defined zero angles correspond to the arm positioned perpendicular to the ground, as illustrated in Fig. 2c. The right-hand rule was applied to determine the positive and negative rotation angles of the joints, representing the normal motion range of the upper limb joints. Upon determining the normal range of motion for human upper limb joints, the rotational limits of the exoskeleton joints can be precisely defined. These constraints are enforced via mechanical stoppers, with the joint motion ranges of the exoskeleton manually specified. The joint motion limits and corresponding constraints of the exoskeleton are shown in Table 1.

The range of joint motion limitations in the exoskeleton is a key design consideration to prevent the user's movements from exceeding physiological boundaries. This design improves user safety and comfort while enhancing operational efficiency. The mechanical structure's constraints precisely regulate joint motion, ensuring effective protection for human joints.

1. Upper limb exoskeleton elbow joint control

1.1 Torque estimation

When assisting the movement of the human elbow joint with the upper limb exoskeleton, careful consideration must be given to the configuration and selection of the assistive motor. A motor that is too small will provide insufficient assistance, while an overly large motor adds unnecessary weight and bulk, diminishing comfort by increasing inertia. Torque estimation at the exoskeleton joint is essential to evaluate the assistive effect and the motor's self-weight. For example, during arm-lifting movements, the torque reaches its peak when the upper arm and forearm are fully extended horizontally. This posture serves as the baseline for joint torque calculations. The state diagram of the exoskeleton in the maximum force-arm position, finite element analysis (FEA) of key components and the control block diagram for position mode are shown in Fig. 3.

The specific state diagram for the upper limb in the maximum force-arm position is shown in Fig. 3a. In Fig. 3, T_1 represents the torque at the shoulder joint

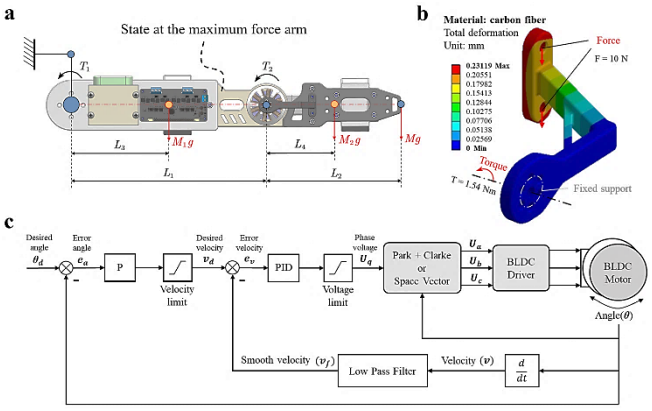

Figure 3. State diagram at the maximum force arm of the upper limb exoskeleton with finite element analysis of key components and control block diagram of the position mode. (a) State diagram at the maximum force arm giving the force analysis. (b) Finite element analysis of key component of the upper limb exoskeleton. (c) Control block diagram of exoskeleton motor position control.
Source: authors

(flexion/extension), and T_2 represents the torque at the elbow joint (flexion/extension). L_1 denotes the length of the exoskeleton's upper arm, $L2$ the length of the forearm (excluding the wrist), L_3 the distance from the center of mass of the upper arm to the shoulder joint, and $L4$ the distance from the center of mass of the forearm to the elbow joint. M_1g represents the weight of the exoskeleton's upper arm, and M_2g represents the weight of the forearm. Mg refers to the compensatory weight at the distal end of the exoskeleton's upper limb. Based on the theorem of static equilibrium, torque can be calculated at the elbow and shoulder joint centers. See eq. (1) and eq. (2):

$$T_2 = Mg \times L_2 + M_2g \times L_4 \tag{1}$$

$$T_1 = Mg \times (L_1 + L_2) + M_2g \times (L_1 + L_4) + M_1g \times L_3 - T_2 \tag{2}$$

After assigning values to the parameters, we obtain the following dimensions from measurements: L_1 =339mm, L_2 =200mm, L_3 = 157mm, L_4 = 96mm, M_1 = 0.5kg, M_2 = 0.4kg. The compensatory mass M of the upper limb is set to 0.6kg, and the gravitational acceleration，g = 9.8N/kg. Substituting these values into the formulas yields T_1 = 4.09Nm, T_2 = 1.55Nm. Thus, the torque required for the assistive motor at the elbow joint must be close to 1.55Nm. As the shoulder joint is supported passively, the necessary torque is compensated entirely by the passive support structure, with no need for active motor assistance. The shoulder joint's three degrees of freedom are supported by mechanical structures containing rolling bearings, ensuring smooth rotation of the exoskeleton's shoulder joint.

The key distinction between an assistive exoskeleton system and other robots lies in the fact that the operator is a human, not the machine. The operator is part of the control

loop, meaning the human is "in the loop". The operator and the exoskeleton interact physically, forming a tightly coupled human-machine system. The objective of controlling this coupled system is to facilitate seamless coordination between the human and machine to accomplish tasks. A key advantage of direct-drive assistance is that it keeps the assistive joints lightweight, eliminating the need for traditional robotic motion planning. The exoskeleton's joint motion only needs to mirror the real-time movements of the human body. When the human body remains stable, the exoskeleton can maintain its stability without requiring additional control, relying entirely on the human body for balance.

1.2 Torque feedback

Based on torque estimation, a 5008-400KV brushless DC (BLDC) motor was chosen as the assistive motor for the exoskeleton's elbow joint. The motor provides a rated torque of 1.54 Nm and a power output ranging from 28.1 to 355.2 W, satisfying the assistive requirements for the elbow joint. A small gimbal motor served as the drive motor, sharing the same axis with the assistive motor. As the elbow bends or extends, the human body exerts a slight torque to activate the drive motor, which operates coaxially with the assistive motor to generate torque feedback. Both motors output torque synchronously, with the assistive motor driving the forearm panel to provide elbow assistance. The elbow control system includes a position sensor, eliminating the need for a position observer.

The Space Vector Pulse Width Modulation (SVPWM) serves as the final execution part of Field-Oriented Control (FOC) [15], receiving the $V\alpha$ and $V\beta$ signals from the FOC to control the stator windings and generate a rotating magnetic field.

The core principle of torque feedback in this exoskeleton robot is to utilize the angular difference between the two motors as the target value in torque mode, ensuring that the angular difference is driven to zero. As one motor rotates, the other generates torque to track and follow the movement. Similarly, when one motor stalls, the other motor halts as the angular difference converges to the stalled motor's angle. Torque feedback eliminates the need for current sampling and can be implemented using voltage mode, which is ideal for low-speed motor control with rapid execution response. Finally, the dual-motor torque feedback control system diagram is shown in Fig. 4.

As shown in Fig. 4c, when the upper limb muscles contract, they generate a force $F_{muscle.}$ Due to the presence of a lever arm r between the muscle force and the joint's center of rotation, F_{muscle} produce a torque T_{muscle} that causes the joint to rotate.

If the forearm is extended, the biceps relax, and the muscles on the opposite side of the joint contract to pull the joint back to a horizontal position, where $T_{muscle} = F_{muscle} \times r_{\circ}$.
According to the control block diagram of the dual-motor torque feedback, when the deviation $e = \theta i - \theta o$ approaches zero, the total torque T_{joint} at the human elbow joint can be

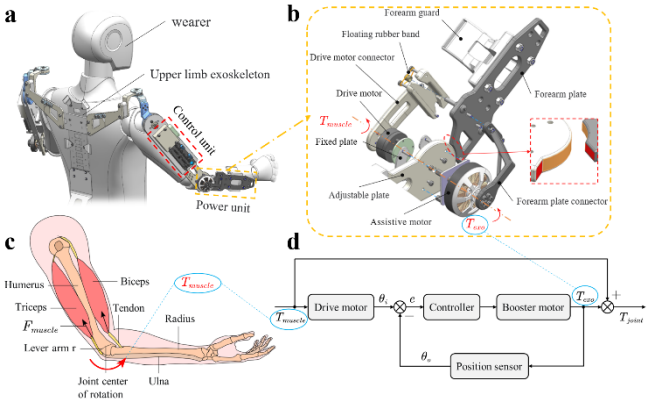

Figure 4. Schematic of the control system for dual-motor torque feedback at the elbow joint of the exoskeleton. (a) Schematic diagram of human wearing the upper limb exoskeleton. (b) Exploded view of the motor assembly at the elbow joint of the exoskeleton. (c) Schematic diagram of human upper limb muscles. (d) Block diagram of the control system at the elbow joint of the exoskeleton.
Source: authors

considered as the sum of the torque generated by the muscles T_{muscle} and the torque provided by the exoskeleton T_{exo}, $T_{joint} = T_{muscle} + T_{exo}$. The torque produced by the dual-motor feedback in the elbow of the exoskeleton is transmitted to the wearer via linkages. Ideally, this setup can reduce the load on human muscles. If the movement direction of the human body and the exoskeleton are aligned (which the control system ensures), the user can leverage the exoskeleton to perform tasks with less effort.

2. Performance evaluation of the exoskeleton

2.1 Preliminary performance evaluation

For performance evaluation [16-18] of the exoskeleton robot, four main aspects are considered: comfort, applicability, safety and reliability. Comfort can be assessed through human-machine interaction forces, muscle fatigue, appearance and noise; applicability can be evaluated through maximum load capacity, endurance and time required for donning and doffing; safety is measured by ensuring that the exoskeleton's range of motion is less than the physiological limits of the human body, with warning and protection mechanisms in place in the event of failure; and reliability can be assessed through the mean time between failures and average repair time.

The performance of this upper limb exoskeleton is evaluated based on two criteria: muscle fatigue and elbow flexion/extension angular velocity. Muscle fatigue is evaluated through electromyography (EMG). Surface electromyography (sEMG) is the composite effect of electrical activity from superficial muscles and nerve trunks on the skin's surface. It represents the bioelectrical changes in the neuromuscular system during voluntary and involuntary movements. These signals are captured, amplified, displayed and recorded as

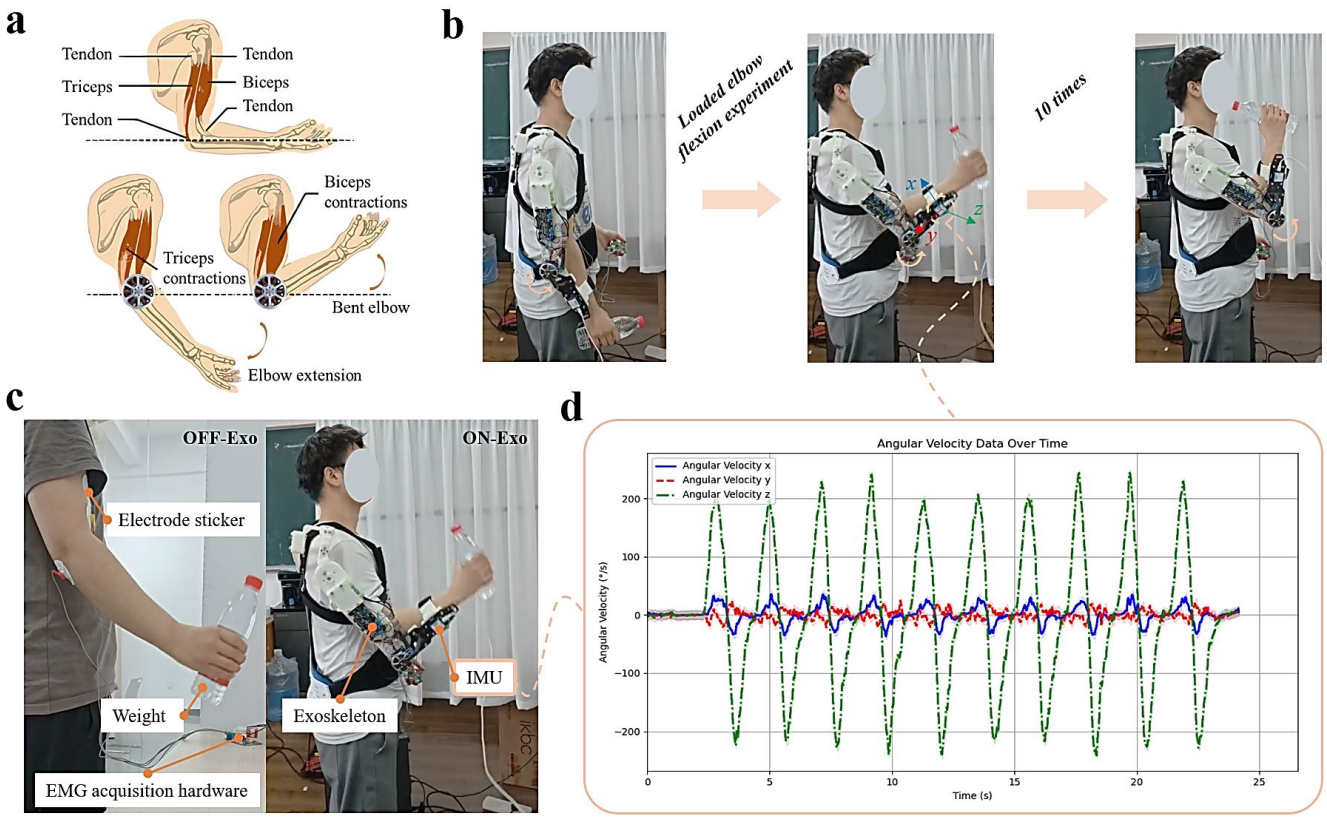

Figure 5. Performance evaluation of the upper limb exoskeleton. (a) Schematic diagram of human upper limb movement. (b) Motion processes in the upper limb exoskeleton. (c) Loaded elbow flexion experiment at the elbow joint. (d) Angular velocity data recording of IMU at the forearm in the upper limb exoskeleton.
Source: authors

one-dimensional voltage-time series through surface electrodes, providing a representation of neuromuscular activities to some extent. The preliminary performance evaluation experiment is a single-arm loaded elbow flexion test, during which EMG signals are collected using an EMG module to monitor changes in upper arm muscle activity. The experiment compares the muscle power output (especially of the biceps) during loaded elbow flexion with and without the exoskeleton. Performance evaluation of the exoskeleton as show in Fig. 5.

To reduce impedance and external interference during surface EMG signal collection, the subject's skin was cleaned with alcohol prior to data acquisition. The subject was a 23-year-old male, 176 cm tall, weighing 75 kg, and in good health. During the experiment, 10 single-arm loaded elbow flexions were performed, with the process of single-arm motion while wearing the upper limb exoskeleton shown in Fig. 5b. EMG signals were collected from the biceps brachii of the subject's upper arm to evaluate the performance of the exoskeleton. Ensuring consistent electrode placement on the same side and positioning them away from power sources is crucial to prevent 50 Hz power frequency interference. The specific experimental setup and hardware for EMG data collection are shown in Fig. 5c.

The angular velocity data from the IMU (Inertial Measurement Unit) sensor can be used to verify the effectiveness of the exoskeleton design, visually demonstrating the role of the exoskeleton in assistive motion. By analyzing the angular velocity of forearm movements, it is possible to evaluate the exoskeleton's impact on motion control and the efficiency of the wearer in performing specific tasks. Fig. 5d displays the angular velocity data recorded by the IMU at the forearm. In the performance evaluation of the exoskeleton, angular velocity data is used to assess the performance of the exoskeleton during specific tasks (such as the loaded elbow flexion experiment). Metrics include smoothness of motion, average speed and peak speed. Motion smoothness is assessed by calculating the standard deviation of angular velocity during movement. A lower standard deviation indicates less fluctuation around the mean, suggesting smoother movement and diminished oscillation. Average speed refers to the mean angular velocity during motion with the exoskeleton, reflecting the overall speed level. Peak speed represents the highest speed during movement, indicating the exoskeleton's capability to support rapid movements, particularly useful for tasks requiring quick responses.

From Fig. 5d, the smoothness (standard deviation) of Angular Velocity *x* is 13.88, the average speed is 9.70°/s, and the peak speed reaches 36.93°/s. This indicates smooth movement along the *x*-axis with moderate speed and quick responsiveness. For Angular Velocity *y*, the smoothness is 7.64, with an average speed of 5.83°/s and a peak speed of 24.41°/s. Compared to the *x*-axis, movements along the *y*-

axis are smoother with less fluctuation but slower, suggesting that the exoskeleton provides stable support in this direction. Angular Velocity z has a very high standard deviation of 122.29, an average speed of 94.12°/s and a peak speed of 243.71°/s. This indicates significant fluctuation along the z-axis (corresponding to elbow movements) and suggests that this is the most active direction of motion, reflecting the upper limb exoskeleton's high responsiveness in supporting rapid movements.

Using EMG hardware and an upper computer for data collection, a single-arm loaded elbow flexion experiment (10 repetitions) was performed, comparing the EMG data collected with and without wearing the exoskeleton (OFF-Exo and ON-Exo). The data collected by the upper computer was imported into Excel for basic processing, followed by electromyography signal analysis using Python. A sampling rate of 1000 was set during filtering, and band-pass filtering was applied to obtain the filtered EMG signals, with low and high cutoff frequencies set to 10 Hz and 450 Hz, respectively. The filtered signal and corresponding smoothed envelopes are shown in Fig. 6, with the vertical axis representing muscle EMG intensity. From the EMG signal envelopes in Fig. 6, it is evident that the EMG intensity is lower in the ON-Exo condition compared to the OFF-Exo condition.

Next, time-domain features of the EMG signals were extracted to provide a comparison, using two relatively stable metrics: root mean square (RMS) and average rectified value (aEMG). See eq. (3) and eq. (4).

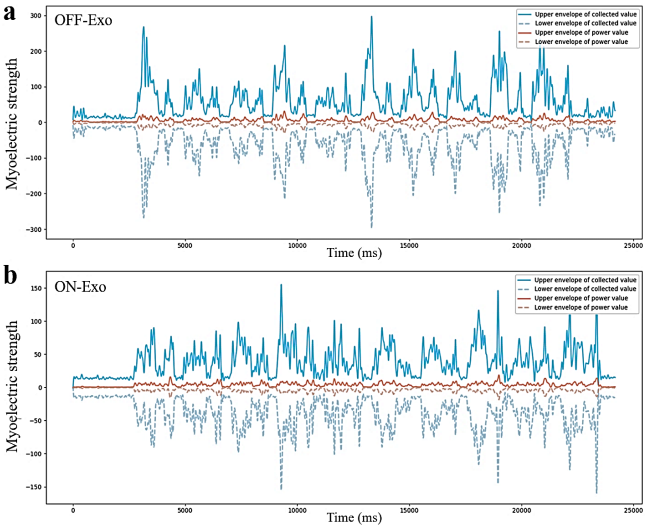

Figure 6. Comparison of the envelope of the filtered EMG signal after the experimental collection. (a) EMG signal envelope (OFF-EXO) during loaded elbow flexion experiments without wearing the upper limb exoskeleton. (b) EMG signal envelope (ON-EXO) during loaded elbow flexion experiments while wearing the upper limb exoskeleton.
Source: authors

$$\mathrm{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x^2(i)} \tag{3}$$

The formula for calculating aEMG is:

$$\mathrm{aEMG} = \frac{1}{N}\sum_{i=1}^{N} |x(i)| \tag{4}$$

Where N represents the total number of samples in the discrete time series x, and i represents the i-th discrete time point. The time-domain feature extraction of EMG power values is shown in Table 2.

In the time-domain feature comparison of EMG, each value in the ON-Exo condition is lower than the corresponding value in the OFF-Exo condition. Specifically, the RMS of the collected values decreased by 41.61%, and the aEMG decreased by 35.79%. The RMS of the power values decreased by 41.44%, and the aEMG of the power values decreased by 36.61%. This result indicates a decrease in muscle activation power under the ON-Exo condition, implying that the upper limb exoskeleton offers a measurable assistive effect.

By comparing the EMG signal envelopes and time-domain features between the OFF-Exo and ON-Exo conditions, it is evident that the muscle activation power during loaded elbow flexion is lower when wearing the exoskeleton. This demonstrates that the upper limb exoskeleton robot offers effective assistance, reducing muscle activation levels with the exoskeleton's support. This can enhance the endurance of upper limb movements or be used for rehabilitation training for individuals with pathological upper limb weakness. Analysis of the EMG features of the biceps confirms the feasibility of the exoskeleton in providing assistance to the elbow joint.

2.1 Comprehensive performance evaluation

To comprehensively validate the effectiveness of the proposed upper limb exoskeleton, a systematic performance evaluation was conducted. Unlike the preliminary assessment based on individual user testing, the present evaluation involved a larger cohort by including five additional participants of varying ages, thereby enhancing the reliability of the study results. During the experiment, each participant performed ten single-arm elbow flexion tasks under load. Furthermore, subjective evaluations of comfort and ease of use were obtained through a structured participant questionnaire, with scores ranging from 1 to 5 (where higher scores indicate better user perception).

Table 2.
Time-domain feature comparison of EMG.

Time-domain feature		Collected value	Reduction rate	Power value	Reduction rate
RMS	OFF-Exo	94.32	41.61%	10.16	41.44%
	ON-Exo	55.07		5.95	
aEMG	OFF-Exo	58.92	35.79%	6.20	36.61%
	ON-Exo	37.83		3.93	

Source: authors

Table 3.
Summary of experimental data on the comprehensive performance evaluation for exoskeleton.

Participant ID	Age (years)	Height (cm)	Weight (kg)	ON-Exo (RMS)	OFF-Exo (RMS)	ON-Exo (aEMG)	OFF-Exo (aEMG)	Comfort Score (1-5)	Ease of Use Score (1-5)
P1	22	170	65	55.1	94.3	37.8	58.9	4	4
P2	24	175	70	54.8	93.5	36.5	57.5	4	5
P3	25	180	75	56.3	95.2	38.1	59.2	3	4
P4	28	165	62	53.2	92.6	36.2	56.3	5	4
P5	26	172	68	55.5	94.8	37.5	58.6	4	5

Source: authors

Table 3 presents a summary of the comprehensive performance evaluation data for the exoskeleton, including participants' anthropometric parameters, electromyographic signal metrics (RMS and aEMG) collected under both exoskeleton-assisted and unassisted conditions, as well as subjective ratings of comfort and ease of use. Each participant is assigned a unique identifier (ID), labeled from P1 to P5, where "P" denotes "Participant".

To further assess the sustained usability of the exoskeleton device, a long-term usability experiment was conducted, with a particular focus on the progression of users' perceived fatigue during continuous wear. In the test protocol, participants performed standardized upper limb tasks while periodically rating their subjective fatigue levels at predefined time intervals (5, 15, 30, 40, and 60 minutes). The fatigue scores were based on a 1–10 scale, with higher values indicating greater perceived fatigue. This score is positively correlated with the RMS measurement value.

As shown in Fig. 7, all five participants exhibited an upward trend in fatigue ratings over time, suggesting that prolonged use of the exoskeleton, even under assistive conditions, may lead to a gradual accumulation of muscular fatigue.

The primary objective of the exoskeleton is to provide assistive support and reduce muscular fatigue; however, it cannot entirely eliminate fatigue accumulation. As such, a gradual increase in perceived fatigue over time is a physiologically expected outcome during extended use. Notably, the subjective fatigue ratings were partially informed by trends observed in electromyographic signal metrics (RMS), thereby enhancing the reliability of fatigue assessment. For comparison, subjective fatigue ratings under non-assisted (no-exoskeleton) conditions were also collected and are presented in Fig. 8.

A comparison between Fig. 7 and Fig. 8 indicates that subjective fatigue scores were consistently lower when participants performed tasks with exoskeleton assistance, as opposed to the non-assisted condition. This suggests that the exoskeleton is effective in mitigating upper limb fatigue to a certain extent during repetitive motion tasks.

Finally, we conducted a systematic analysis of the limitations of the proposed upper limb exoskeleton in practical applications and proposed several feasible optimization strategies based on its current design characteristics. Although the upper limb exoskeleton exhibited satisfactory performance across the aforementioned core experimental evaluations, it still presents certain limitations in terms of accommodating a

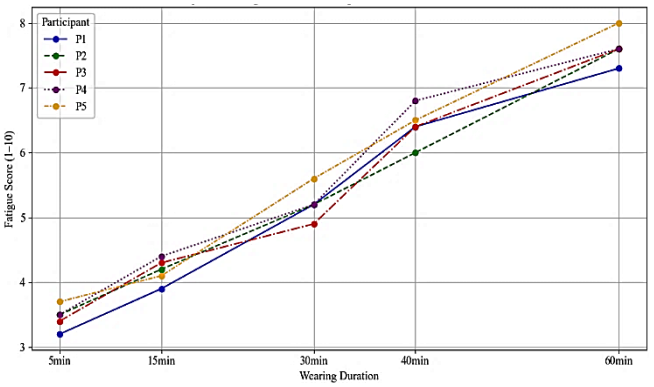

Figure 7. Subjective fatigue score curves of different participants using exoskeleton device.
Source: authors

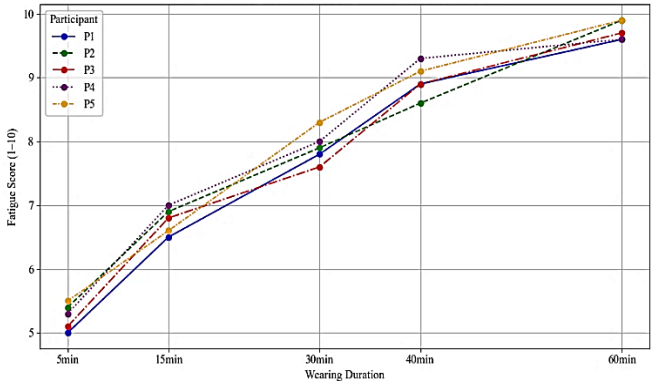

Figure 8. Subjective fatigue score curves of different participants without using exoskeleton devices.
Source: authors

wide range of user profiles. Specifically, when accommodating participant users with diverse body types (e.g., significant differences in height or weight) and varying levels of motor ability (e.g., individuals in early-stage rehabilitation versus healthy subjects), the device may encounter issues such as structural misalignment, inconsistent assistive effectiveness, and reduced wearing comfort. To enhance the individual adaptability and large-scale deployment potential of the upper limb exoskeleton system, future work will focus on adjustable structural design, dynamic regulation algorithms based on anthropometric parameters, and user state-aware feedback mechanisms. For example, modular or adaptive adjustment components could be introduced to accommodate variations in upper limb length and elbow joint axis alignment. In parallel, real-time optimization of control parameters using physiological data from the user could improve both wearing comfort and cooperative assistance performance. These improvements are expected to significantly extend the applicability of the proposed exoskeleton system across a range of scenarios, including clinical rehabilitation, human–robot collaboration, and industrial assistance.

1. Conclusion

This work proposes a low-cost, portable upper limb exoskeleton device that can be worn like a backpack, connecting to the wearer's back and arm. The device can alleviate the burden on the arm during lifting or carrying heavy objects and support rehabilitation training for patients with upper limb injuries in the later stages of elbow joint rehabilitation. The structural design of the exoskeleton is customized to align with the degrees of freedom of the human upper limb, offering flexible and smooth rotational freedom for each joint and delivering controllable assistive torque at the elbow joint. Additionally, passive support structures and active assistive motors improve the smoothness of elbow joint movements, enabling dual-motor torque feedback to enhance elbow assistance. To lower manufacturing costs and simplify production, most of the exoskeleton components were made using 3D printing with white resin. Safety is ensured by mechanical limits within the exoskeleton to restrict its workspace, keeping it within the normal range of human motion. The control strategy for the exoskeleton adopts a voltage-based FOC method with torque feedback that does not require current sampling. Synchronous rotation between the inner gimbal motor and the outer brushless motor, in conjunction with the forearm support board, enables the user to exert slight effort to achieve synchronized motor-driven assistance. This study seeks to improve upper limb endurance in specific populations, facilitating the recovery or enhancement of the wearer's motor function. Furthermore, it holds potential for advancing the development and adoption of upper limb exoskeleton robots, thereby increasing the accessibility and impact of these devices across diverse user groups.

References

[1] Siviy, C., Baker, L.M., Quinlivan, B.T. et al., Opportunities and challenges in the development of exoskeletons for locomotor assistance. Nature Biomedical Engineering,7(4), pp. 456-472, 2023. DOI: https://doi.org/10.1038/s41551-022-00984-1

[2] Zimmermann, Y., Sommerhalder, M., Wolf, P. et al., ANYexo 2.0: a fully actuated upper-limb exoskeleton for manipulation and joint-oriented training in all stages of rehabilitation. IEEE Transactions on Robotics, 39(3), pp. 2131-2150, 2023. DOI: https://doi.org/10.1109/TRO.2022.3226890

[3] Nassour, J., Zhao, G., and Grimmer, M., Soft pneumatic elbow exoskeleton reduces the muscle activity, metabolic cost and fatigue during holding and carrying of loads. Scientific Reports,11(1), art. 12556, 2021. DOI: https://doi.org/10.1038/s41598-021-91702-5

[4] Georgarakis, A-M., Xiloyannis, M., Wolf, P., et al., A textile exomuscle that assists the shoulder during functional movements for everyday life. Nature Machine Intelligence, 4(6), pp. 574-82, 2022. DOI: https://doi.org/10.1038/s42256-022-00495-3

[5] Walsh, C.J., Paluska, D., Pasch, K., et al., Development of a lightweight, under. actuated exoskeleton for load-carrying augmentation, in: Proceedings 2006 IEEE International Conference on Robotics and Automation, 2006 ICRA, 2006, pp. 15-19. DOI: https://doi.org/10.1109/ROBOT.2006.1642234

[6] Wu, K.Y., Su, Y.Y., Yu, Y.L., et al., A 5-Degrees-of-freedom lightweight elbow-wrist exoskeleton for forearm fine-motion rehabilitation. IEEE/ASME Transactions on Mechatronics, 24(6), pp. 2684-2695, 2019. DOI: https://doi.org/10.1109/TMECH.2019.2945491

[7] Collins, S.H, Wiggin, M.B., and Sawicki, G.S., Reducing the energy cost of human walking using an unpowered exoskeleton. Nature, 522(7555), pp. 212-215, 2015. DOI: https://doi.org/10.1038/nature14288

[8] Li, H., Sui, D., Ju, H., et al., Mechanical compliance and dynamic load isolation design of lower limb exoskeleton for locomotion assistance. IEEE/ASME Transactions on Mechatronics, 27(6), pp. 5392-5402, 2022. DOI: https://doi.org/10.1109/TMECH.2022.3181261

[9] Gull, M.A., Bai, S., and Bak, T., A Review on Design of Upper Limb Exoskeletons. 9(1), art, 9010016, 2020. DOI: https://doi.org/10.3390/robotics9010016

[10] Kim, H., and Asbeck, A.T., Just noticeable differences for elbow joint torque feedback. Scientific Reports, 11(1), art. 23553, 2021. DOI: https://doi.org/10.1038/s41598-021-02630-3

[11] Kim, H., and Asbeck, A.T., The effects of torque magnitude and stiffness in arm guidance through joint torque feedback. IEEE Access, 10, pp. 5842-5854, 2022. DOI: https://doi.org/10.1109/ACCESS.2022.3141981

[12] Vitiello, N., Lenzi, T., Roccella, S., et al., NEUROExos: a powered elbow exoskeleton for physical rehabilitation. IEEE Transactions on Robotics, 29(1), pp. 220-235, 2013. DOI: https://doi.org/1109/TRO.2012.2211492

[13] Kim, H., and Asbeck, A.T., An elbow exoskeleton for haptic feedback made with a direct drive hobby motor. HardwareX, 8, art. e00153, 2020. DOI: https://doi.org/10.1016/j.ohx.2020.e00153

[14] Perry, J.C., Rosen, J., Burns, S., Upper-Limb powered exoskeleton design. IEEE/ASME Transactions on Mechatronics, 12(4), 408-417, 2007. DOI: https://doi.org/10.1109/TMECH.2007.901934

[15] Abassi, M., Khlaief, A., Saadaoui, O., et al., Performance analysis of FOC and DTC for PMSM drives using SVPWM technique, in: Proceedings of the 2015 16th International Conference on Sciences and Techniques of Automatic Control and Computer Engineering (STA), 2015, pp. 21-23. DOI: https://doi.org/10.1109/STA.2015.7505167

[16] Pinto-Fernandez, D., Torricelli, D., Sanchez-Villamanan, M.D.C., et al., Performance evaluation of lower limb exoskeletons: a systematic review. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 28(7), pp. 1573-1583, 2020. DOI: https://doi.org/10.1109/TNSRE.2020.2989481

[17] Z. Du, et al., Mechanical design and preliminary performance evaluation of a passive arm-support exoskeleton, 2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp. 3371-3376, 2020. DOI: https://doi.org/10.1109/IROS45743.2020.9341290

[18] Liu, Y., Li, X., Zhu, A., Zheng, Z., and Zhu, H., Design and evaluation of a surface electromyography-controlled lightweight upper arm exoskeleton rehabilitation robot. International Journal of Advanced Robotic Systems. 18(3), art. 003461, 2021. DOI: https://doi.org/10.1177/17298814211003461

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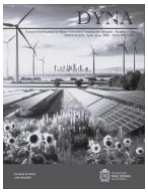

UNIVERSIDAD NACIONAL DE COLOMBIA

A catalog of API Gateway metrics and its quantitative evaluation

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Abstract
In the rapidly evolving API Economy, quality of API management software has become a critical concern. This work analyzed the API management industry with a particular focus on the metrics available for various API Gateway products. The primary artifact is a catalog with 59 metrics, compiled from global industry reports and technical documentation of 68 leading API Gateway products. The Design Science Research (DSR) approach was adopted to design the catalog, and metrics were categorized based on clear definitions in recent scientific literature. Secondly, a quantitative analysis method was proposed and systematically performed. Findings indicate that the metrics mainly focus on latency, response time, API performance, error capturing, and traffic monitoring. Features such as caching, resource utilization, and system health were scarcely addressed by the examined products. The proposed artifacts provide an objective foundation for a deeper understanding of API Management software quality, and lay the groundwork for future research.

Keywords: API management; API gateway; design science research; software engineering; software metrics; software quality.

Un catálogo de métricas de API Gateway y su evaluación cuantitativa

Resumen
En la Economía de las API, la calidad del software de administración de API se ha convertido en una preocupación crítica. Este trabajo analizó productos de administración de API con un enfoque particular en las métricas disponibles en productos API Gateway. Se obtuvo un catálogo de 59 métricas, compiladas y categorizadas a partir de la literatura vigente, reportes globales y documentación técnica de 68 API Gateways. Se adoptó el enfoque Design Science Research (DSR) para el diseño. Adicionalmente, se propuso y se implementó un método de análisis cuantitativo. Los hallazgos indican que las métricas se centran principalmente en latencia, tiempo de respuesta, rendimiento, captura de errores y monitoreo del tráfico. Características como almacenamiento en caché, utilización de recursos y estado del sistema fueron escasamente abordadas. Los artefactos propuestos proporcionan una base objetiva para comprender más profundamente la calidad del software de administración de API, y sientan bases para futuras investigaciones.

Palabras clave: administración de API; API Gateway; Design Science Research; ingeniería de software; métricas de software; calidad de software.

1. Introduction

In recent years, the distribution models for information systems have been moving towards Everything-as-a-Service (XaaS) [1] paradigms. These paradigms are based primarily on microservice architectures that provide a flexible framework [2], enabling organizations to efficiently distribute their information systems into a highly scalable set of services. Within such a framework, APIs are essential in streamlining the development process and fostering interoperability and collaboration between multiple software applications and platforms [3,4]. As a result, effective quality management over API Management products has emerged as a critical aspect for organizations striving to harness the full potential of their digital assets and remain competitive in fast-paced market environments. The global API Management market grew by 13. 7\% and reached 3.3 billion USD in 2023[1].

At the core of API Management products lies the API Gateway. The API Gateway acts as a centrally managed, API-oriented control service that encapsulates, exposes, secures, and manages back-end data and services as RESTful APIs, which provides a framework

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for establishing a facade on top of these services. API Gateway's main features may include security, traffic management, service and data mapping, caching, load balancing, error reporting, and performance monitoring, among others. API Gateways provide a broad set of metrics that enable the production of business-value reports and user-friendly dashboards aiming at helping to understand who uses available APIs and how they are utilized [3].

Current industry reports[2] indicate that there are 68 API Gateway offerings available nowadays. In such a competitive landscape, it is essential to understand how quality is measured and what metrics these products provide to achieve it. However, research in this domain is still emerging. A systematic mapping study conducted in [5] indicates that only 20 studies addressed a handful of quality characteristics among a small selection of available API Management software products.

The main aim of this work is to develop the third step towards an expressive, platform-neutral API Gateway quality model that can be used to create open tools for API Management quality characterization, measurement, and evaluation. The main contributions of this paper include a) a catalog of 59 metrics collected from eight industry-leading API Gateway products; b) the specification of a flexible, domain-neutral quantitative analysis method based on scoring and comparison, adapted from [6]; c) an analysis based on the described method, which highlighted trends and gaps in the metrics provided by the examined products; and iv) an open dataset that allows to replicate and improve this research.

This paper is structured as follows: Section 2 introduces the methodologies employed in designing the catalog artifact and its quantitative analysis method. Section 3 presents the API Gateway products included in this study, as well as the catalog of metrics and its classification. Next, Section 4 discusses the empirical evaluation of the catalog, and additional insights are provided in Section 5. Finally, concluding remarks and insights into future research are encompassed in Section 6.

2. Methods

The study presented herein was conducted during August and October 2024 and represents a primary investigation in which we analyzed 68 API Gateway products. This work followed the DSR methodology [7], a systematic approach to building and evaluating artifacts such as models, frameworks, and software tools. It emphasizes the iterative cycle of designing, implementing, and refining these artifacts while rigorously assessing their effectiveness and utility in real-world settings. The DSR activity phases conducted in this study are summarized as follows:

1. Problem Identification and Motivation: The lack of a tailored quality model for API Gateway in-depth evaluation.
2. Objectives of a Solution: To design a comprehensive and integrated framework driven by metrics to measure, assess and improve API Gateway software quality.
3. Design and Development: To conduct an extensive review of 68 API Gateway products. Build a catalog of metrics.
4. Demonstration: To present the catalog of metrics; to perform a descriptive analysis over a set of eight real-world API Gateways.
5. Evaluation: Interpretation by employing a quantitative analysis model.
6. Communication: To elaborate and publish this paper and a public dataset.

2.1 DSR development

2.1.1 Research problem identification and motivation

Despite the proliferation of software quality models in the literature, there is a notable gap regarding API management software quality models and metamodels [5]. Additionally, existing research primarily focuses on benchmarking a limited set of quality characteristics across a few API Management platforms. This void motivated the development of the present work.

2.1.2 Objectives of a solution

This work proposes designing and developing a catalog of API Gateway metrics as a comprehensive, platform-neutral, flexible, scalable, and integrated framework that facilitates the characterization and measurement of software quality.

2.1.3 Design and development of the artifact

This study aimed to identify, characterize, and classify metrics provided by industry-leading API Gateway products. To achieve this, we conducted an iterative six-step bottom-up process, which consisted of the following activities:

D1. Initial metrics collection:

During this activity, several approaches were reviewed from the current literature. We prioritized works that (i) provided clear and operational definitions of metrics, (ii) were widely cited or recognized as foundational in the domain, and (iii) offered complementary perspectives or categorization schemes. Based on these criteria, definitions from [3, 8, 9] were adopted and a preliminary set of 31 metrics, grouped by categories, was established.

D2. Initial products compilation:

This step involved identifying API Gateway products from global reports on the API "state of the market".

D3. Quality criteria definition:

Two objective quality criteria were defined, namely: a) visibility among different API landscapes - API vendors identified within the three industry reports were included in this study; and b) integration with analytics third-party software - products that contain integration plugins for widely used analytics and dashboard platforms such as Grafana, Prometheus and Datadog were added to this work.

D4. Technical Documentation Analysis:

This step involved a detailed review of the technical documentation for each software product to identify the metrics provided. Due to limitations of scope and space, this study did not aim at exploring measurement practices within the scientific literature.

D5. Data Extraction:

We created three data extraction forms. The first was designed

[2] The industry reports mentioned in this section are further discussed in section 3.

to collect basic information regarding all identified products and their vendors and included the first quality criterion as outlined in D3. Subsequent forms retrieved data for the API Gateways that met the quality criteria. The second form captured the company activity information, and the third form compiled the complete list of identified metrics from the selected products.

D6. Grouping Metrics:

Based on their definitions, metrics were grouped into categories according to the classification scheme proposed in [3].

2.1.4. Demonstration

The metrics catalog introduced in this paper contains data retrieved from a real-world scenario, as described in D5. Therefore, this phase involved presenting the artifact and showcasing the final data obtained. Section 3 details this step-in depth.

2.1.5. Evaluation

This step assesses the effectiveness and relevance of the artifact by employing an adapted version of the analytical model proposed by [6]. The collected data was quantified and used to benchmark the API Gateway products by scoring and comparison. Section 4 encompasses the results of this step.

2.1.6. Communication

This paper articulates the findings and insights from developing and evaluating the metrics catalog. This document also discusses implications, identifies gaps, and outlines future research avenues to enhance the present work. Also, the data collected during this was deposited in a publicly available repository.

3. Results

3.1 API Gateway offerings

An initial set of 68 API Gateway products was identified through the comprehensive review of industry reports conducted during the activity D2. Table 1 summarizes the total number of API management vendors and API Gateway products identified in each report. This overview establishes the context of API Gateway offerings and introduces the results that follow.

Table 1.
Summary of API Management Global Reports reviewed in this study.

Report	API Management Vendors	API Gateway Products
API State of the Market (Sep 2024)	71	62
Magic Quadrant for API Management (Oct 2023)	19	19
State of the API (Jun 2023)	20	20

Source: Own elaboration.

Table 2.
API Gateway products included in the catalog development.

Product	Vendor	Since
AWS API Gateway	Amazon	2006
Amplify API Gateway	Axway	2001
API Management & Gateway	Boomi	2000
Gravitee API Gateway	Gravitee.io	2015
IBM API Connect	IBM	2013
Kong API Gateway	Kong	2017
Tyk API Gateway	Tyk	2014
WSO2 API Gateway	WSO2	2005

Source: Own elaboration.

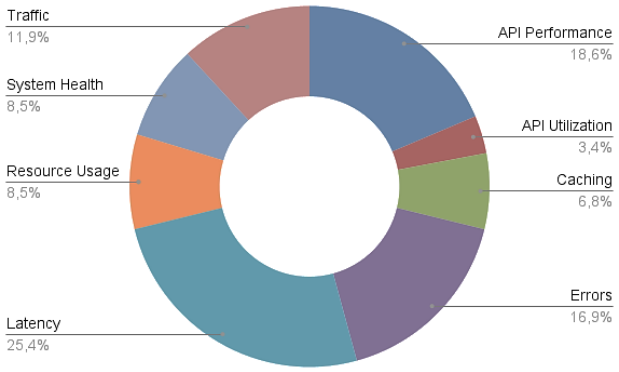

Figure 1. Metrics of the Catalog per each category.
Source: Authors' own data.

After applying the quality criteria described in D3, we selected eight products for developing the catalog since they met all inclusion requirements. Table 2 presents this subset and displays the product name, the vendor's name, and the product version (latest in all cases). The column Since was included to indicate the vendors' experience in the domain, and contains the year in which each company started to develop its first software product line related to API Management or previously-related technologies, such as web services.

3.2 Preliminary metrics catalog

A total of 59 metrics were identified during the analysis. These metrics were grouped according to the criteria outlined in D6. Fig. 1 illustrates the total numbers of metrics identified for each category, while Fig. 2 summarizes the total number of metrics for each API Gateway included in this study.

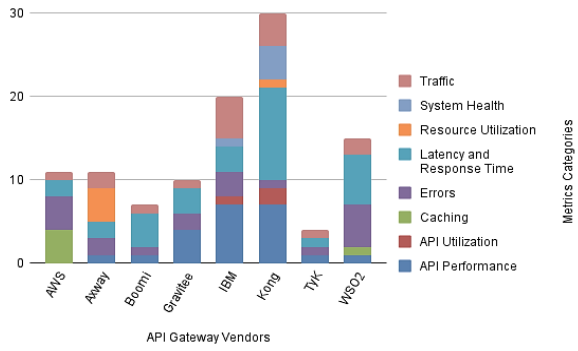

Figure 2. Metrics per each API Gateway.
Source: Authors' own data.

Table 3.
Traffic metrics.

Metric	Gateways
T.1.1 Total APIs Counts all the APIs that are deployed and being managed within the API Gateway.	1
T.1.2 Total number of Products Total number of products available in the API Gateway, which includes collections of APIs and usage plans (e.g. rate-limited plans).	1
T.1.3 Total API Requests Number of incoming requests processed by the API Gateway over a given period.	8
T.2.1 Total data transferred The amount of data that has been transferred through the API Gateway over a given time period. Includes both incoming and outgoing traffic.	2
T.2.2 Total inbound data The total volume of data received by the API Gateway from clients during a specified time period.	2
T.2.3 Total outbound data The total volume of data sent from the API Gateway to clients during a specified time period.	2
T.4.1 Throttling Errors The number of failing requests due to exceeding rate limits or throttling rules set for APIs or subscriptions.	1

Source: Own elaboration.

Next, the metrics are presented to the groupings as described in D6.

3.2.1 Traffic monitoring

Traffic metrics primarily focus on the volume and frequency of requests. These metrics capture the flow and volume of data transmitted through an API or network over a specified period, thus providing insights into user engagement, network activity, and usage patterns. Consequently, traffic metrics help to understand how much data is processed, its source, and its destination. Table 3 synthesizes the identified metrics within this category.

3.2.2 System health

Table 4 depicts the metrics encompassed in this category. System health metrics assess the overall operational status and connectivity of the API Gateway and its dependencies, such as upstream services and back-end databases.

Table 4.
System Health metrics.

Metric	Gateways
SH.1.1 Database Reachability Status A gauge type with a value of 0 or 1, which represents whether the database can be reached by the API Gateway (or not).	1
SH.2.1 Upstream Health Status Reflects the health status of upstream targets.	1
SH.3.1 Active Reading Connections Current number of connections where the Gateway is reading request headers.	1
SH.3.2 Idle Waiting Connections Current number of idle client connections waiting for requests to be processed.	1
SH.3.3 Active Writing Connections Current number of connections where the Gateway is writing responses back to clients.	1

Source: Own elaboration.

Table 5.
Caching metrics.

Metric	Gateways
C.1.1 Total Cache Hits Number of requests that were successfully served from the cache, rather than requiring fresh retrieval from the back-end.	1
C.1.2 Cache Hit Rate % of requests served from the cache compared to the overall total of requests.	2
C.2.1 Total Cache Misses Number of requests that required retrieval from the back-end system (since they could not be served from the cache).	1
C.2.2 Cache Miss Rate % of cache misses compared to the overall total of requests.	1

Source: Own elaboration.

Table 6.
API Utilization metrics.

Metric	Gateways
AU.1.1 Active inbound data The total volume of inbound data currently being processed by the API Gateway. Reflects the real-time data received from clients.	2
AU.1.2 Active outbound data The total volume of data currently being sent from the API Gateway to clients. Reflects the real-time data being transmitted in response to client requests.	1

Source: Own elaboration.

3.2.3 Caching

This category included metrics that evaluate the efficiency and effectiveness of the caching mechanism in the API Gateway, as described in Table 5. These measures reflect the role of caching efficiency and its impact on the system's overall performance. Therefore, they help provide insights into how effectively cached data can improve response times and reduce back-end load.

3.2.4 API utilization

API Utilization metrics are summarized in Table 6. Rather than cumulative or average data over time, the metrics in this category typically provide snapshots of real-time workload and resource usage by the API Gateway.

Table 7.
System Health metrics.

Metric	Gateways
SH.1.1 Database Reachability Status A gauge type with a value of 0 or 1, which represents whether the database can be reached by the API Gateway (or not).	1
SH.2.1 Upstream Health Status Reflects the health status of upstream targets.	1
SH.3.1 Active Reading Connections Current number of connections where the Gateway is reading request headers.	1
SH.3.2 Idle Waiting Connections Current number of idle client connections waiting for requests to be processed.	1
SH.3.3 Active Writing Connections Current number of connections where the Gateway is writing responses back to clients.	1

Source: Own elaboration.

3.2.5 System health

Table 7 depicts the metrics encompassed in this category. System health metrics assess the overall operational status and connectivity of the API Gateway and its dependencies, such as upstream services and back-end databases.

3.2.6 Latency and response time

Latency and Response Time Metrics are summarized in Table 8. These measures evaluate the time taken for an API Gateway to process incoming requests and relay responses, providing insights into the overall efficiency of the API Gateway and its interactions with upstream services. Various aspects can be analyzed, including service-level agreements (SLAs), performance issues, traffic patterns and response behaviors.

3.2.7 Resource utilization

This category focuses on monitoring and assessing how the API Gateway uses the underlying resources, such as compute power and memory, to handle API requests and traffic. It helps ensure that the infrastructure effectively supports API workloads and that resources are not over-utilized or under-utilized. Therefore, these measures provide insights to optimize system performance, resource usage, and scalability. Metrics are summarized in Table 9.

Table 8.
Latency and Response metrics.

Metric	Gateways
RT.1.1 Internal Processing Time (IPT) The total time taken to route a request through the API Gateway and execute all configured plugins.	1
RT.1.2 IPT (90th percentile) IPT measured at the 90th percentile.	1
RT.1.3 IPT (95th percentile) IPT measured at the 95th percentile.	1
RT.1.4 IPT (99th percentile) IPT measured at the 99th percentile.	1
RT.2.1 Total Response Time (TRT) The total time taken from when the API Gateway receives a request to when it returns a response to the client, this including processing time by the API Gateway and upstream services.	6
RT.2.2 Maximum Response Time The peak response time recorded for API calls.	3
RT.2.3 Minimum Response Time. The shortest recorded response time for API calls.	2
RT.2.4 Standard Deviation of Response Time The standard deviation of response times.	1
RT.2.5 TRT (50th Percentile) TRT measured at the 50th percentile.	1
RT.2.6 TRT (90th Percentile) TRT measured at the 90th percentile.	1
RT.2.7 TRT (95th Percentile) TRT measured at the 95th percentile.	5
RT.2.8 TRT (99th Percentile) TRT measured at the 99th percentile.	2
RT.3.1 Upstream Response Time (UpRT) The time taken for the API Gateway to relay a request to the back-end service and receive a response.	4
RT.3.2 UpRT (90th Percentile) UpRT measured at the 90th percentile.	1
RT.3.3 UpRT (95th Percentile) UpRT measured at the 95th percentile.	2

Source: Own elaboration.

Table 9.
Resource Utilization metrics.

Metric	Gateways
RU.1.1 CPU Utilization Percentage % of CPU resources utilized by the API Gateway instance.	1
RU.2.1 Disk Utilization Percentage % of disk space used by the API Gateway instance.	1
RU.3.1 Memory Usage in the Last Hour The average amount of memory utilized by the API Gateway instance over the past hour.	1
RU.3.2 Maximum Memory Utilization The peak memory usage recorded by the API Gateway instance during its operation.	1
RU.3.3 Memory Usage by Node The amount of memory being used by each individual node within a distributed API Gateway architecture.	1

Source: Own elaboration.

3.2.8 API Performance

API performance metrics, documented in Table 10, focus on the efficiency and responsiveness of API responses, aiding in evaluating the API's operational performance. These metrics allow for monitoring the overall reliability of the API service.

3.2.9 Errors

Portrayed in Table 11, the metrics included in this category measure all types of failures and issues that occur during API interactions such as client-side and server-side errors. These metrics help identify issues that may affect user experience or system functionality.

Table 10.
API Performance metrics.

Metric	Gateways
AP.1.1 Informational Response Rate % of responses that fall within the 1xx status coded (informational responses) over all received requests.	2
AP.2.1 Successful Response Rate % of responses that fall within the 2xx status codes (successful responses) over all received requests.	2
AP.2.2 Total Successful Requests Number of API requests that received a successful response, typically indicated by a 2xx status code.	3
AP.3.1 Redirection Response Rate % of responses that fall within the 3xx status codes (redirection responses) over all received requests.	2
AP.4.1 Request Throughput The total number of API requests processed by the API Gateway per unit of time (typically requests per second).	4
AP.5.1 Average inbound data The average volume of data received per specified time unit during a given period.	2
AP.5.2 Maximum inbound data The largest volume of data received in a single specified time unit during a given period.	2
AP.5.3 Minimum inbound data The smallest volume of data received in a single specified time unit during the given period.	2
AP.6.1 Average outbound data The average volume of outbound data (in bytes) sent per specified time unit during a given period.	1
AP.6.2 Maximum outbound data The largest volume of data sent to clients in a single specified time unit during a given period.	1
AP.6.3 Minimum outbound data The smallest volume of data sent to clients in a single specified time unit during a given period.	1

Source: Own elaboration.

Table 11.
Errors metrics.

Metric	Gateways
ER.1.1 Total Error Count Total number of failed API calls (both client and server errors) during a given period.	4
ER.1.2 Overall Error Rate % of failed transactions (including all 4xx and 5xx responses) during a specified time interval.	3
ER.2.1 Client Error Count Total number of client-side errors (4xx responses) logged within a specified period.	1
ER.2.2 Client Error Rate % of client-side errors relative to all responses in a given period.	3
ER.3.1 Server Error Count Total number of server-side errors (5xx responses) recorded in a specified time frame.	1
ER.3.2 Server Error Rate % of server-side errors compared to all responses over a designated period.	3
ER.4.1 Total Other Errors Count of all other error types not classified as client or server errors, including mediation errors and resource-not-found errors.	1
ER.4.2 Exception Count Raw count of transactions completed with an "exception" status.	1
ER.4.3 Total Authentication Errors Total number of authentication-related errors, which includes expired, missing, or invalid credentials.	1
ER.4.4 Total Target Connection Errors Total number of back-end connection errors. Typically includes timeouts and other back-end issues.	1

Source: Own elaboration.

4. Validation

Each metric sourced in this study represents a distinct element of the proposed catalog. Hence, using mutually exclusive set theory, it was possible to quantify the metrics available for each API Gateway product and assign a score, both globally and by category. In this framework, the catalog (C) serves as the universal set of metrics, *Mp* represents the metrics, and the API Gateway's benchmark score (S) is figured by comparing the metrics of the product against the comprehensive set of metrics in the catalog, as illustrated in (1):

$$S = \frac{\sum(M_p)}{\sum(C)} where M_p \in C \quad (1)$$

This quantitative method provides a detailed assessment through both internal and external comparison, yielding an understandable benchmark score. Appraisal schema is outlined as follows: metrics present on the API Gateway are compared to the metrics catalog, with each metric present marked as '1', and each metric missing marked as '0'. Metrics within the same category are summed to generate a category score.

Table 12 displays the scores for each API Gateway. The total of metrics from the universal set was included in row Catalog to facilitate comparison.

Table 12.
API Gateway metric raw scores (total of metrics).

API Gateway	Product Raw Benchmark Score (S)
AWS API Gateway	11
Amplify API Gateway	11
API Management & Gateway	7
Gravitee API Gateway	10
IBM API Connect	20
Kong API Gateway	30
Tyk API Gateway	4
WSO2 API Gateway	15
Catalog	59

Source: Own elaboration.

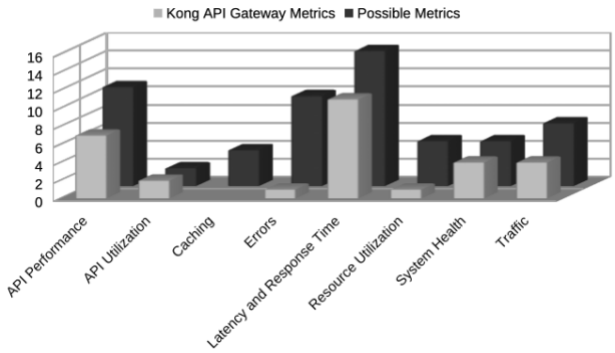

Figure 3. Comparison between Kong API Gateway metrics and the catalog. Source: Authors' own data.

To further facilitate a comprehensive visual comparison, Fig. 3 presents the raw score achieved by Kong API Gateway alongside the catalog of metrics. In the three-dimensional space, the front gray category score for all metrics in the API Gateway can be visually benchmarked against the darker catalog of metrics for each category, highlighting key gaps. This approach can similarly be applied to the overall API Gateway score (*S*).

The relative contribution of a category, derived from its metrics, is characterized by the maximum number of metrics present within that category, with '10' used to standardize the metrics into a comparable subset solution. As a result, a normalization function is implemented as follows (2):

$$F_j = \frac{10}{x_j} \sum_{i=1}^{x_j} c_{ij} \quad (2)$$

In order to compare different products, category scores were collated into a product level (P_{jk}) normalized benchmark score (3), derived with (x_{jk}) as the maximum number of metrics present in each category *j* of the API Gateway (*k*) and y_k as the maximum number of metrics in this API Gateway.

$$P_{jk} = \sum_{j=1}^{y_k} \frac{10}{x_{jk}} \sum_{i=1}^{x_{jk}} c_{ijk} \quad (3)$$

Table 13.
API Gateway metric normalized scores.

API Gateway	Product normalized benchmark score (P)
AWS API Gateway	16,76
Amplify API Gateway	15,10
API Management & Gateway	6,00
Gravitee API Gateway	9,06
IBM API Connect	25,51
Kong API Gateway	40,41
Tyk API Gateway	4,00
WSO2 API Gateway	15,27

Source: Own elaboration.

Table 13 displays the product level normalized scores of each API Gateways. The values within the table indicate the normalized benchmark score for each product.

5. Discussion

The field of API management remains underexplored in scientific research. In [10], a systematic literature review was performed to identify practices and capabilities in API Management. The authors compiled 24 unique definitions, along with 114 practices and 39 capabilities. A recent systematic mapping study [5] highlights a limited body of work, primarily focusing on a small set of quality attributes assessed using benchmarking tools. In terms of Web API quality modeling, several authors have made contributions. [11] proposed a maturity model for API management from an organizational perspective, while [12] introduced a quality model with three attributes and their quantitative evaluation in real-world applications. Additionally, [13] presented a GQM-based catalog of metrics to assess API usability. Despite these contributions, there remains a significant gap in research on software quality within the domain of API management. This gap motivated the development of our study, which aims to create an integrated framework to characterize, measure, assess, and improve the product quality.

There exist several systematic literature reviews and mappings that study different aspects of API lifecycle. These works provide valuable perspectives by exploring various aspects of API Management and API quality, such as documentation [14-16], usability [17-19], security vulnerabilities [20], architectural patterns [21], API evolution [22], and API research [23].

The outcomes of this study demonstrate that API Gateway tools provide metrics that align with several established methods related to system monitoring. These methods offer a comprehensive perspective on system reliability and responsiveness. For instance, the Utilization-Saturation-Errors (USE) method [9] and the Four Golden Signals [8] are designed to monitor the performance and health of APIs by defining metrics that identify performance issues, including systemic bottlenecks concerning utilization, saturation, errors, latency, response time, and traffic. In this context, our findings indicate that Errors, Latency, Response Time, and Traffic are prominently addressed features among the various API Gateway offerings analyzed in this study. However, metrics related to saturation were absent from the compiled data. Saturation is a critical concern that encompasses various aspects linked to Service Level Agreements (SLAs) and influences the business objectives of both software vendors and users. This void suggests a development opportunity for vendors to focus on developing saturation-based strategies to enhance their products.

In alignment with the previous findings, most of the tools examined also provided metrics in the category of API Performance. On the other hand, API Utilization, Caching, Resource Utilization, and System Health metrics were notably scarce. This disparity suggests that vendors prioritize specific aspects of API Management over others, potentially missing relevant features that could enhance overall product effectiveness. Addressing these gaps could lead to more robust API management solutions and better alignment with user needs and expectations.

The quantitative analysis method developed in this work revealed that Kong achieved the highest product normalized score, while Tyk, Boomi, and Gravitee.io presented the lowest scores. However, this disparity is not definitive enough to determine which product is inherently "better" than others. In this sense, this work presents two implications. On the one hand, low product scores may signify the absence of metrics that may add significant business value if addressed; for instance, caching may be a critical factor under different scenarios, although most products did not specify any metrics in this domain. On the other hand, examining high product scores against industry benchmarks can be crucial to confirm the appropriateness of each metric.

In validating our work, we employed a quantitative analysis method that effectively corroborated the catalog of metrics we developed. This method was theoretically grounded, as it integrated a mutually exclusive set theory with the four principles of causation theory, following the framework established in [6]. To further enhance the robustness of our findings, we meticulously reviewed three industry reports, minimizing the risk of bias and ensuring a well-rounded perspective on market offerings. Additionally, we exclusively relied on official sources of technical documentation, which helped guarantee the accuracy of the compiled data. Together, these approaches contribute to the overall validity and reliability of our study's conclusions.

6. Conclusions and future work

In this paper, we systematically analyzed 68 API Gateway offerings and developed a comprehensive catalog of 59 metrics using the DSR approach. These metrics were categorized based on existing literature, providing a structured set-theory framework. To validate this catalog, we implemented a quantitative analysis method that involved scoring and comparing a final set of eight products. Our findings indicate that current tools focus on critical aspects such as latency, response time, API performance, error capturing, and traffic monitoring. However, we also observed that other important factors - such as caching, saturation, and overall system health - are scarcely addressed in these applications. This disparity highlights potential gaps

in the current API Gateway landscape.

In this paper, we systematically analyzed 68 API Gateway offerings and developed a comprehensive catalog of 59 metrics using the DSR approach. These metrics were categorized based on existing literature, providing a structured set-theory framework that organizations can use to guide the evaluation and selection of API Gateway tools. To validate this catalog, we implemented a quantitative analysis method involving the scoring and comparison of a final set of eight products, demonstrating the practical applicability of our framework in real-world assessments.

Practical implications: Our findings indicate that current tools primarily focus on critical aspects such as latency, response time, API performance, error capturing, and traffic monitoring — factors that are essential for ensuring baseline operational quality. However, we also observed that other important aspects — such as caching mechanisms, saturation management, and comprehensive system health monitoring — are seldom addressed. This disparity highlights actionable gaps in the current API Gateway landscape, signaling areas where tool providers can innovate and improve. Consequently, this work serves as a guide for both adopters and developers aiming to enhance API infrastructure resilience and effectiveness. Finally, this work also offers a practical benchmarking methodology that can be adopted in other software quality domains, such as performance evaluation of service meshes, observability platforms, or other infrastructure-level tools. By providing a replicable and structured approach, the methodology supports broader efforts to assess, compare, and improve software quality across diverse technological contexts.

As with any study, this work has limitations that can guide future research in various directions. a) The primary source for consultation and analysis was the technical documentation of each tool, which may have concealed unidentified metrics. Future research could enhance this by exploring deployed tools to validate the provided metrics. b) Employing different research techniques to uncover black-box metrics could yield valuable insights into the current research. c) While metrics focus on the quantitative dimension of software quality, future efforts might expand this catalog into a tailored quality model, creating a flexible and robust framework that encompasses conceptual, operational, and quantitative levels of software quality. d) Furthermore, externally validating the developed artifacts through techniques such as surveys with practitioners and expert judgment could strengthen the findings of this research. e) Finally, as a flexible framework, this work could be broadened to include API management platforms, providing a more comprehensive understanding of the API ecosystem and its management practices.

References

[1] Duan, Y., et al. Everything as a service (XaaS) on the cloud: origins, current and future trends. En 2015 IEEE 8th International Conference on Cloud Computing. IEEE, 2015. p. 621-628.

[2] Gamez-Diaz, A, Fernandez, P., and Ruiz-Cortes, A. An analysis of RESTful APIs offerings in the industry. International Conference on Service-Oriented Computing. Cham: Springer International Publishing, 2017. pp. 589-604.

[3] De, B. API Management: An Architect's Guide to Developing and Managing APIs for Your Organization. Apress Berkeley, 2023.

[4] Preibisch, S. API Development: a practical guide for business implementation success. New York: Springer Science+Business Media, 2018.

[5] dos Santos, E. and Casas, S., Unveiling quality in API management: A systematic mapping study. Proceedings of L Latin American Computer Conference, (CLEI), 2024, pp 1-10.

[6] Cassidy, L. and Hamilton, J. design science research approach to website benchmarking, Benchmarking: An International Journal 23(5), pp. 1054-1075, 2016. DOI: https://doi.org/10.1108/BIJ-07-2014-0064

[7] Peffers, K., et al. design science research methodology for information systems research, Journal of Management Information Systems, 24(3), pp. 45-77, 2007. DOI: https://doi.org/10.2753/MIS0742-1222240302

[8] Beyer, B., et al. Site reliability engineering: How Google runs production systems. Sebastopol: O'Reilly Media, Inc., 2016.

[9] Gregg, B. Thinking methodically about performance, Communication of the ACM, 56 (2), pp. 45-51, 2013. DOI: https://doi.org/10.1145/2408776.2408791

[10] Mathijssen, M., Overeem, M., and Jansen, S. Identification of practices and capabilities in API management: a systematic literature review. arXiv preprint, 2020. DOI: https://doi.org/10.48550/arXiv.2006.10481

[11] Overeem, M., Mathijssen, M., and Jansen, S. API-m-FAMM: A focus area maturity model for API Management, Information and Software Technology, 147, 2022. DOI: https://doi.org/10.1016/j.infsof.2015.03.007

[12] Yamamoto, R., et al, A quality model and its quantitative evaluation method for web APIs. Proceedings of 5th Asia-Pacific Software Engineering Conference (APSEC), 2018. pp. 598-607. DOI: https://doi.org/10.1109/APSEC.2018.00075

[13] Machini, A. and Casas, S., A preliminary GQM model to evaluate web API usability, Proceedings of Jornadas Argentinas de Informática (JAIIO), 2024. pp 1-13.

[14] Nybom, K., Ashraf, A. and Porres, I., Systematic Mapping Study on API Documentation Generation Approaches. 44th Euromicro Conference on Software Engineering and Advanced Applications (SEAA), IEEE, Prague, 2018. pp 462–469. DOI: https://doi.org/10.1109/SEAA.2018.00081

[15] Casas, S., et al, Uses and applications of the OpenAPI/Swagger specification: a systematic mapping of the literature. 40th International Conference of the Chilean Computer Science Society (SCCC), IEEE, La Serena, Chile, 2021. pp 1–8, DOI: https://doi.org/10.1109/SCCC54552.2021.9650408

[16] Cummaudo, A., Vasa, R. and Grundy, J. What should I document? A preliminary systematic mapping study into API documentation knowledge. ACM/IEEE International Symposium on Empirical Software Engineering and Measurement (ESEM). IEEE, Porto de Galinhas, 2019. pp 1–6, DOI: https://doi.org/10.1109/ESEM.2019.8870148

[17] Mosqueira-Rey, E., et al. A systematic approach to API usability: Taxonomy-derived criteria and a case study, Information and Software Technology, 97, pp. 46-63, 2018. DOI: https://doi.org/10.1016/j.infsof.2017.12.010

[18] Rauf, I., Troubitsyna, E. and Porres, I. A systematic mapping study of API usability evaluation methods, Computer Science Review, 33, pp. 49-68, 2019. DOI: https://doi.org/10.1016/j.cosrev.2019.05.001

[19] Burns, C. et al, Usable results from the field of API usability: A systematic mapping and further analysis. 2012 IEEE Symposium on Visual Languages and Human-Centric Computing (VL/HCC), IEEE, Innsbruck, 2012, pp 179–182, DOI: https://doi.org/10.1109/VLHCC.2012.6344511

[20] Diaz-Rojas, J. A., et al, Web API Security Vulnerabilities and Mitigation Mechanisms: A Systematic Mapping Study. 9th International Conference in Software Engineering Research and Innovation (CONISOFT), IEEE, San Diego, CA, USA, 2021. pp 207–218, DOI: https://doi.org/10.1109/CONISOFT52520.2021.00036

[21] Taibi, D., Lenarduzzi, V. and Pahl, C., Architectural Patterns for Microservices: A Systematic Mapping Study, Proceedings of the 8th International Conference on Cloud Computing and Services Science - (CLOSER), 2018. INSTICC. SciTePress, Funchal, pp 221–232, DOI: https://doi.org/10.5220/0006798302210232

[22] Koci, R., et al, Classification of Changes in API Evolution. IEEE 23rd International Enterprise Distributed Object Computing Conference (EDOC). IEEE, Paris, France, 2019. pp 243–249, DOI: https://doi.org/10.1109/EDOC.2019.00037

[23] Ofoeda, J., Boateng, R. and Effah, J. Application Programming Interface (API) Research: A Review of the Past to Inform the Future, International

Journal of Enterprise Information Systems, 15(3), pp. 76-95, 2019. DOI: https://doi.org/10.4018/IJEIS.2019070105

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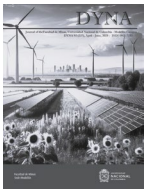

UNIVERSIDAD NACIONAL DE COLOMBIA

Challenges and opportunities of urban mobility in Latin America: strategies toward sustainable development

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Abstract
Urban mobility in Latin America is a relevant area of research because of the negative effects of vehicular pollution on human health and the environment. In recent years, mobility patterns have shifted globally as a result of technological advancements and growing environmental awareness. Accordingly, this study aims to identify emerging trends in sustainable urban mobility in the region through bibliometric analysis, text mining, and content analysis. The findings indicate that early studies primarily focused on transport development, congestion, and pollution. However, more recent research has incorporated sustainable approaches, emphasizing public transportation, the use of electric vehicles, and their connection to social inclusion, particularly among low-income workers. Additionally, the COVID-19 pandemic had a notable impact by promoting the creation of bicycle lanes and the expansion of sidewalks to facilitate social distancing, thereby reshaping urban dynamics in several Latin American cities.

Keywords: sustainable mobility; urban mobility; urban transport; sustainable development; climate change.

Desafíos y oportunidades de la movilidad urbana en América Latina: estrategias hacia el desarrollo sostenible

Resumen
La movilidad urbana en América Latina es un campo de investigación relevante debido a los efectos negativos de la contaminación vehicular sobre la salud y el medio ambiente. En los últimos años, los patrones de movilidad han cambiado globalmente por avances tecnológicos y una mayor conciencia ambiental. Por ello, esta investigación busca identificar tendencias emergentes en movilidad urbana sostenible en la región, utilizando análisis bibliométrico, minería de texto y análisis de contenido. Los hallazgos muestran que los estudios iniciales se enfocaban en el desarrollo del transporte, la congestión y la contaminación. No obstante, investigaciones recientes incorporan enfoques sostenibles, destacando el transporte público, el uso de vehículos eléctricos y su relación con la inclusión social, especialmente entre trabajadores de bajos ingresos. Además, la pandemia de COVID-19 influyó notablemente, promoviendo la creación de carriles para bicicletas y la ampliación de aceras para facilitar el distanciamiento social, transformando así la dinámica urbana en varias ciudades latinoamericanas.

Palabras clave: movilidad sostenible; movilidad urbana; transporte urbano; desarrollo sostenible; cambio climático.

1. Introduction

Mobility patterns have changed significantly each year worldwide due to continuous improvements in transportation technologies and growing environmental awareness regarding the protection of the planet. Urban mobility is one of the primary challenges that contemporary cities must confront. It is crucial to recognize that mobility is essential for economic, cultural development, and knowledge management in both developed and developing countries, and Latin American countries are not immune to these challenges [1].

The need to promote sustainability and sustainable mobility in Latin America has been widely acknowledged by the Economic Commission for Latin America and the Caribbean, which has conducted comprehensive analyses

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and generated valuable reports on the subject over the past 15 years to raise public awareness about the importance of sustainable mobility [2]. Urban transportation planning and the promotion of environmentally friendly transport modes have been highlighted in the reviewed literature as tools for developing more coordinated transportation policies and advancing sustainable urban development, with sustainable mobility being a fundamental requirement [3].

This study aims to identify influential actors who have played a decisive role in the evolution of urban and sustainable mobility in Latin America. Additionally, it seeks to identify new thematic trends and patterns in urban mobility, as well as to explore new mobility alternatives, such as the use of bicycles and electric vehicles, to counteract high levels of air pollution. Overall, this research examined the development of the literature on sustainable urban mobility in Latin America and identified emerging trends and potential future directions in this field.

2. Methodology

To examine the existing literature on sustainable mobility in Latin America, this research adopted a mixed-methods approach that combined quantitative and qualitative analyses, focusing on a literature review [4]. The following sections describe the steps taken, search strategies employed, and data analysis techniques.

2.1 Search strategy and selection criteria

The research focused on identifying original articles, review papers, and conference proceedings related to sustainable urban mobility in Latin America, published between 2005 and May 2025. Keywords such as “urban mobility”, “sustainable mobility”, and “Latin America”, including the countries within the region, were used for document retrieval and selection. Although the research did not restrict its search to any specific language, it was observed that 78.5% of the 438 documents were written in English, 20% in Spanish, and 5.7% in Portuguese.

2.2 Data processing and analysis

This research employed three data analysis techniques along with statistical analyses to explore the evolution of the research field related to sustainable mobility in Latin America. The methodology includes bibliometric analysis, text mining, and content analysis.

This study used a bibliometric analysis approach involving mathematical tools to investigate research perspectives in terms of trends and research sources. The statistical examination of articles, documents, authors, institutions, and countries plays a crucial role in quickly understanding the evolution of the literature over time. Additionally, citation analysis can reveal critical details about the literature and influential researchers, facilitating comprehension of research perspectives and trends within a specific knowledge area [5].

According to Yu et al. [6], bibliometric analysis aids in detecting internal relationships in the literature and identifying central citations and key knowledge clusters. Consequently, a bibliometric analysis of the literature from Scopus on sustainable mobility in Latin America was conducted to determine the detailed characteristics of the literature and identify research trends and innovative perspectives.

Text mining, which is defined as the process of extracting relevant information from a set of documents, was employed to explore text patterns and semantic structures that better explain complex data [6,7]. Similarly, content analysis was used as a qualitative method to provide additional detailed insights regarding the quantitative findings and to identify the most influential published documents in the field of sustainable mobility in Latin America, aiming to uncover common patterns.

This research employed two software tools for data analysis. For the bibliometric and scientometric analysis, Bibliometrix was used—an essential tool for simultaneously analyzing and mapping bibliographic data [8]. Similarly, VOSviewer was utilized to construct network maps and visually explore different perspectives, thereby simplifying the interpretation of the bibliometric analysis results. [9].

3. Results

3.1 Evolution of the literature over time

This research explored the literature by analyzing articles published between 2005 and May 2025, identifying influential authors, representative countries, and relevant journals, resulting in 438 documents. The evolution of scientific output on urban and sustainable mobility is presented in Fig. 1. It was noted that before 2005, only four documents were found that lacked relevant information for the analysis or were not directly related to the research topic, leading to their exclusion.

The results indicate a significant increase in the number of articles published in the last five years, representing more than 70% of the total. 2023 had the highest number of articles published, with a total of 71 documents. In terms of citations, 2024 had the highest number, with a total of 1,124. This suggests a correlation between the number of citations and the number of articles published during the period 2019 to

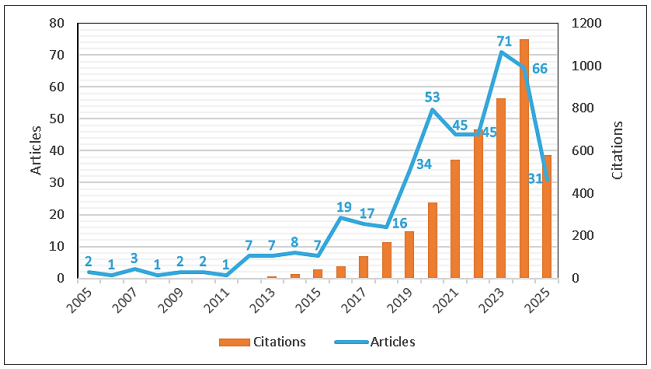

Figure 1. Evolution of literary production and scientific citations.
Source: Own elaboration based on Scopus and WoS data.

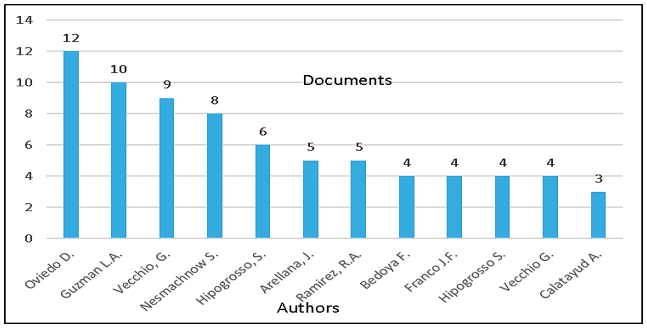

Figure 2. Influential researchers.
Source: Own elaboration based on Scopus and WoS data.

2024. Based on this trend, it can be inferred that the field of urban and sustainable mobility in Latin America will continue to expand in the coming years, increasing the number of researchers interested in the topic.

3.2 Influential researchers

During the period 2005 to 2025, twelve influential researchers who produced quality articles on urban and sustainable mobility in Latin America were identified. The most influential author was Oviedo Daniel Ricardo from University College London in the United Kingdom, with twelve publications indexed in Scopus; in second place was Guzman LA from the Universidad de los Andes in Colombia, with ten publications; in third place was Vecchio Giovanni from Pontificia Universidad Católica de Chile, with nine indexed publications in Scopus in the field of research. The most influential researchers are shown in Fig. 2.

3.3 Influential institutions

This research identified the ten most influential institutions based on the first author's affiliation data. The Pontificia Universidad Católica de Chile has 25 articles with lead authors. Likewise, Universidad de los Andes in Colombia has 19 articles related to research on urban and sustainable mobility in Latin America. Curiously, among the 10 most relevant institutions is University College London, which has 18 publications. It can also be said that of the ten most influential institutions shown in Fig. 90% of them are in Latin America; which indicates great interest in this field of research.

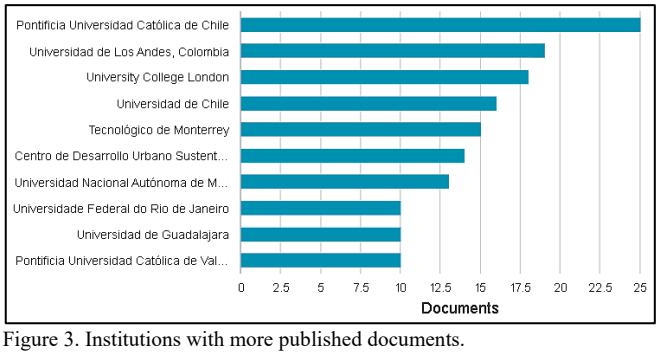

Figure 3. Institutions with more published documents.
Source: Own elaboration based on Scopus and WoS data.

3.4 Influential countries

By 2025, 45 countries were identified with published articles related to urban and sustainable mobility in Latin America. Figure 4 shows the 10 countries with the highest number of publications. Among them, Mexico and Chile occupy first and second place, respectively, with 90 and 76 publications, respectively. Additionally, Colombia, Brazil, Spain, and Ecuador are among the top five countries. Notably, countries in Latin America without publications in this area include Guatemala, Cuba, Venezuela, and Nicaragua. Additionally, the results indicate that 3 articles from the sample have an undefined country affiliation.

3.5 Analysis of research areas

This research identified several domains within the field of urban and sustainable mobility in Latin America through keyword cluster analysis. Keywords serve as a primary representation of the information contained in an article, allowing for an understanding of the scope of the research topic through analysis. Specifically, the VOSviewer software was used to examine keywords in the 438 selected articles. The main keywords were chosen based on a threshold of eight occurrences, resulting in 79 relevant keywords from an initial count of 1,390. However, not all keywords were related to the study topic, leading to refinement that yielded 40 relevant keywords.

Following this analysis, it was observed that the keywords "urban mobility", "sustainable mobility", and "mobility" occurred 133, 70, and 60 times, respectively. The results are presented in Fig. 5 reveal the identification of five different keyword clusters in the 438 documents analyzed. The clusters related to urban and sustainable mobility research in Latin America are identified as "urban mobility", "sustainable mobility", "sustainability", "accessibility", and "urban transport". Furthermore, a strong interdependence among several research clusters was observed. For example, the red cluster represents sustainable mobility and includes keywords such as "electromobility", "climate change", electric vehicles "greenhouse gases", among others.

The first cluster (blue) could be termed sustainable urban transport, as it primarily includes keywords such as public transportation, bicycles, and traffic congestion. The third cluster, identified in green, focuses on mobility and sustainability and includes terms such as transportation policy, cycle transport, accessibility, and COVID-19. A strong relationship and dependency between this cluster and others was noted.

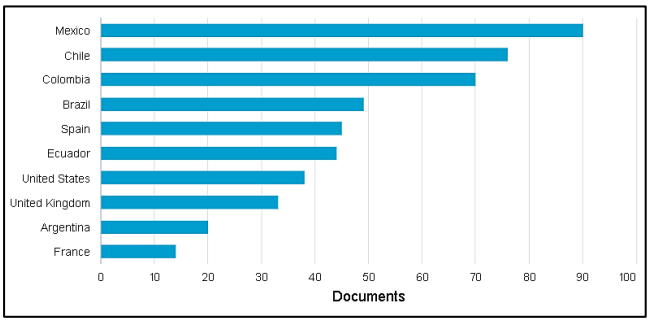

Figure 4. Countries with the most published documents.
Source: Own elaboration based on Scopus and WoS data.

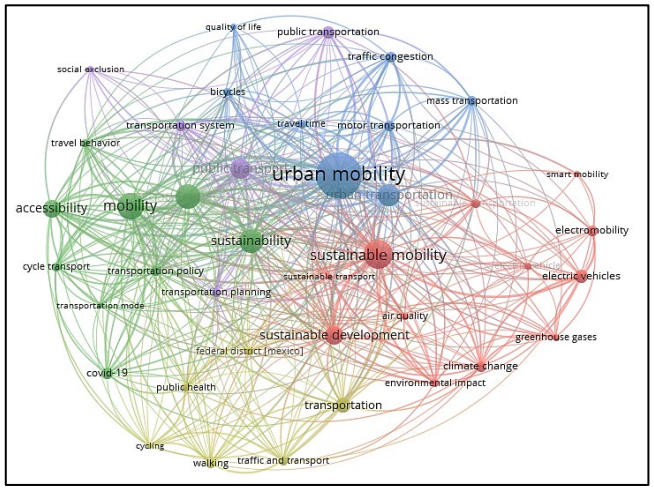

Figure 5. Visualization Map of Thematic Keyword Clusters.
Source: Own elaboration using VOSviewer software.

Although cycling, walking, public health, traffic and transport (yellow) clusters have a lesser representation, they also play a crucial role in the context of urban and sustainable mobility. Additionally, the results indicate that the impacts generated by mobility on transport users in recent years are directly related to human behavior and quality of life in terms of health.

Fig. 6 presents the chronology and trends of various research topics from 2005 to 2025. It is evident that before 2010, terms such as "Sustainable mobility", "Electric vehicles", and "Electromobility" had low annual frequencies. However, by 2011, researchers had begun to explore the interrelationships among urban mobility, climate change, and traffic congestion.

Overall, there has been a notable increase in the significance of research on sustainable mobility in Latin America, particularly over the last decade. Initially, studies focused on the development of public transport, traffic congestion, and air pollution caused by buses, motorcycles and other vehicles. By 2019, concepts such as sustainable urban transportation, urban mobility, electric vehicles, and sustainable development began to gain traction in research. Similarly, from 2021, researchers began investigating new mobility patterns, especially those related to the COVID-19 pandemic and the lockdown measures imposed by authorities to curb the virus's spread [10].

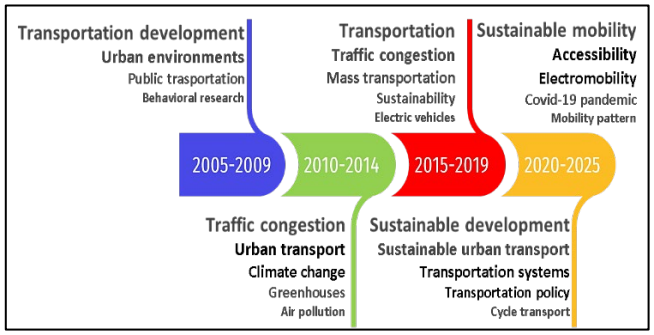

Figure 6. Chronology and thematic trends.
Source: Own elaboration.

4. Discussion

4.1 Summary of the Literature

Initially, the literature on urban mobility focused on transportation development and traffic control, exploring topics such as the urban environment, information technology, user behavior, bus and vehicle transport, traffic congestion, and accidents. Over time, the focus has expanded to include urban mobility and the concept of sustainable development, as well as environmental issues like air pollution from combustion emissions, which are associated with approximately 200,000 premature deaths annually [10]. In the last two years, the literature has also addressed the impact of COVID-19 on public transportation and its transmission.

Sustainable mobility and its related factors have gained importance over the last decade, becoming a relevant topic for current governments seeking to mitigate the negative effects of individual motorization, such as traffic accidents. It is estimated that by 2030, traffic accidents will be the fifth leading cause of death globally [11]. Additionally, the literature indicates that the trend of mobility in Latin America is generally unsustainable [12], which is why bicycles and electric bicycles have emerged as an economic mobility alternative for both users and cargo transport, significantly improving aspects such as well-being, health, quality of life, and job opportunities [13,14].

According to the results of a study conducted by Hipogrosso S. and Nesmachnow S. in Montevideo in 2020 on the use of three sustainable transportation modes—electric buses, public bicycles, and electric scooters—through quantitative and qualitative indicators of sustainable mobility, the coverage area of these initiatives is limited, leaving a large part of the population without access to these transportation modes [15]. Public bicycles are the most affordable option, followed by electric buses due to public subsidies. Electric scooters are priced too high, making them inaccessible for low-income individuals. Public bicycles were the fastest and most environmentally friendly option for both short (less than 5 km) and long distances, although they showed deficiencies in terms of comfort. Additionally, although these modes offer intermodal connectivity among themselves, they lack effective integration, largely due to insufficient infrastructure (such as bike lanes, parking facilities, and showers at workplaces), which discourages their use [15].

Given sustainability challenges, the literature also notes the rise of bike-sharing systems in several Latin American cities as an attractive and sustainable travel option [16], with positive effects on reducing traffic congestion and emissions in large metropolitan areas [17]. To address these themes, the study grouped the literature into three categories: transport and social exclusion; urban mobility and its related factors during the COVID-19 pandemic; and urban transport and the synergies between the environment and health.

4.2 Transport and social inclusion

In recent years, several cities in Latin America have developed and implemented public transportation projects, such as bus rapid transit (BRT) lines in Bogotá, cable cars,

and rail systems in Lima, aimed at reducing accessibility disparities between low-income communities and other urban areas [18]. Despite these efforts, research indicates that these investments have not always effectively improved accessibility and have failed to alleviate inequalities related to public transportation. Research conducted in various Colombian cities has shown a direct relationship between access to transportation and social inclusion, especially for domestic workers who primarily rely on public transport due to their identity, gender, and low incomes [19]; Also, according to Rodríguez et al, bicycle-sharing systems in Santander (Spain) and Cartagena (Colombia) offer an efficient urban mobility solution for young women by reducing traffic congestion and improving health [20].

On the other hand, according to Montoya Robledo and Escovar Álvarez, "some studies in Latin American cities reveal that women feel safer using bicycles than walking or using public transport at night" [21] (p. 401). A study conducted by Rivero et al. in the city of Bahía Blanca (Argentina) revealed that active mobility is primarily used by men, city center residents, bicycle users, and people without cars for short leisure trips, while public transport is preferred by women, students, workers, and young people for longer, less frequent trips [22].

The criteria defining transportation systems in Latin America have evolved in recent years, shifting from a focus on speed and reduced travel times to emphasizing reliability, environmental impact, accessibility, and social equity. This change, illustrated by examples in European countries like France's LOTI Transport Act (1982) and policies from the United Kingdom's Department for Transport, incorporates accessibility as an essential element of affordable, high-quality mobility. Major cities in Latin America and other regions follow this trend, including equity and social inclusion in transportation planning [23]. However, many Latin American cities lack specific and robust tools to assess how transport projects impact accessibility and social inclusion, especially for poorer and more disadvantaged populations.

Similarly, the literature has developed several survey methods to investigate associations between cultural habits and inclusive means of transport used by populations, as seen in Barranquilla, Colombia. Research by Reniz Acosta et al. [24] highlighted the need to implement programs that encourage the use of inclusive transportation options, such as bicycles, while ensuring the necessary infrastructure and safety for active population participation in daily mobility. Coello- Salcedo et al. [25] comparatively analyzed the perceptions and operating parameters of mechanical and electric bicycles in the city of Cuenca, Ecuador. The results showed that electric bicycles were rated more highly by users, highlighting the greater enjoyment of the ride and their widespread recommendation, supported by better speed and acceleration data.

Lastly, the rapid urban expansion in cities such as Bogotá and Cali in Colombia, combined with informal peripheral urbanization and a centralized labor market, has affected the mobility of both high- and low-income residents alike [26]. In South American countries, transportation planning must address infrastructure deficits and connectivity gaps while reducing social, spatial, economic, and environmental inequalities [18,23]. The findings highlight the need to implement transportation policies that promote equitable access to enable social and economic participation, in line with the Sustainable Development Goals (SDGs); especially as part of the SDG 11 targets "sustainable cities and communities" and the United Nations New Urban Agenda on access to transportation for low-income populations. The capabilities approach, focused on individuals' freedom to pursue valuable opportunities, offers a useful perspective to address sustainable mobility challenges, as access to transportation enhances material assets, social connections, and opportunities, supporting broader human and social capital beyond work and education [18]. In Latin America, such access is a central objective of urban mobility policies in pursuit of sustainability.

4.3 Urban mobility and its related factors during the COVID-19 pandemic

According to the literature, the COVID-19 pandemic has significantly impacted mobility, especially in public transport, due to the risk of contagion and social distancing measures implemented by authorities [27]. Following the World Health Organization's declaration of COVID-19 as a pandemic on March 11, 2020, many governments adopted drastic measures to slow the virus's spread, including restrictions on urban mobility and public space closures [28]. These measures resulted in changes in travel behavior, and Latin America was no exception to this trend.

The necessity for physical distancing during the COVID-19 pandemic has impacted sustainable mobility initiatives. Cities in Europe and Latin America have implemented temporary changes in public spaces, such as creating bike lanes and widening sidewalks to facilitate mobility while ensuring physical distance [29]. Additionally, there has been a shift in people's inclination toward walking in urban green spaces, distancing them from crowded locations [30].

Overall, the reviewed literature indicates that most articles related to COVID-19 focused on restrictions on people's mobility and their relationship to decreasing virus transmission cases after authorities implemented health measures in Latin American cities [31].

4.4 Urban transport and the synergies between environmental and health

One of the most researched topics regarding sustainable urban mobility in Latin America relates to air pollution, which has become a critical concern in cities and leads to numerous deaths each year [32]. According to the World Health Organization (WHO), approximately 99% of the global population breathes air that exceeds quality limits, with developing countries facing the harshest exposures. Both ambient and household air pollution are responsible for approximately 7 million deaths annually [33].

Ochoa-Covarrubias et al. (2021) stated that air pollution is caused by the presence of particulate matter and gases that pose risks to human health and other living organisms [32]. The WHO identifies particulate matter (PM), carbon

monoxide (CO), carbon dioxide (CO_2), ozone (O_3), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) as the most concerning pollutants for public health [33].

In 2023, Bedoya-Maya et al. reported that "road traffic is one of the critical contributors to high levels of CO_2 and NO_2 in the air" [11] (p. 1). The literature maintains that these pollution levels are linked to health issues primarily affecting the lungs, larynx, pharynx, and eyes [11]. According to Higgins et al. [34], this type of pollution is significant in large urban centers, and it is driven by the increasing number of vehicles on the streets, which increases traffic congestion and pollution.

According to the United Nations Human Settlements Programme, Latin America and the Caribbean are the most urbanized regions in the world, with about 80% of its population concentrated in cities [35]. If this growth trend continues, by 2025, approximately 100 million people will reside in just six megacities [36]. Research by Grassi et al. [37] found that urban traffic has adversely affected the environment and human health in populated areas, with around 80% of atmospheric pollutants coming from mobile sources. Other authors, such as Huerta and Fuentes [38], have identified additional factors associated with urban mobility in a study conducted with users of the Metrobús in Mexico City. They found that certain aspects, such as travel time, crowding during peak hours, and comfort, significantly influenced the quality of life for those using public transportation to commute to work.

In 2024, Quezada et al. showed how women in Santiago, Chile engage with electric mobility in the context of carbon neutrality and the importance of inclusive policies to reduce inequalities and improve environment with electric the mobility [39].

Lastly, some authors express concern over the disposal and recycling of end-of-life vehicles (ELVs), as these vehicles are considered a significant category of hazardous waste. They pointed out that poor management of ELVs contributes to various environmental issues, including groundwater contamination and soil pollution by heavy metals [5,40].

4.5 Considering electric and hybrid vehicles as sustainable mobility alternatives

Electric and hybrid vehicles have emerged as key factors in combating climate change [41]. However, their high purchase prices have created social inequities, leaving many communities excluded from public policy promoting green economies and climate change mitigation [42,43]. Lastly, the literature indicates persistent mobility differences between gender and socioeconomic groups, which are influenced by the economic landscape of cities and the spatial distribution of job opportunities and salaries [44].

5. Future trends and research directions

Urban and sustainable mobility in Latin America encompasses various facets involving different components throughout the mobility process. Strengthening and promoting environmentally friendly mobility systems has become a primary concern for Latin American governments and researchers alike. Researchers are advocating for and investigating new transportation alternatives to address air pollution, particularly diesel- and gasoline-powered vehicles.

Electric vehicles are emerging as a significant alternative for both public and private transport, helping to reduce pollution levels in urban areas. Literature indicates that bicycles also play a crucial role in mobility across several Latin American cities, serving as an entirely eco-friendly mode of transport for short to medium distances without emitting harmful gases.

In the future, the quest for new mobility alternatives is likely to inspire researchers to raise awareness among citizens about adopting innovative transportation methods and technologies that minimize greenhouse gas emissions. The authors will also highlight the health and environmental detriment of fossil fuel-based vehicles, thereby discouraging their use and promoting more sustainable and economical alternatives. This direction presents a promising avenue for future research, particularly in the context of combating climate change.

It is essential to review literature from not only Latin America but also from countries such as the United States, the United Kingdom, and various European nations. Such comparisons can guide future researchers toward identifying potential directions for urban and sustainable mobility research. Furthermore, there is a clear lack of public management from governments to support new transportation systems in populated areas; thus, governments should encourage and promote mobility alternatives that target global warming.

The recent COVID-19 pandemic undoubtedly triggered significant changes in urban-transport modes and models, prompting many individuals and organizations to seek and adopt new mobility alternatives, particularly through increased bicycle and electric motorcycle use. These shifts present shared benefits for health and environmental mobility in urban centers, warranting thorough investigation in future studies. Several researchers have already begun discussing new lessons in mobility during pandemic situations and the transition toward safer, more environmentally sustainable mobility alternatives.

6. Conclusions

The findings revealed a significant increase in the number of published articles over the past five years. Mexico and Colombia have emerged as leading producers of influential urban and sustainable mobility in Latin America.

The institutions with the highest number of publications related to urban and sustainable mobility in Latin America are the Pontificia Universidad Católica de Chile, the Universidad de los Andes in Colombia, and the University College London in England. The results also show interrelations between different research groups in Latin America and the United Kingdom.

Differences were found between gender groups and socioeconomic strata in terms of the use of urban mobility systems. These differences are influenced by the spatial distribution of job opportunities and are more noticeable in

the most disadvantaged social classes.

The findings also indicate that most existing research has focused on local and specific scenarios within the field of mobility, highlighting the need for more comprehensive studies that incorporate global perspectives, alternatives, and technologies to improve urban mobility and sustainability in Latin America. Additionally, it was noted that existing literature tends to prioritize material and economic perspectives over the social aspect in urban mobility research, underscoring the importance of raising social awareness to promote the use of less polluting, environmentally friendly vehicles in pursuit of a sustainable future for all.

Finally, the study found that electric vehicles, electric bicycles, and scooters are key factors in combating climate change. However, although they offer potential benefits for public health and the environment, electric bicycles have also created a social inequality gap due to their high purchase prices, excluding many families from public policies that support green economies.

References

[1] Recasens-Alsina, M., Challenges for sustainable urban mobility in Barcelona. Ciudad y Territorio, Estudios Territoriales, 52(204), pp. 236-276, 2020.

[2] Vasconcellos, E., Contribuciones a un gran impulso ambiental para América Latina y el Caribe: movilidad urbana sostenible. [en línea]. 2019. Disponible en: https://repositorio.cepal.org/handle/11362/44668

[3] Næss Strand, P., and Næss Strand A., Oslo's Farewell to Urban Sprawl. European Planning Studies. 19(1), pp. 113-139, 2011. DOI: https://doi.org/10.1080/09654313.2011.530395

[4] Ñaupas, H., Mejía, E., Novoa-Ramírez, E. and Paucar-Villagómez, A., Metodología de la investigación cuantitativa - cualitativa y redacción de la investigación, 4ta edición, Ediciones de la U, 2014.

[5] Pilkington, A., and Meredith, J., The evolution of the intellectual structure of operations management-1980-2006: A citation/co-citation analysis. Journal of Operations Management, 27(3), pp. 185-202, 2009. DOI: https://doi.org/10.1016/J.JOM.2008.08.001

[6] Yu, Z., Khan, S., Zia-ul-haq H., Tanveer, M., Sajid, M., and Ahmed S., A bibliometric analysis of end-of-life vehicles related research: exploring a path to environmental sustainability. Sustainability, 14(14), pp. 1-21, 2022. DOI: https://doi.org/10.3390/su14148484

[7] Gulo, C., Rúbio, T., Tabassum, S., and Pradot, S., Mining scientific articles powered by machine learning techniques. Open Access Series in Informatics, (ICCSW 2015), pp. 21-28, 2015. DOI: https://doi.org/10.4230/OASIcs.ICCSW.2015.21

[8] Dervisu, H., Bibliometric analysis using bibliometrix an R package. Journal of Scientometric Research. 8(3), pp. 156-160, 2019. DOI: https://doi.org/10.5530/JSCIRES.8.3.32

[9] Van Eck, N., and Waltman, L., Manual for VOSviewer version 1.5.2, Leiden Univeristy. [online]. 2023, pp. 1-28. Available at: https://www.vosviewer.com/documentation/Manual_VOSviewer_1.5.4.pdf

[10] De Oliveira, G. L., Lima, L., Silva, I., Ribeiro-Dantas, M.D., Monteiro, H., and Endo, P.T., Evaluating social distancing measures and their association with the covid-19 pandemic in South America. International Journal of Geo-Information. 10(3), art. 30121, 2021. DOI: https://doi.org/10.3390/ijgi10030121

[11] Bedoya-Maya, F., Calatayud, A., and González Mejía, V., Estimating the effect of road congestion on air quality in Latin America. Transportation Research Part D: Transport and Environment. 113, art. 103510, 2022. DOI: https://doi.org/10.1016/j.trd.2022.103510

[12] Asprilla-Lara, Y., Mosquera-Palacios, D.J., and González-Pérez, M.G., Sustainable mobility in cities of the XXI century: road perspectives in Bogotá-Colombia and Guadalajara-México. Ciudad y Territorio Estudios Territoriales, 54(212), pp. 429-442; 2022. DOI: https://doi.org/10.37230/CyTET.2022.212.8

[13] Bermúdez-Hernández, J., Cardona-Acevedo, S., Valencia-Arias, A., Palacios-Moya, L., and Dioses-Lescano, N., Behavioural factors for users of bicycles as a transport alternative: a case study. Sustainability. 14(24), art. 16815, 2022. DOI: https://doi.org/10.3390/su142416815

[14] Gonzalez-Calderon, C.A., Posada-Henao, J.J., Granada-Muñoz, C.A., Moreno-Palacio, D.P., and Arcila-Mena, G., Cargo bicycles as an alternative to make sustainable last-mile deliveries in Medellin, Colombia, Case Studies on Transport Policy. 10(2), pp. 1172-1187, 2022. DOI: https://doi.org/10.1016/j.cstp.2022.04.006

[15] Hipogrosso, S., and Nesmachnow, S., Assessment of sustainable mobility initiatives developed in montevideo, Uruguay. Smart Cities, 3(2), pp. 479-510, 2020. DOI: https://doi.org/10.3390/smartcities3020026

[16] Binatti, G., Batalha, Y., De Castro, J., and De Sousa Oliveira, M., Latin American bike sharing ecosystem overview: from data collection to implementation model portraits. Revista Brasileira de Gestão Urbana. 14, pp. 1-16, 2022. DOI: https://doi.org/10.1590/2175-3369.014.E20210066.

[17] Mix, R., Hurtubia, R., and Raveau, S., Optimal location of bike-sharing stations: a built environment and accessibility approach. Transportation Research Part A: Policy and Practice. 160, pp. 126-142, 2023. DOI: https://doi.org/10.1016/j.tra.2022.03.022

[18] Oviedo, D., and Guzman, L.A., Revisiting accessibility in a context of sustainable transport: capabilities and inequalities in Bogotá. Sustainability. 12(11), art. 14464, 2020. DOI: https://doi.org/10.3390/su12114464

[19] Bocarejo, J.P, Portilla, I.J, Velásquez, J.M., Cruz, M.N., Peña, A., and Oviedo, D.R., An innovative transit system and its impact on low-income users: the case of the Metrocable in Medellín. Journal of Transport Geography. 39, pp. 49-61, 2014. DOI: https://doi.org/10.1016/j.jtrangeo.2014.06.018

[20] Rodríguez, A., Delgado-Lindeman, M., Sipone, S., and dell'Olio, L., Gender dynamics in electric bike-sharing: Insights on usage and fare structures. Research in Transportation Economics. 111, art. 101561, 2025. DOI: https://doi.org/10.1016/j.retrec.2025.101561

[21] Montoya-Robledo, V., and Escovar-Álvarez, G., Domestic workers' commutes in Bogotá: transportation, gender and social exclusion. Transportation Research Part A: Policy and Practice. 139(8), pp. 400-411, 2020. DOI: https://doi.org/10.1016/j.tra.2020.07.019

[22] Rivero, M.A., Pesce, G., and Pedroni, F., Urban mobility decisions in the city of Bahía Blanca (Argentina): How to contribute to sustainable development. Investigaciones Geográficas. 83, pp. 197-217. 2025. DOI: https://doi.org/10.14198/INGEO.27615

[23] Bocarejo, J.P., and Oviedo, D.R., Transport accessibility and social inequities: a tool for identification of mobility needs and evaluation of transport investments. Journal of Transport Geography. 24, pp. 142-154, 2012. DOI: https://doi.org/10.1016/j.jtrangeo.2011.12.004

[24] Reniz-Acosta, K.P., Fábregas, C.J., Vidarte, J., Claros-Rodado, A., and Nuñez-Bravo, N., Healthy culture and inclusive means of transport in the city of Barranquilla / Colombia | Cultura saludable y medios de transporte incluyentes en la ciudad de Barranquilla/Colombia. Espacios. 39(16), 2018.

[25] Coello-Salcedo, M.F., Mendoza-Vázquez, I.A., Coello-Salcedo, B.M., and Romero-González, J.A., Comparison of mechanical bicycle and e-bike in the public bicycle-sharing system of Cuenca-Ecuador. Revista Facultad de Ingeniería. 114, pp. 19-31, 2025. DOI: https://doi.org/10.17533/udea.redin.20240937

[26] Jaramillo, C., Lizárraga, C., and Grindlay, A., Spatial disparity in transport social needs and public transport provision in Santiago de Cali (Colombia). Journal of Transport Geography. 24, pp. 340-357, 2012. DOI: https://doi.org/10.1016/J.JTRANGEO.2012.04.014

[27] Trejo, J.R., De la Llata-Gómez, R., and Biosca, S.A., Variables explaining the modal shift in public transport use due to COVID-19 in an urban environment in Queretaro. Investigaciones Geográficas. 109, pp. 1-16, 2022. DOI: https://doi.org/10.14350/rig.60590

[28] Kellermann, R., Sivizaca-Conde, D., Rößler, D., Kliewer, N., and Dienel, H.L., Mobility in pandemic times: exploring changes and long-term effects of COVID-19 on urban mobility behavior. Transportation Research Interdisciplinary Perspectives. 15(3), art. 100668, 2022. DOI: https://doi.org/10.1016/j.trip.2022.100668

[29] Vecchio, G., Tiznado-Aitken, I., and Mora-Vega, R., Pandemic-related streets transformations: accelerating sustainable mobility transitions in Latin America. Case Studies on Transport Policy. 9(4), pp. 1825-1835, 2021. DOI: https://doi.org/10.1016/j.cstp.2021.10.002
[30] Sainz-Santamaria, J., Moctezuma, D., Martinez-Cruz, A.L., Téllez, E.S., Graff, M., and Miranda-Jiménez, S., Contesting views on mobility restrictions in urban green spaces amid COVID-19 - Insights from Twitter in Latin America and Spain. Cities. 132, art. 104094, 2023. DOI: https://doi.org/10.1016/j.cities.2022.104094
[31] Paternina-Caicedo, A., Alvis-Guzmán, N., Duenãs, C., Narvaez, J., Smith, A.D., and De La Hoz-Restrepo, F., Impact of mobility restrictions on the dynamics of transmission of COVID-19 in Colombian cities. International Health. 14(3), pp. 332-335, 2023. DOI: https://doi.org/10.1093/inthealth/ihab064
[32] Ochoa-Covarrubias, G., González-Figueredo, C., Dealba-Martínez, H., and Grindlay, A.L., Air quality and active transportation modes: a spatiotemporal concurrence analysis in Guadalajara, Mexico; Sustainability. 13(24), art. 13904, 2021. DOI: https://doi.org/10.3390/su132413904
[33] Air pollution, [online]. 2022. [accessed Mar. 15, 2022]. Available at: https://www.who.int/westernpacific/health-topics/air-pollution#tab=tab_1
[34] Higgins, C.D., Adams, M.D., Réquia, W.J., and Mohamed, M., Accessibility, air pollution, and congestion: capturing spatial trade-offs from agglomeration in the property market. Land Use Policy. 84, pp. 177-191, 2019. DOI: https://doi.org/10.1016/J.LANDUSEPOL.2019.03.002
[35] UN Habitat. The state of the world's cities 2006/2007: The Millennium Development Goals and urban sustainability, 2006.
[36] Cahill, M., Housing and urban development, in The Environment and Social Policy. pp. 92-112, 2018.
[37] Grassi, Y.S., Brignole, N.B., and Díaz, M.F., Pandemic impact on air pollution and mobility in a Latin American medium-size city. International Journal of Environmental Studies. 79(4), pp. 624-650. DOI: https://doi.org/10.1080/00207233.2021.1941662
[38] Huerta, G.C. and Fuentes Flores, C.M., Smart mobility in the creation of public value for Metrobus users in Mexico City. Revista de Urbanismo, 46, pp. 40-56; 2022. DOI: https://doi.org/10.5354/0717-5051.2022.64500
[39] Quezada, C.R., Vecchio, G., and Waintrub, N., Women's attitudes towards electromobility. Revista de Urbanismo, 51, 2024. DOI: https://doi.org/10.5354/0717-5051.2024.75881
[40] Nwachukwu, M.A., Feng, H., and Achilike, K., Integrated studies for automobile wastes management in developing countries. In the concept of environmentally friendly mechanic village. Environmental Monitoring and Assessment. 178, pp. 581-593, 2011. DOI: https://doi.org/10.1007/s10661-010-1714-y
[41] Barkenbus, J.N., Prospects for electric vehicles. Sustainability. 12(14), pp. 1-13, 2020. DOI: https://doi.org/10.3390/su12145813
[42] Requia, W.J., Mohamed, M., Higgins, C.D., Arain, A. and Ferguson M., ¿How clean are electric vehicles? Evidence-based review of the effects of electric mobility on air pollutants, greenhouse gas emissions and human health. Atmospheric Environment. 185(4), pp. 64-77, 2018. DOI: https://doi.org/10.1016/j.atmosenv.2018.04.040
[43] Vecchio, G., Tiznado-Aitken, I., and Hurtubia, R., Transport and equity in Latin America: a critical review of socially oriented accessibility assessments. Transport Reviews. 40(3), pp. 354-381, 2020. DOI: https://doi.org/10.1080/01441647.2020.1711828
[44] Da Silva, A.C., and Pizzolato, N.D., Using electric vehicles for freight transport purposes and challenges to do an implementation in Brazil. Ambiente & Sociedade. 25, 2022. DOI: https://doi.org/10.1590/1809-4422ASOC20210183R2VU2022L3OA

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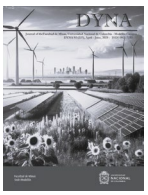

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Manufacture of open source bioprinter injector, remote controlled by APP

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Abstract
This project proposes to use an open-source injector called "Poseidon" for a bioprinter, introducing the novelty of remote control through the development of a web application. It is proposed to make remote access for procedures carried out in a bioprinter more flexible, facilitating the creation of tissues and organs through the use of the proposed Smart Medicine technology. A functional injector was developed at a mechanical and electronic level which allows microextrusion with a syringe; for which motion control algorithms will be used to guarantee precise and smooth displacement; executing a reliable remote communication with the bioprinter; according to the above, a graphical user interface will be designed to carry out the control of the injector.

Keywords: injector; open source; serial communication.

Fabricación de inyector para bioimpresora de código abierto, controlado a distancia por medio de una APP

Resumen
En este proyecto se propone usar un inyector de código abierto denominado "Poseidón" para una bioimpresora, introduciendo la novedad del control remoto mediante el desarrollo de una aplicación web. Se propone flexibilizar el acceso a distancia para los procedimientos llevados a cabo en una bioimpresora, facilitando la creación de tejidos y órganos mediante el uso de la tecnología Smart Medicine propuesta. Se desarrolló un inyector funcional a nivel mecánico y electrónico el cual permite la microextrusión con jeringa; para lo cual se emplearán algoritmos de control de movimiento que garantizarán el desplazamiento preciso y suave; ejecutando una comunicación remota confiable con la bioimpresora; de acuerdo a lo anterior se diseñará una interfaz gráfica de usuario para llevar a cabo el control del inyector.

Palabras clave: inyector; código abierto; comunicación serial.

1. Introducción

Durante los últimos dos años, el panorama de los trasplantes de órganos en el país ha revelado cifras significativas: el 64.6% (606 casos) en 2022 y el 69.07% (822 casos) en 2023 de todos los trasplantes realizados fueron trasplantes de riñón. Este incremento refleja una creciente demanda, evidenciada por el aumento del 17% en la lista de espera por un riñón durante el último año, llevando el total a 3,663 personas en espera de este vital órgano. Este contexto crítico ha impulsado la búsqueda de soluciones innovadoras, entre las cuales la bioimpresión emerge como una prometedora frontera de la medicina regenerativa. Un estudio realizado por el Instituto Roche ha sido particularmente revelador, posicionando a la bioimpresión no solo como el futuro de los trasplantes sino también como una técnica viable para reemplazar órganos enfermos, dañados o envejecidos.

A lo largo de los años se ha presenciado la gran evolución de las bioimpresoras de órganos vitales en todo el mundo, como lo menciona el artículo sobre la bioimpresora rentable asistida por microválvulas para ingeniería de tejidos, que detalla el desarrollo y validación de una bioimpresora basada en microválvulas, rentable y centrada en gotas [1]. Por otro

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lado, también interviene el prototipo de bioimpresora 3D híbrida de código abierto diseñada para imprimir simultáneamente termoplásticos e hidrogeles. Utilizando una impresora Prusa i3 MK3 convencional con dos cabezales de impresión independientes, permite la adaptación a diversos materiales blandos y la impresión con patrones arbitrarios en cada capa [2].

Igualmente, se encuentra el artículo "Una Bioimpresora 3D para la Producción de Esferoides Multicelulares en Matriz" destaca una tecnología con una bioimpresora 3D personalizada para imprimir esferoides en una matriz de hidrogel, permitiendo controlar el tamaño y la cantidad de células con baja variabilidad [3]. Uno de los criterios base para la innovación de la bioimpresión es el manejo de tecnologías accesibles de bajo costo para la creación rápida de una bioimpresora, considerando métodos de fácil acceso para este proceso, que también proporcionan un sistema de aprendizaje para la construcción mecánica y la robótica del software de la bioimpresora a diseñar [4].

En respuesta a este desafío, se presentará un proyecto que busca marcar un antes y un después en el ámbito de la bioimpresión. La propuesta se centra en el desarrollo de un inyector de alta precisión, diseñado específicamente para integrarse en la bioimpresora de código abierto Poseidón. La bioimpresión es una técnica innovadora dentro del ámbito de la impresión 3D, especialmente diseñada para la deposición precisa de materiales biológicos, tales como células vivas, con el propósito de fabricar andamios celulares y la creación de tejidos.

Uno de los aspectos clave de este proyecto es la implementación de la comunicación TCP (Protocolo de Control de Transmisión) para el manejo remoto del inyector. El Protocolo de Control de Transmisión es un protocolo de comunicación de red ampliamente utilizado que garantiza la entrega confiable y ordenada de los datos entre dispositivos conectados a una red. En el caso presentado, este protocolo permitirá el control preciso y en tiempo real del inyector desde una interfaz de usuario remota.

El proceso de transmisión de datos para el movimiento del motor del inyector se llevará a cabo de la siguiente manera: La interfaz de usuario enviará instrucciones a través de la red utilizando el protocolo TCP. Estas instrucciones incluirán parámetros críticos como aceleración, desaceleración, velocidad y otros parámetros relevantes para el control preciso del inyector. Las instrucciones serán recibidas por un módulo ESP WiFi, un dispositivo de bajo costo y bajo consumo de energía que permite la comunicación inalámbrica. El módulo ESP WiFi estará conectado a un microcontrolador Arduino, el cual interpretará las instrucciones recibidas y controlará el movimiento del motor NEMA, un tipo de motor paso a paso altamente preciso utilizado en aplicaciones de control de movimiento.

El microcontrolador Arduino estará programado para traducir las instrucciones recibidas a través del protocolo TCP en señales eléctricas que controlarán el movimiento del motor NEMA. Esto permitirá al operador, desde la interfaz de usuario remota, ajustar con precisión los parámetros mencionados anteriormente durante el proceso de fabricación de andamios celulares y creación de tejidos. Esta arquitectura de comunicación remota basada en el Protocolo de Control de Transmisión (TCP), en conjunto con el módulo ESP WiFi, el microcontrolador Arduino y el motor NEMA, permitirá un control preciso y en tiempo real del inyector, facilitando así el proceso de bioimpresión de manera eficiente y confiable.

En el presente documento, se encuentra estructurado de manera coherente y organizada. En la sección de materiales y métodos, se detallan los materiales utilizados en la fabricación del inyector, tales como el PLA, motor NEMA 17, tornillos, cables, Arduino, ESP32 WiFi, entre otros. Esta selección de materiales es fundamental para el proceso de fabricación del inyector.

Posteriormente, en la sección de resultados, se describe el proceso de elaboración de algoritmos para el movimiento del motor NEMA desde el módulo de Arduino. Los resultados obtenidos son positivos, ya que se logró el movimiento del motor en ambas direcciones. Este movimiento es esencial para facilitar tanto la extrusión del material hacia adelante como la retracción de la jeringa que dispensa el material. Finalmente, en las conclusiones, se evidencia que el movimiento del motor NEMA se logró mediante la programación, lo que representa un avance significativo para iniciar el proceso de comunicación serial destinado al control del inyector a través de una aplicación.

2. Objetivos

2.1 Objetivo general

Desarrollar e implementar una aplicación remota que permita controlar y mover el inyector de una bioimpresora de código abierto, con el fin de mejorar la precisión y la capacidad de impresión.

2.2 Objetivos específicos

Construir un inyector que opere correctamente de forma mecánica y electrónica, para que pueda desempeñar su función de manera eficiente.

Desarrollar algoritmos de control de movimiento que permitan un desplazamiento preciso y suave del inyector, considerando aspectos como la velocidad, aceleración, desaceleración y ajustes de posición, con el propósito de optimizar su rendimiento.

Implementar una comunicación remota confiable entre la aplicación y el inyector utilizando tecnologías apropiadas, como sockets TCP/IP o protocolos de comunicación; que permitan que el control a distancia sea efectivo y seguro.

Diseñar y desarrollar una interfaz gráfica de usuario intuitiva y amigable que permita a los usuarios controlar el movimiento del inyector de manera precisa y segura, con el fin de facilitar su uso y maximizar la experiencia de interacción.

3. Materiales y métodos

Para el desarrollo óptimo del inyector y su funcionalidad con la aplicación, se realiza una investigación de tipo exploratoria, dado que se centra en la creación de una nueva tecnología para controlar el inyector de una bioimpresora, y para llegar a esto se requirió de una indagación exhaustiva

sobre los sistemas empleados en la actualidad para el control de estas, así como el movimiento de sus partes mecánicas; de igual manera, el método seleccionado es mixto, ya que para el análisis de los respectivos resultados se opta por una forma cualitativa como la visualización en el comportamiento del inyector y su correspondencia con lo asignado en la aplicación, y un enfoque cuantitativo que permite relacionar variables de movimiento del inyector como velocidad y aceleración con respecto al tiempo que tarda el inyector en vaciar completamente el material.

A su vez, para el prototipo del inyector se empleó impresión 3D, por medio de PLA (ácido poliláctico) el cual fue seleccionado como la opción óptima para la creación de las piezas, ya que garantiza durabilidad, resistencia y precisión durante el ensamblaje; así mismo en los componentes electrónicos de relevancia como el motor, se escogió el motor Nema 17, ya que por sus características de torque, exactitud y precisión en el giro es usado ampliamente en la industria de las impresoras 3D; también, para la configuración del sistema de funcionamiento del inyector se emplea un módulo inalámbrico con disposición WiFi, en este caso el ESP 32 que permite la conexión remota y además es ampliamente utilizado en la programación IoT lo que facilita la interacción con el motor, y para darle la precisión para los giros y el torque suficiente se usa un driver para motor paso a paso de referencia DRV8825.

4. Metodología

Agregando a lo anterior, para la ejecución del inyector y la conexión remota con la aplicación, se divide el proceso en cuatro etapas, que se evidencian en la Fig. 1 y se explican a continuación.

Etapa 1: *Construcción del inyector y verificación de funcionamiento mecánico y de componentes electrónicos.*

En un proceso inicial se aborda la fabricación del inyector, basado en un modelo predefinido encontrado en la bioimpresora de código abierto “Poseidon”; por medio del proceso de impresión 3D se realiza la base del inyector y algunas piezas mecánicas, para lo cual se emplea el programa SolidWorks que permite exportar los archivos en una extensión compatible denominada stl, dado que, las partes se encuentran en el programa de CAD Fusion 3D que no permite la creación de archivos con esta denominación; para el proceso de impresión el material PLA (ácido poliláctico) fue seleccionado como la opción óptima para la creación de las piezas, ya que garantiza durabilidad, resistencia y precisión para el ensamblaje y funcionalidad total del inyector. Una vez impresas las piezas, se realiza el proceso de lijado y pegado de las mismas, el cual permite una integración de componentes mecánicos clave, como el motor, junto con su correspondiente driver de control, los elementos adicionales como varillas lisas y roscadas, acoples y rodamientos. Posteriormente, se procede a realizar la verificación del funcionamiento mecánico mediante un

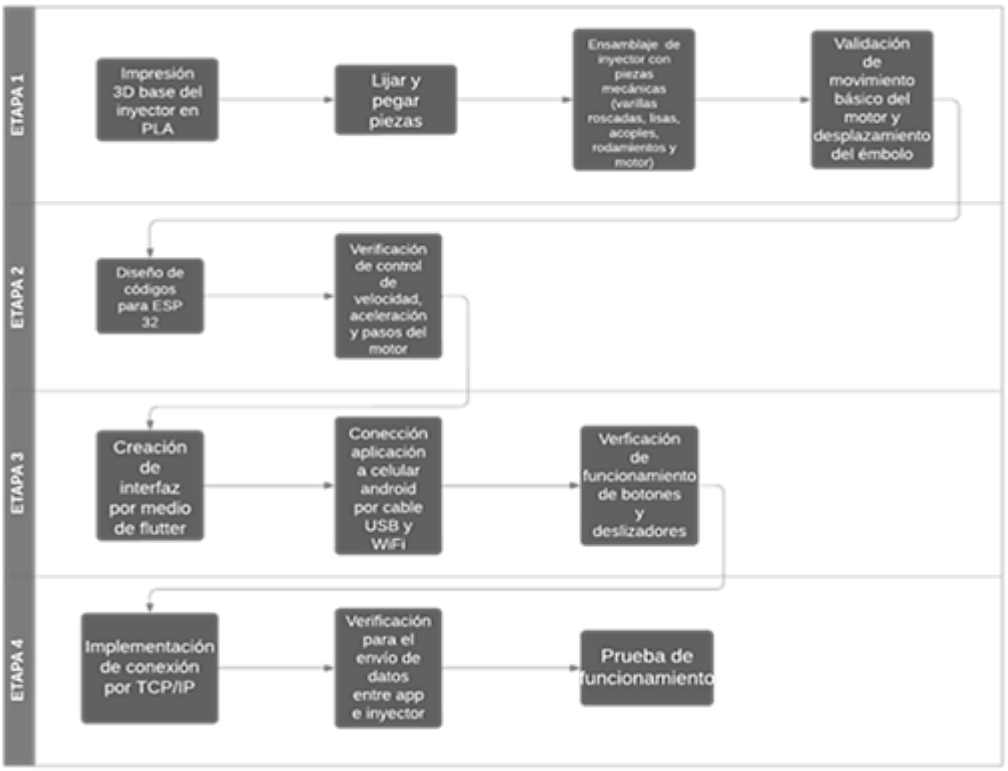

Figura. 1. Metodología del proyecto.
Fuente: propia.

programa de prueba diseñado específicamente para este propósito; eligiendo el motor Nema 17 como el más óptimo para este proyecto, dado que brinda el torque necesario para mover el émbolo de la jeringa junto a las piezas mecánicas; por medio de las verificaciones se hace la validación del movimiento del motor en ambas direcciones, reproduciendo así las condiciones de funcionamiento realistas, de forma que, se corrobora que el desplazamiento del émbolo de la jeringa se ajusta a los parámetros requeridos para la deposición del material.

Etapa 2: Desarrollo de algoritmos de control de movimiento, considerando velocidad, aceleración y ajustes de posición.

Esta etapa se enfoca en la implementación de códigos aplicados por medio del microcontrolador Arduino que brinda la practicidad de ser ejecutado por diferentes módulos con igual lenguaje de programación como el Arduino Uno y el ESP 32-Wifi, para garantizar el funcionamiento preciso y eficiente del inyector; se realizan pruebas para determinar la dirección de giro óptima del motor para que la deposición del material se realice de forma exitosa y completa hasta que el émbolo de la jeringa llegue a su tope, así como su retroceso para facilitar la recarga del dispositivo; los códigos diseñados tienen en cuenta la necesidad de modificar parámetros clave como la velocidad, la aceleración o la posición del émbolo, de modo que pueda adaptarse a las características específicas del material con el que se esté trabajando y a las necesidades de bioimpresión que tenga el usuario, por ende las variables que se encuentran en el código son speed, acceleration y motor steps; así mismo, las pruebas realizadas en esta fase se hacen empleando un microcontrolador Arduino Uno, conectado a un driver para motor paso a paso de referencia DRV8825, el cual permite modificar la dirección del giro del motor, dependiendo la polarización de las bobinas y aporta la potencia máxima al mismo, es programado por medio de Arduino IDE y con base a las pruebas se identifican y corrigen posibles fallos o limitaciones del rendimiento del inyector; todo lo anterior, para escoger el mejor algoritmo e implementarlo al modelo final.

Etapa 3: Diseño y desarrollo de una interfaz gráfica de usuario que permite controlar el movimiento del inyector.

En la tercera etapa el enfoque principal es la creación de una aplicación intuitiva que facilite la interacción entre el usuario y el inyector; se crea una interfaz por medio del desarrollador Amazon Web Services, que da la posibilidad de probar la aplicación en un dispositivo móvil cuyo sistema operativo sea Android, dado que es el compatible con Google y da más facilidad de programación que iOS, lo cual da mayor amplitud a su utilidad tanto de forma online por medio de Google Chrome como en dispositivos móviles. La aplicación diseñada brinda al usuario la capacidad de controlar el proceso de deposición de material de manera remota, dado que cuenta con deslizadores para controlar el valor de la velocidad en $^{mm}/_{s}$ y de la aceleración en $^{mm}/_{s^2}$, así como monitorear por un cronómetro el tiempo que lleva el inyector realizando la bioimpresión y un conteo de la cantidad de pasos que ha dado el motor es decir el aproximado de la distancia que ha recorrido el émbolo en la jeringa; para que esta interacción sea satisfactoria se realiza la prueba de envio de datos modificando los parámetros disponibles entre un emisor en este caso un dispositivo móvil de la marca Samsung con un sistema operativo Android 13 ejecutando la aplicación y el programador Amazon Web Services como el receptor, para lo cual, solo se requiere estar conectado a una misma red WiFi, en la cual se tenga una dirección IP que permita la conexión remota entre los dispositivos.

Etapa 4: Implementación de comunicación remota confiable por protocolos TCP/IP.

Una vez diseñada la aplicación, como última etapa se establece una conexión de comunicación segura y eficiente entre la aplicación de control del inyector y el dispositivo físico; para esto, se realizó la configuración del módulo ESP 32-WiFi con la misma programación implementada en la primera etapa para el Arduino Uno, posteriormente se ajusta su conexión WiFi y se hace un reconocimiento de su dirección IP; para la unión entre el dispositivo y la aplicación se elige el protocolo de comunicación de más fiabilidad y seguridad siendo el TCP/IP por medio de WiFi, que adicionalmente proporciona una conectividad más estable y de mayor alcance en comparación con otras opciones como la comunicación inalámbrica por Bluetooth e infrarrojos que requieren mayor proximidad física y pueden experimentar pérdida de datos durante la transmisión. Una vez implementada la comunicación se realizan las pruebas de envio y recepción de datos empleando el mismo dispositivo móvil Samsung y verificando el funcionamiento acorde del motor para evaluar la confiabilidad y la consistencia del sistema en condiciones operativas que son similares a las reales.

Es importante destacar, que para la Etapa 2, se empleó un código de prueba que permite a cabalidad el control de las variables principales del motor como lo son velocidad, aceleración y sentido de giro; así como limitar la cantidad de pasos que da el motor en un sentido, con el fin de que cuanto el embolo de la jeringa llegue al tope el motor no funcione más en ese sentido, sino en el contrario para devolver la jeringa a su estado inicial y permite un retiro y cargue de biomaterial más rápido; el funcionamiento del código en cuestión, se relaciona en la Fig. 2.

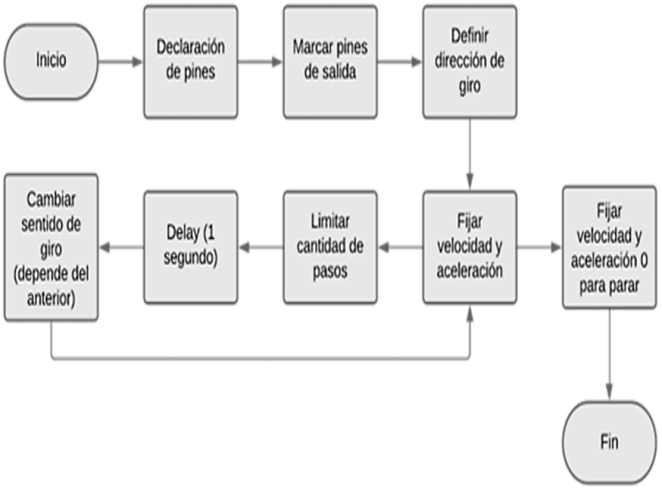

Figura. 2. Código prueba de variables velocidad y aceleración.
Fuente: propia.

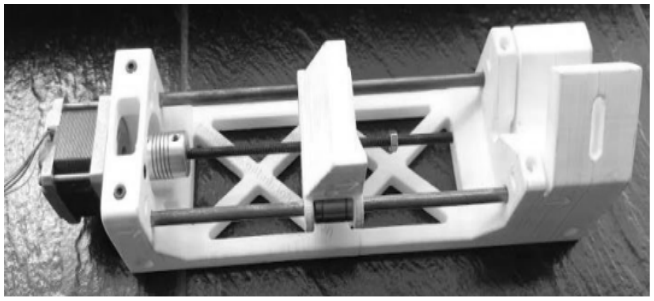

Figura. 3. Inyector ensamblado.
Fuente: Propia.

5. Resultados

En primera instancia se observa un funcionamiento adecuado del inyector, bajo la programación básica que permitió ver el giro del motor y su movimiento conjunto con las piezas mecánicas, lo cual aportó a la verificación del correcto ensamblaje en conjunto de todas las partes y los respectivos componentes, lo cual se evidencia en la Fig. 3.

Posteriormente para la creación de los códigos que permiten controlar velocidad y aceleración, se realizan 3 pruebas modificando estas variables y tomando el tiempo que tardaba el émbolo de la jeringa en completar el recorrido por la misma, es decir, simular el proceso de vaciado completo del inyector, teniendo en cuenta los datos obtenidos, se realizó el respectivo análisis consolidado en la Tabla 1.

6. Discusión

Inicialmente, se observó un funcionamiento adecuado del inyector bajo una programación básica, verificando el correcto ensamblaje de todas las partes y componentes mecánicos y electrónicos. A continuación, se llevaron a cabo tres pruebas específicas modificando las variables de velocidad y aceleración, documentando el tiempo necesario para completar el recorrido del émbolo de la jeringa.

En términos de velocidad y aceleración del inyector, los resultados muestran que una mayor velocidad y aceleración no siempre conducen a un mejor rendimiento en la deposición de material. La prueba a 1000 mm/s y 50 mm/s², aunque es rápida, no es adecuada para aplicaciones que requieren precisión debido al control menos estable del material depositado. Por otro lado, una velocidad moderada de 500 mm/s y una aceleración de 40 mm/s² parece ser más equilibrada para aplicaciones que no requieren alta precisión, pero sí eficiencia en el tiempo.

La prueba más lenta, a 250 mm/s con 30 mm/s², aunque es la más precisa, sugiere que una reducción adicional en la aceleración podría mejorar aún más la suavidad y precisión del recorrido del émbolo. Esto es crucial para aplicaciones donde la exactitud en la deposición del material es fundamental, como en la creación de estructuras complejas y detalladas en bioimpresión.

En segundo lugar, se recomienda el desarrollo de algoritmos de control avanzados que puedan adaptarse dinámicamente a las condiciones de impresión, mejorando la estabilidad y precisión del inyector en tiempo real. Finalmente, investigar cómo los parámetros óptimos varían según el tipo de material biológico y la estructura a imprimir, permitiendo así personalizar las configuraciones del inyector para diferentes aplicaciones en medicina regenerativa y otros campos biomédicos.

Además, estos resultados deben ser considerados dentro del contexto de la tecnología de bioimpresión de código abierto, donde la capacidad de ajustar y controlar de manera precisa estos parámetros es necesaria para el desarrollo de dispositivos accesibles y personalizables, que puedan adaptarse a las diversas necesidades de investigación y aplicación en el campo biomédico.

Tabla 1.
Resultados de tiempo de vaciado del inyector considerando las variables velocidad y aceleración.

Velocidad	Aceleración	Tiempo	Análisis
$1000\,{}^{mm}/_{s}$	$50\,{}^{mm}/_{s^2}$	20s	El recorrido es demasiado rápido por lo cual no es conveniente aplicarlo para la deposición favorable del material
$500\,{}^{mm}/_{s}$	$40\,{}^{mm}/_{s^2}$	75s	Es apropiado para deposiciones rápidas, que no requieran precisión en la fabricación de la estructura
$250\,{}^{mm}/_{s}$	$30\,{}^{mm}/_{s^2}$	130s	En las pruebas fue el más lento, pero se recomienda bajar la aceleración para que el recorrido del émbolo sea más suave y la estructura quede con la mejor exactitud al modelo planteado.

Fuente: Propia.

7. Conclusiones

Los resultados del proyecto demostraron que la configuración óptima del inyector para la bioimpresora de código abierto se logra mediante un equilibrio cuidadoso entre velocidad y aceleración, donde las pruebas revelaron que a una velocidad de 250 mm/s y una aceleración de 30 mm/s², el inyector proporciona la mayor precisión en la deposición del material biológico. Esto es crucial para aplicaciones donde la exactitud en la estructura impresa es primordial, lo que determina la importancia de ajustar finamente estos parámetros para maximizar tanto la precisión como la eficiencia en los procesos de bioimpresión del inyector.

El desarrollo del sistema de control remoto basado en el protocolo TCP/IP y el uso del módulo ESP WiFi junto con el microcontrolador Arduino y el motor NEMA 17 ha permitido un control preciso y en tiempo real del inyector. Esta innovación facilita la bioimpresión de manera más eficiente y confiable, permitiendo a los operadores ajustar parámetros críticos de forma remota. Este avance no solo mejora la funcionalidad del sistema, sino que también representa un paso significativo hacia la accesibilidad de tecnologías avanzadas de bioimpresión para diversas aplicaciones biomédicas.

El proyecto sigue en desarrollo, con varias líneas de investigación abiertas para optimizar aún más el inyector. Se sugiere la exploración de nuevos algoritmos de control que adapten dinámicamente los parámetros de impresión

según las condiciones en tiempo real. Además, es necesario investigar cómo diferentes materiales biológicos y configuraciones estructurales afectan el rendimiento del inyector. La continuidad de este proyecto promete no solo mejorar la tecnología actual, sino también expandir sus aplicaciones en la medicina regenerativa y otros campos biomédicos, promoviendo una mayor precisión y eficiencia en la fabricación de tejidos y órganos impresos en 3D.

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Referencias

[1] Okubo, N., Qureshi, A. J., Dalgarno, K., Goh, K. L., & Derebail, S. Cost-effective microvalve-assisted bioprinter for tissue engineering. Bioprinting, 13, e00043, 2019. DOI: https://doi.org/10.1016/j.bprint.2019.e00043

[2] Koch, F., Thaden, O., Tröndle, K., Zengerle, R., Zimmermann, S., & Koltay, P. Open-source hybrid 3D-bioprinter for simultaneous printing of thermoplastics and hydrogels. HardwareX, 10, e00230, 2021. DOI: https://doi.org/10.1016/j.ohx.2021.e00230

[3] Bharadwaj, T., & Verma, D. Open source bioprinters: Revolutionizing the accessibility of biofabrication. Bioprinting, 23, e00155, 2021. DOI: https://doi.org/10.1016/j.bprint.2021.e00155

[4] Moukachar, A., Harvey, K., Roke, E., Sloan, K., Pool, C., Moola, S., ... & Castell, O. Development and evaluation of a low-cost lego 3D bioprinter: from building-blocks to building blocks of life. Advanced Materials Technologies, 8(6), 2100868, 2023. DOI: https://doi.org/10.1002/admt.202100868

[5] Boutros, M. J. Ingeniería de tejidos: una visión general. IEEE Revista de Ingeniería Biomédica, 17(3), 77-84, 1998.

[6] Chae, H. J., Lee, S., Son, H., Han, S., & Lim, T. Generating 3D bio-printable patches using wound segmentation and reconstruction to treat diabetic foot ulcers. In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition (pp. 2539-2549), 2022. DOI: https://doi.org/10.1109/CVPR52688.2022.00257

[7] Choudhury, D., Anand, S., & Naing, M. W. The arrival of commercial bioprinters Towards 3D bioprinting revolution!. International Journal of Bioprinting, 4(2), 2018. DOI: https://doi.org/10.18063/IJB.v4i2.139

[8] Duan, B., Hockaday, L. A., Kang, K. H., & Butcher, J. T. 3D Bioprinting of heterogeneous aortic valve conduits with alginate/gelatin hydrogels. Journal of Biomedical Materials Research Part A, 101(5), 1255-1264, 2013. DOI: https://doi.org/10.1002/jbm.a.34420

[9] Engberg, A., Stelzl, C., Eriksson, O., O'Callaghan, P., & Kreuger, J. An open source extrusion bioprinter based on the E3D motion system and tool changer to enable FRESH and multimaterial bioprinting. Scientific Reports, 11(1), 21547, 2021. DOI: https://doi.org/10.1038/s41598-021-00931-1

[10] Gao, Y., Moshayedi, A. J., Sanatizadeh, E., Behfarnia, P., Kolamroudi, M. K., Semirumi, D. T., & Yusof, M. Y. P. M. Analysis of amorphous structure with polycaprolactone-hydroxyapatite nanoparticles fabricated by 3D bioprinter technique for bone tissue engineering. Ceramics International, 49(10), 16053-16060, 2023. DOI: https://doi.org/10.1016/j.ceramint.2023.01.203

[11] Gusmão, A., Sanjuan-Alberte, P., Ferreira, F. C., & Leite, M. Design, fabrication, and testing of a low-cost extrusion-based 3D bioprinter for thermo-sensitive and light sensitive hydrogels. Materials Today: Proceedings, 70, 148-154, 2022. DOI: https://doi.org/10.1016/j.matpr.2022.09.010

[12] Hinton, T. J., Hudson, A., Pusch, K., Lee, A. & Feinberg, A. 3D Printing PDMS Elastomer in a Hydrophilic Support Bath via Freeform Reversible Embedding. Nature Communications, 11(1), 1-11, 2020. DOI: https://doi.org/10.1021/acsbiomaterials.6b00170

[13] Kolesky, D. B., Truby, R. L., Gladman, A. S., Busbee, T. A., Homan, K. A., & Lewis, J. A. Bioprinting 3D vascularized tissues. Advanced Materials, 26(19), 3124-3130, 2014. DOI: https://doi.org/10.1002/adma.201305506

[14] Lanaro, M., Luu, A., Lightbody-Gee, A., Hedger, D., Powell, S. K., Holmes, D. W., & Woodruff, M. A. Systematic design of an advanced open-source 3D bioprinter for extrusion and electrohydrodynamic-based processes. The International Journal of Advanced Manufacturing Technology, 113, 2539-2554, 2021. DOI: https://doi.org/10.1007/s00170-021-06634-1

[15] McElheny, C., Hayes, D., & Devireddy, R. Design and fabrication of a low-cost three-dimensional bioprinter. Journal of Medical Devices, 11(4), 041001, 2017. DOI: https://doi.org/10.1115/1.4037259

[16] Mironov, V., Trusk, T., Kasyanov, V., Little, S., Swaja, R., & Markwald, R. Biofabrication: a 21st century manufacturing paradigm. Biofabrication, 1(2), 022001, 2009. DOI: https://doi.org/10.1088/1758-5082/1/2/022001

[17] Mun, K. S., Kim, H., Pandol, S. J., & Naren, A. P. Mo1122: A novel approach to creating 3D matrix using a 3D bioprinter to study CFTR related disorders. Gastroenterology, 162(7), S-706, 2022. DOI: https://doi.org/10.1016/S0016-5085(22)61655-X

[18] Ozbolat, I. T., Chen, H., & Yu, Y. Development of 'Multi-arm Bioprinter' for hybrid biofabrication of tissue engineering constructs. Robotics and Computer-Integrated Manufacturing, 30(3), 295-304, 2014. DOI: https://doi.org/10.1016/j.rcim.2013.10.005

[19] Pereira, F. D. A. S., Parfenov, V., Khesuani, Y. D., Ovsianikov, A., & Mironov, V. Commercial 3D bioprinters. 3D Printing and Biofabrication. Springer International Publishing, Cham, Switzerland, 535-549, 2018. DOI: https://doi.org/10.1007/978-3-319-45444-3_12

[20] Tashman, J. W., Shiwarski, D. J., & Feinberg, A. W. Development of a high performance open-source 3D bioprinter. Scientific Reports, 12(1), 22652, 2022. DOI: https://doi.org/10.1038/s41598-022-26809-4

[21] Tong, A., Pham, Q. L., Abatemarco, P., Mathew, A., Gupta, D., Iyer, S., & Voronov, R. Review of low-cost 3D bioprinters: State of the market and observed future trends. SLAS Technology: Translating Life Sciences Innovation, 26(4), 333-366, 2021. DOI: https://doi.org/10.1177/24726303211020297

[22] Utama, R. H., Atapattu, L., O'Mahony, A. P., Fife, C. M., Baek, J., Allard, T., ... & Gooding, J. J. A 3D bioprinter specifically designed for the high-throughput production of matrix-embedded multicellular spheroids. iScience, 23(10), 2020. DOI: https://doi.org/10.1016/j.isci.2020.101621

[23] Wagner, M., Karner, A., Gattringer, P., Buchegger, B., & Hochreiner, A. A super low-cost bioprinter based on DVD-drive components and a raspberry pi as controller. Bioprinting, 23, e00142, 2021. DOI: https://doi.org/10.1016/j.bprint.2021.e00142

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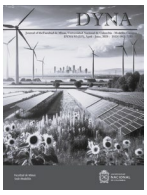

UNIVERSIDAD NACIONAL DE COLOMBIA

The threads of learning: weaving connections between machines and human minds

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Abstract
Since 2018, OpenAI has led the development of artificial intelligence following the popularization of its ChatGPT tool, promoting research into human-machine communication, which still struggles to represent a person's personality. Therefore, the objective of this study is to identify deep learning methods that can truly recreate human personality. This research used the PICO query, the PRISMA methodology, and a search of the SCOPUS database to identify articles linked to different deep learning approaches to improve human-machine communication. The most notable deep learning models were the mixed model that integrates LSTM with RNN and FNN, the Multi-Distribution Noise algorithm, and Latent Semantic Indexing. It is concluded that deep learning offers powerful tools for human-machine communication but requires continued research to optimize and automate its practical application.

Keywords: machine learning; deep learning; human behavior; artificial intelligence.

Los hilos del aprendizaje: tejiendo conexiones entre máquinas y mentes humanas

Resumen
Desde 2018, OpenAI ha liderado el desarrollo de inteligencia artificial tras la popularización de su herramienta ChatGPT, promoviendo la investigación de la comunicación humano-máquina que sigue teniendo problemas para representar la personalidad de una persona. Por ello, el objetivo del presente estudio es identificar métodos de Deep Learning que puedan recrear genuinamente la personalidad humana. Esta investigación utilizó la pregunta PICO, la metodología PRISMA y la búsqueda en la base de datos SCOPUS para identificar artículos vinculados a diferentes enfoques de aprendizaje profundo para mejorar la comunicación Humano-Máquina. Se identificaron como modelos más destacados de Deep Learning el modelo mixto que integra LSTM con RNN y FNN, el algoritmo Multi-Distribution Noise y el Latent Semantic Indexing. Se concluye que el Deep Learning ofrece herramientas poderosas para la comunicación Humano-Máquina, pero requiere investigaciones continuas para optimizar y automatizar su aplicación práctica.

Palabras clave: aprendizaje mecánico; aprendizaje profundo; comportamiento humano; inteligencia artificial.

1. Introducción

Desde el año 2018, tras el origen de OpenAI (Empresa creadora de ChatGPT) con su modelo de lenguaje GPT-1se han incrementado los estudios de la comunicación Humano-Máquina (H-M) [1] y esto evidencia el desafío de querer desarrollar una inteligencia artificial (IA) con una personalidad genuina que sea similar al complejo comportamiento humano [2]. El concepto de la comunicación H-M a cobrado protagonismo con la popularización de la IA y sus capacidades para imitar de forma auténtica a un humano [3], sin embargo, los usuarios aún detectan patrones repetitivos y respuestas artificiales al interactuar con una IA lo que puede generar una experiencia de conversación rígida y restar naturalidad a la interacción [2-4]. Por ello, resulta importante comprender la estrecha relación entre la IA y el Deep Learning (DL), explorar el funcionamiento de las redes neuronales profundas y analizar su capacidad para procesar grandes volúmenes de datos sin la intervención humana [2].

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Estos conocimientos son fundamentales para combinar técnicas de IA basadas en distintos enfoques lógicos que potencien las capacidades del DL [3].

A pesar del avance de la IA aún se observa una reducida cantidad de estudios comparativos que analicen de manera rigurosa los métodos que integren el Machine Learning (ML) y DL por lo que aún no se pueden identificar enfoques eficaces para fortalecer la interacción entre H-M [3]. Sin una evaluación profunda de estas técnicas, existe el riesgo de desaprovechar plenamente sus capacidades lo que podría reducir el avance tecnológico por una falta de comprensión en el comportamiento H-M [2,3,5].

La dificultad para lograr una interacción efectiva entre H-M podría deberse a las limitaciones de las redes neuronales profundas ya que a pesar de su eficacia en diversos campos mediante aprendizaje por ensayo y error, pueden fallar catastróficamente al enfrentarse a grandes volúmenes de datos cuya distribución difiere de la utilizada durante el entrenamiento [2,3,5]. El DL (como evolución del ML) utiliza redes neuronales profundas y supera a las redes neuronales estándar mediante la implementación de algoritmos complejos que simulan procesos cognitivos humanos, permitiendo emular la estructura de la lógica humana y derivar a conclusiones a partir del análisis de los datos pero aún presenta limitaciones en su capacidad de adaptación y evolución debido a errores inherentes a su forma de aprendizaje lo que afecta su flexibilidad y podría detener su progreso [3].

La presente investigación busca aportar información para el desarrollo de sistemas más robustos de IA en la comunicación H-M. Diversos artículos han destacado las limitaciones de los modelos tradicionales en el DL y la necesidad de integrar técnicas adicionales para abordar los desafíos presentados por los datos académicos [6]. Hooshyar et al. [5] proponen enriquecer las Redes Neuronales Artificiales (RNA) con conocimiento simbólico con el fin de potenciar su capacidad de generalización y adaptabilidad permitiéndoles aprender de grupos de datos escasos. A pesar del incremento de artículos que abordan estas características, ninguno tiene una visión tan clara sobre el DL [4]. El DL se centraba en la profundidad de las redes neuronales pero este concepto ha evolucionado hasta abarcar técnicas de aprendizaje más complejas y dinámicas [7]. El impacto del DL se ha extendido significativamente impulsando el desarrollo de dominios y aplicaciones que se apoyan de arquitecturas profundas [3]. Por ello, es relevante una investigación que destaque la capacidad de estas técnicas de recopilar datos y en base a ellos aprender sobre el comportamiento humano.

Por lo tanto, el objetivo de la presente investigación es identificar métodos de Deep Learning que puedan recrear genuinamente la personalidad humana, incluso en contextos con un elevado volumen de datos. Es esencial conocer el rendimiento de los modelos ante cambios en las distribuciones de datos, así como también identificar propuestas de soluciones innovadoras que contribuyan a mejorar la comunicación entre H-M.

2. Metodología

Para la presente RSL se realizó una búsqueda de información integral (sin límite de años para las publicaciones) para identificar los métodos de DL que puedan recrear genuinamente la personalidad humana. La búsqueda se realizó empleando la pregunta PIO (Problema, Intervención y Resultados) lo que permitió realizar una búsqueda más rigurosa en la base de datos seleccionada y como estrategia metodológica se emplearon los lineamientos PRISMA [8].

La pregunta de investigación formulada en la presente investigación fue: ¿Qué patrones de comunicación empleando métodos de Deep Learning se pueden emplear para identificar la comunicación H-M? Con dicha pregunta se generó la siguiente ecuación de búsqueda: ("artificial neural network" OR "deep-learning neural network" OR "unsupervised neural network") AND (("human behavior" OR "human conduct" OR "human attitude" OR "language technology" OR "technological language") OR ("method comparison" OR "comparison of methods" OR "methods analysis" OR "procedure comparison" OR "comparison of procedures")). La búsqueda se realizó en la base de datos SCOPUS durante los meses de abril a junio del 2024 empleando los criterios "document type" siendo estos "Article" y "Conference paper". Para la selección de publicaciones se establecieron los siguientes criterios:

Criterios de Inclusión: CI-1: Estudios de neural networks aplicados al aprendizaje, CI-2: Estudios de DL orientados a la comunicación, CI-3: Estudios de métodos o procedimientos aplicados en adultos.

Criterios de Exclusión: CE-1 Estudios de neural networks aplicados a la salud, CE-2 Estudios de Deep Learning orientados a las enfermedades, CE-3 Estudios que se encuentren en un idioma diferente al español e inglés, CE-4: Estudios que no sean de acceso abierto.

Como resultado de la aplicación de la ecuación de búsqueda se identificaron 486 publicaciones las que fueron filtradas conforme al diagrama de flujo PRISMA y los criterios de inclusión y exclusión seleccionándose 10 artículos (Fig. 1).

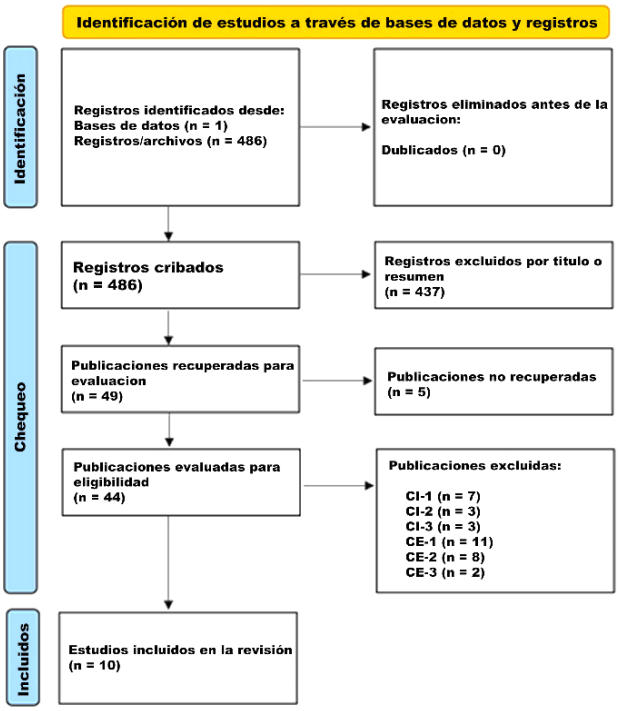

Figura 1. Flujograma PRISMA para la filtración y selección de fuentes.
Fuente: Elaboración propia.

3. Resultados

Los resultados de la presente RSL se han organizado en dos niveles: un análisis descriptivo de los datos bibliométricos y un análisis detallado de las características técnicas relevantes, de acuerdo con el objetivo de esta investigación.

3.1 Análisis bibliométrico

En la Tabla 1 se resumen los principales datos bibliométricos de las investigaciones identificadas. Hasta junio del 2024 solo se identificaron 10 publicaciones que cumplían con los criterios de inclusión y exclusión indicados en la presente RSL. El artículo con mayor número de citaciones fue el de Hasibuan, Nugroho y Santosa [17], mientras que las investigaciones con menor cantidad de citas fueron las de Kuroki y Gottschalg-Duque [10] y de Jäger y Reisinger [14].

Tabla 1.
Datos bibliométricos de artículos seleccionados

Ref/Titulo/Año	Revista			Citas
[9]	Harnessing the flexibility of neural networks to predict dynamic theoretical parameters underlying human choice behavior	2024	PLoS Computational Biology	4
[10]	Information architecture applied on natural language processing: a proposal. Information Science contributions on data pre-processing for training and learning of artificial neural networks	2023	Revista Digital de Bibliotecono mia e Ciencia da Informacao	1
[11]	Application of artificial neural networks for personality traits prediction based on handwriting	2023	Indonesian Journal of Electrical Engineering and Computer Science	1
[12]	Multi-distribution noise quantisation: an extreme compression scheme for transformer according to parameter distribution	2022	Connection Science	10
[13]	Natural language processing with improved deep learning neural networks	2022	Scientific Programming	11
[14]	Can we replicate real human behaviour using artificial neural networks?	2022	Mathematical and Computer Modelling of Dynamical Systems	4
[15]	On logical inference over brains, behaviour, and artificial neural networks	2021	Computational Brain and Behavior	33
[16]	Comparing feedforward and recurrent neural network architectures with human behavior in artificial grammar learning	2020	Scientific Reports	14
[17]	Model Detecting Learning Styles with Artificial Neural Network	2019	Journal of Technology and Science Education	45
[18]	Experimental research on encoder-decoder architectures with attention for chatbots	2018	Computacion y Sistemas	4

Fuente: Elaboración propia

3.2 Modelos de aprendizaje y sus métodos

El modelo Transformer-based ha demostrado una alta capacidad para alcanzar buenos niveles de precisión en tareas de procesamiento del lenguaje natural siendo empleado por Yu et al. [12], Kuroki y Gottschalg-Duque [10], y Costa-Jussà et al. [18]. Sin embargo, este tipo de modelo requiere elevados recursos computacionales y gran capacidad de almacenamiento debido a la gran cantidad de datos necesarios para su entrenamiento por ello Yu et al. [12] propusieron un enfoque alternativo mediante el método Multi-Distribution Noise (MDN) capaz de generar múltiples resultados posibles junto con sus respectivas probabilidades lo que aligera el procesamiento. Kuroki y Gottschalg-Duque [10] evaluaron el rendimiento de una variante específica (el modelo BERTimbau) analizando su comportamiento al procesar datos con o sin la arquitectura Multimodal Information Architecture (MIA) encontrando que su desempeño varía según el tipo de información utilizada. Costa-Jussà et al. [18] aplicaron un enfoque híbrido entre distintos modelos de redes neuronales desarrollando una arquitectura evolutiva centrada en la codificación y decodificación en el procesamiento del lenguaje natural (NLP) mediante el uso del mecanismo "Attention-based" el que permite al modelo enfocarse en partes específicas de los datos de entrada durante el aprendizaje o la inferencia asignando distintos niveles de importancia a cada segmento para mejorar su rendimiento en tareas como la traducción automática o el procesamiento de imágenes.

El modelo Long Short-Term Memory (LSTM) (orientado al procesamiento del lenguaje natural) fue utilizado por Kuroki y Gottschalg-Duque [10], YiTao [13] y Alamia et al. [16]. Se trata de una variante de Recurrent Neural Networks (RNN), diseñada para capturar y retener dependencias a largo plazo en secuencias. Kuroki y Gottschalg-Duque [10] observaron que el modelo presenta dificultades al captar relaciones entre palabras dentro de una misma oración. Debido a estas limitaciones YiTao [13] propuso un entrenamiento híbrido compuesto por Feed-Forward Neural Network (FNN) para retroalimentación, RNN para modelado secuencial y LSTM como fase final formando así una red evolutiva donde cada componente compensa las debilidades de los demás. Alamia et al. [16] comparan la precisión entre varios modelos cuantificando el entrenamiento de estos y la problemática identificada (incluso con más datos) e identifican que puede ser difícil establecer comparaciones justas con el desempeño humano debido a que los humanos pueden interpretar mejor ciertos tipos de información lo que puede conducir a la generación de personalidades distintas según el modelo y los datos de entrenamiento.

El modelo RNN es un tipo de red neuronal en la que las conexiones entre neuronas forman ciclos lo que permite la

propagación de información en ambas direcciones haciendo que sean adecuadas para manejar datos secuenciales o temporales y conservar estados anteriores. Su uso fue identificado en los trabajos de YiTao [13], Alamia et al. [16], Ger et al. [9] y Costa-jussá [18] quienes lo emplean como una de las fases dentro del entrenamiento hibrido entre el FNN, RNN y LSTM con el objetivo de mejorar la precisión y evitar limitaciones propias de utilizar un solo tipo de red proponiéndose este enfoque como un modelo evolutivo que combina las fortalezas de varias arquitecturas. Alamia et al. [16] observaron que RNN fue el modelo más utilizado en los entrenamientos siendo utilizado en múltiples estudios con diversos conjuntos de datos y estructuras gramaticales. Ger et al. [9] emplearon el entrenamiento de dos variantes del modelo RNN el Recurrent Neural Network Teórica (t-RNN) fundamentada en principios teóricos y matemáticos sólidos cuyo enfoque implicó el estudio detallado de las propiedades internas de las RNN y su aplicación en el diseño de modelos más eficientes y efectivos; y la variante Data-driven Recurrent Neural Network (d-RNN), basada en grandes conjuntos de datos de entrenamiento y en técnicas de aprendizaje automático tanto supervisado como no supervisado que permitieron ajustar los parámetros del modelo para optimizar su rendimiento en tareas específicas. El estudio incluyó una comparativa entre ambas variantes para determinar cuál presentaba un mejor desempeño en función del contexto de aplicación. El estudio incluyó una comparativa entre ambas variantes para evaluar cuál presentaba un mejor desempeño según el contexto de aplicación. Costa-Jussà [18] implementó el modelo RNN dentro de un enfoque híbrido en combinación con el modelo Transformer-based con el objetivo de alcanzar un alto nivel de desempeño en el procesamiento del NPL y simular una personalidad coherente. Para ello se utilizaron procesos de codificación y decodificación aplicados a las frases empleadas durante los entrenamientos lo que permitió modelar patrones de comportamiento y lenguaje más cercanos a los humanos.

El modelo FNN es una red neuronal simple de retroalimentación, capaz de aprender representaciones jerárquicas de datos estructurados y no estructurados a través de múltiples capas. Este modelo fue utilizado por YiTao [13], Alamia et al. [16] y Costa-Jussà et al. [18] dentro de esquemas de aprendizaje híbrido. YiTao [13] lo propuso como una etapa dentro de la evolución de su arquitectura que combinó tres tipos diferentes de redes neuronales. Alamia et al. [16] identificaron que a pesar de realizar 96,000 sesiones de entrenamiento en total un enfoque híbrido que integraba FNN requirió solo 500 entrenamientos mostrando eficiencia en determinadas tareas. Finalmente, Costa-Jussà et al. [18] emplearon un modelo centrado en el NPL en el que el FNN fue sofisticado mediante múltiples capas para potenciar la evolución de su arquitectura principal.

El modelo Artificial Neural Network (ANN) ha sido aplicado en diversos campos del aprendizaje automático siendo utilizado por Guest y Martin [15], Jäger y Reisinger [14], Hasibuan, Nugroho y Santosa [17], y Remaida et al. [11] cada uno con métodos distintos según el objetivo del modelo. Guest y Martin [15] diseñaron su enfoque basándose completamente en el comportamiento cerebral humano con el propósito de evaluar hasta qué punto una IA puede aprender a replicar dichos patrones extendiendo su aplicación más allá del NPL hacia áreas como el habla y la interpretación de expresiones. Jäger y Reisinger [14] implementaron un modelo Agent-Based Model (ABM) que simula sistemas complejos mediante agentes individuales que interactúan entre sí y con su entorno bajo reglas simples y aunque no se enfoca en NPL este modelo permite que una IA desarrolle una personalidad emergente a partir de dichas interacciones con resultados que varían según el contexto de aplicación. Hasibuan, Nugroho y Santosa [17] propusieron el modelo Latent Semantic Indexing (LSI) que emplea descomposición de valores singulares para detectar significados semánticos latentes en textos lo que permite generar contenidos personalizados a partir de datos fuente y mejorar la experiencia de aprendizaje incluyendo aplicaciones en lenguaje natural. Remaida et al. [11] desarrollaron el modelo Automatic Personality Prediction from Handwriting que es un algoritmo de aprendizaje automático que infiere rasgos de personalidad a partir de características gráficas de la escritura manual, como tamaño o inclinación de las letras y busca que la IA pueda no solo aprender lenguaje natural sino también construir una personalidad propia basada en los datos escritos por individuos.

3.3 Categorías de los algoritmos de aprendizaje

3.3.1 Algoritmos de aprendizaje y procesamiento de datos

Esta categoría agrupa algoritmos cuya principal fortaleza es su capacidad para procesar eficientemente datos complejos y estructurados. Entre ellos se encuentra el modelo FNN propuesto por Alamia et al. [16] el que permite aprender representaciones jerárquicas a través de múltiples capas aplicable tanto a datos estructurados como no estructurados. Hasibuan, Nugroho y Santosa [17] utilizaron el algoritmo LSI destacando por su habilidad para identificar significados y relaciones semánticas ocultas en grandes volúmenes de texto. Remaida et al. [11] emplearon el enfoque Multi-Layer Perceptron que es una variante específica de red neuronal artificial compuesta por múltiples capas de unidades de procesamiento lo que permite modelar patrones complejos mediante operaciones matemáticas. Estos algoritmos mostraron un desempeño sobresaliente en tareas como predicción de personalidad, análisis semántico y clasificación, tal como se refleja en sus niveles de precisión reportados en la Tabla 2.

3.3.2 Algoritmos de modelado y manejo de datos

El algoritmo MDN propuesto por Yu et al. [12] permite modelar datos distribuidos incorporando ruido e incertidumbre probabilística lo que lo hace robusto frente a entradas variables. YiTao [13] implementó el modelo LSTM que es una arquitectura eficaz para procesar secuencias de lenguaje natural que requieren retención de información a largo plazo. Alamia et al. [16] emplearon RNN para tareas de generación y traducción de texto aprovechando su capacidad para capturar dependencias en datos secuenciales. Ger et al.

[9] desarrollaron dos variantes de RNN que fueron t-RNN (basada en fundamentos matemáticos para optimizar la arquitectura) y d-RNN (que se entrena directamente sobre grandes volúmenes para adaptarse a patrones específicos). Ambos enfoques buscan maximizar la eficacia en el modelado secuencial y la representación de comportamientos complejos.

3.3.3 Algoritmos de tratamiento y arquitectura de datos

Kuroki et al. [10] propusieron la arquitectura MIA centrada en el diseño, organización y representación de datos para facilitar su interpretación semántica. Guest y Martin [15] desarrollaron el algoritmo Cognitive Computational Neuroscience (CCN) mediante el cual simularon procesos mentales complejos utilizando modelos computacionales basados en principios neuronales y neurocientíficos. Jäger et al. [14] emplearon el modelo ABM para simular comportamientos emergentes mediante agentes autónomos destacando su utilidad para estudiar la formación de rasgos de personalidad a partir de interacciones sociales. Remaida et al. [11] diseñaron un algoritmo de predicción automática de la personalidad a partir de la escritura manual combinando múltiples fuentes de información gráfica para inferir rasgos psicológicos con técnicas de análisis de datos. Costa-Jussà et al. [18] implementaron el algoritmo Attention-based Mechanisms caracterizado por su capacidad para procesar secuencias extensas, enfocándose en segmentos específicos de entrada y reconociendo estructuras informativas clave que mejoran la comprensión del lenguaje.

3.4 Resultados de entrenamiento y comparativa para la comunicación H-M

Una vez analizados todos los algoritmos, es crucial determinar el grado de precisión que estos algoritmos alcanzaron para recrear la personalidad humana, comenzando por presentar la precisión de algunos de los algoritmos (Tabla 2).

Con esta información se pudo identificar el grado de precisión alcanzado por distintos algoritmos de aprendizaje en la recreación de la personalidad humana, destacando los modelos de Jager et al. [14] y Hasibuan, Nugroho y Santosa [17] por su mayor grado de precisión (Fig. 2).

Tabla 2.
Algoritmos de diferentes autores, tareas y precisión promedio.

Ref.	Algoritmos	Tarea	Precisión Promedio
[10]	MIA	Análisis de dominios de conocimiento para generar predicciones	77.02%
[11]	Automatic personality prediction from handwriting	Predecir personalidad en base a la escritura a mano	73.60%
[12]	LSTM-RMC	Cuantificación de datos	31.60%
[12]	LRLSTM	Cuantificación de datos	89.46%
[14]	ABM	Agentes que recrean rasgos de la personalidad (Altruismo)	97.00%
[17]	LSI	Aprendizaje de modelos de detección	93.50%

Fuente: Elaboración propia.

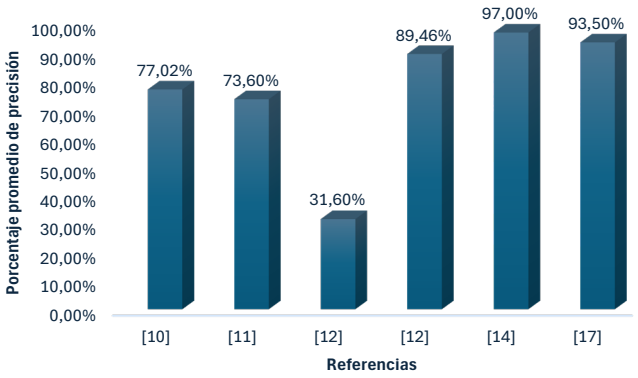

Figura 2: Porcentaje promedio de precisión de los algoritmos identificados
Fuente: Elaboración propia.

Existen algoritmos orientados a mejorar la interacción H-M mediante la recreación más precisa de rasgos de personalidad. Un ejemplo destacado es el algoritmo propuesto por Costa-Jussà et al. [18] quienes demostraron que el uso de mecanismos de atención permite aumentar la precisión del modelo y reducir las limitaciones comunicativas de los chatbots. Esta mejora fue evidenciada a través de evaluaciones externas que calificaron positivamente el desempeño conversacional tras su implementación.

El resultado de este proceso se relaciona con la propuesta de Guest y Martin [15] quienes investigaron el uso ANN en el ámbito de la neurociencia para modelar y comprender procesos cerebrales complejos como la toma de decisiones y el razonamiento metateórico. Su estudio identificó relaciones clave y desafíos en el uso de modelos de aprendizaje profundo para representar funciones cognitivas humanas. Esta perspectiva resulta fundamental para evaluar el rendimiento de los algoritmos y mejorar su capacidad de adaptación en tareas cognitivas avanzadas.

Ger et al [9] demostraron cómo el uso de redes neuronales permite modelar con mayor fidelidad la predicción de acciones y la toma de decisiones humanas, mediante el análisis de datos estructurados a través de sus algoritmos d-RNN y t-RNN.

Las arquitecturas LSTM se destacan por su capacidad para aprender dependencias a largo plazo en secuencias de datos lo que las hace especialmente útiles para capturar patrones complejos del comportamiento humano relacionados con la estructura gramatical, en concordancia con hallazgos previos en percepción visual [8]. En este sentido, Yu et al. [12] y YiTao [13] han resaltado cómo el modelo LSTM contribuye significativamente al entendimiento del lenguaje natural, aunque requiere grandes volúmenes de datos para lograr una representación más fiel de la personalidad humana. Alamia et al. [16] compararon múltiples configuraciones del modelo LSTM y analizaron la cantidad de secuencias de datos necesarias para su entrenamiento (Fig. 3). Sus hallazgos sugieren que, en general, a mayor volumen de datos, mayor es la precisión alcanzada por el modelo.

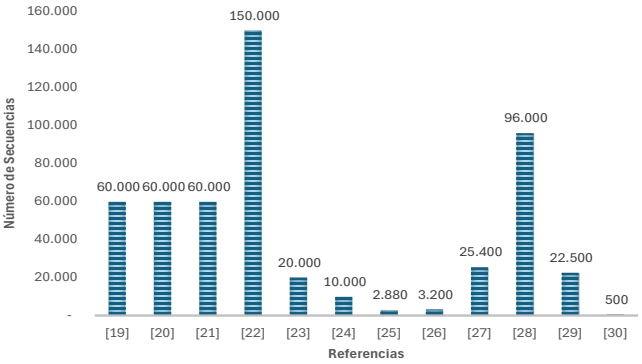

Figura 3: Cantidad de Secuencias de Datos usadas por distintos algoritmos
Fuente: Elaboración propia.

En resumen, los avances en algoritmos de aprendizaje profundo están transformando las interacciones H-M al mejorar significativamente la capacidad de representar con mayor fidelidad la personalidad humana [15]. Estos progresos incluyen tanto modelos basados en mecanismos de atención como redes neuronales recurrentes (como las LSTM) ofreciendo cada uno fortalezas particulares en la captura de comportamientos complejos (Tabla 3) [16]. Además, la cantidad de datos utilizada en el entrenamiento de estos modelos desempeña un rol crucial en su precisión y eficacia (Fig. 3) lo que subraya la necesidad constante de investigación y desarrollo en este campo dinámico y en rápida evolución [9].

Tabla 3.
Comparación de Fortalezas y Debilidades de Modelos de Aprendizaje Profundo

Modelos	Fortalezas	Debilidades
Enfoque Híbrido con LSTM, RNN y FNN	Combina la estructura de memoria a largo plazo con el modelado secuencial de RNN y la extracción de características FNN	Arquitectura compleja que exige mayor poder de cómputo
	Mejora la coherencia y entiende el contexto en las respuestas	Difícil ajuste de hiperparámetros al integrar varios submodelos
	Mayor flexibilidad ante distintas clases de datos	Riesgo de sobreajuste si no se cuenta con suficiente volumen de datos
MDN (Multi-Distribution Noise)	Permite modelar incertidumbre y variaciones en los datos de entrada	Requiere un diseño cuidadoso de las distribuciones para cada tarea
	Genera múltiples hipótesis de salida con sus probabilidades	Incrementa la complejidad probabilística del modelo
	Robusto frente a ruido y datos heterogéneos	Puede ser inestable si las distribuciones no están bien parametrizadas
LSI (Latent Semantic Indexing)	Captura relaciones semánticas latentes más allá de la coincidencia de términos	Pierde eficacia con vocabularios muy amplios o jerga local sin suficiente representación
	Útil para agrupar textos según subtexto emocional o temático	Depende de la calidad y tamaño de la matriz término-documento

Fuente: Elaboración propia

4. Discusión

La presente RSL reveló aspectos fundamentales para el desarrollo de la comunicación H-M mediante técnicas de DL, describiendo como ejemplo métodos para evitar pérdidas en los datos (como Transformer-based) que si bien ofrecen alta precisión exigen una gran cantidad de capacidad computacional, por lo que propusieron enfoques como el método MDN para prevenir gran pérdida de la precisión y menos consumo en almacenamiento y al ser comparado con otros modelos se pudo obtener mejores precisiones con menos datos [12].

También se identificó como una tendencia común en métodos y modelos el uso de modelos híbridos o mixtos que combinan diferentes modelos de red neuronal o métodos dentro de estas bases para compensar las debilidades individuales [12-18]. Este enfoque evolutivo es clave para estos estudios enfocados en la creación de una IA que no solo sea capaz de comunicarse sino que genere vínculos reales con el usuario reproduciendo rasgos de personalidad extraídos de información humana, con la posibilidad de construir incluso una moral emergente basada en dichos datos.

Entre los modelos analizados por Yu et al. [12] se observó que el modelo LSTM-RMC obtuvo un porcentaje de precisión menor al resto de algoritmos (31.60%) utilizando una gran cantidad de conjuntos de datos de WikiText-103 (122900 secuencias de datos) a diferencia de LRLSTM-1500 que empleó PENN Treebank consiguiendo un mayor porcentaje de precisión (89.46%) a pesar de usar una menor cantidad de datos (23,720 secuencias de datos). Uno de los mayores porcentajes de precisión (93.50%) fue obtenido por Hasibuan, Nugroho y Santosa [17] empleando el modelo LSI debido al trabajo en conjunto a las ANN demostrando una mejoría en el nivel de precisión del modelo y su representación de la personalidad humana.

Esto confirma que la calidad de los datos incide directamente en la precisión de los modelos de aprendizaje profundo afectando su capacidad para facilitar una comunicación H-M efectiva y una representación fidedigna de la personalidad humana.

Como se observa en la Fig. 3 la cantidad de datos utilizada por cada modelo puede variar significativamente. Por ejemplo, el modelo de Cohen et al. [29] empleó 225 000 secuencias mientras que el de Alamia et al. [30] trabajó con solo 500. Esta diferencia sugiere que el rendimiento puede depender no solo del volumen, sino también de la calidad del contenido y de la capacidad del algoritmo para extraer patrones significativos.

El análisis comparativo de los tres modelos principales (el enfoque híbrido -LSTM + RNN + FNN-, el algoritmo MDN y la técnica LSI) pone en evidencia tanto sus aportes al campo como las limitaciones y sesgos que pueden surgir en su aplicación a la replicación de la personalidad humana en sistemas de comunicación.

4.1 Complejidad y ajuste de modelos híbridos

Las arquitecturas híbridas combinan la memoria a largo plazo de LSTM, la secuencialidad de RNN y la extracción de características de FNN, logrando respuestas más coherentes

y contextualizadas. Sin embargo, requieren gran poder de cómputo y son complejas de ajustar: cada submodelo introduce hiperparámetros propios, lo que eleva el riesgo de sobreajuste si los datos de habla hispana no abarcan adecuadamente variaciones dialectales y expresiones regionales [13,16].

El MDN modela incertidumbre generando varias hipótesis de salida con sus probabilidades, lo que aumenta la robustez ante datos ruidosos o heterogéneos [12]. No obstante, depende de una parametrización cuidadosa de las distribuciones de lo contrario podría acentuar sesgos mayoritarios del corpus y perder matices culturales de subgrupos menos representados lo que podría limitar su aplicabilidad en contextos culturalmente diversos. El modelo LSI extrae relaciones semánticas latentes mediante SVD [17] pero sólo analiza texto estático sin capturar la dimensión temporal o emocional del discurso, además, en vocabularios extensos o con abundante jerga local se ve adectada la fidelidad de las representaciones semánticas y limita su aplicabilidad a contextos conversacionales reales.

Un reto común a todos los modelos es la representatividad del conjunto de datos. La mayoría de los estudios utilizan corpus en inglés o español formal, dejando fuera expresiones coloquiales y variaciones dialectales regionales lo que introduce sesgos sistemáticos en los resultados [5,6] y limita la capacidad de generalización de los modelos a entornos socioculturales diversos.

Toda esta información demuestra el papel fundamental que desempeñan las redes neuronales en el aprendizaje profundo, al facilitar el procesamiento eficiente de grandes volúmenes de información mediante diversos algoritmos. Asimismo, se destaca la relación planteada por Guest y Martin [17] entre las ANN y la ciencia cognitiva lo que respalda su potencial para simular de manera más realista la personalidad humana.

5. Conclusiones

En conclusión, se identificaron 3 enfoques de aprendizaje profundo con alto potencial para fortalecer la comunicación H-M mediante la recreación genuina de la personalidad, destacando entre ellos el modelo mixto de YiTao [13] que combina LSTM, RNN y FNN en un esquema de retroalimentación para mejorar la precisión y logró resultados más precisos que el resto de modelos al emplear múltiples modelos que se retroalimentan mutuamente para identificar relaciones dentro de la información y recrear mejor la personalidad humana. Hasibuan, Nugroho y Santosa [17] emplearon un modelo basado en LSI que fue capaz de hallar relaciones semánticas en grandes volúmenes de datos y el algoritmo de MDN de Yu et al. [12] se orientó a generar múltiples resultados al comprimir secuencias de datos extensas y reducir el almacenamiento, aumentando la precisión de su análisis mediante un procesamiento más sencillo y sin depender de grandes cantidades de datos. Por esa razón, estos modelos podrían llegar a ser muy buenos al imitar la gran mayoría de aspectos necesarios para hacer una comunicación lo más cercana a una personal real.

Los modelos basados en redes neuronales como Transformer, LSTM y RNN demostraron ser eficaces para comprender la personalidad humana y la captura de relaciones complejas de datos, permitiendo una mayor precisión debido a su facilidad para la comprensión de información abstracta. Las redes neuronales como ANN mostraron versatilidad al ser aplicadas no solo en NPL sino también se les puede dar un enfoque holístico tanto en la escritura como en el reconocimiento de voz o la reproducción propia de sonido para imitar el habla. La dependencia de grandes conjuntos de datos, la calidad del contenido y la distribución siguen representado un obstáculo para alcanzar este objetivo a pesar de que modelos como LSI han demostrado que es posible lograr buenos resultados sin grandes cantidades de datos, especialmente si se emplean técnicas adecuadas de aprendizaje.

Es esencial continuar investigando y desarrollando técnicas que no solo se enfoquen en la precisión, sino también métodos de aprendizaje mixto que permitan una mayor adaptabilidad en distintos contextos de interacción. Estos hallazgos pueden servir como base para futuras propuestas para optimizar la adaptabilidad de los modelos en diferentes contextos de interacción para mejorar su precisión y la naturalidad de la comunicación entre H-M.

Referencias

[1] Radford, A., Narasimhan, K., Salimans, T., and Sutskever, I., Improving language understanding by generative pre-training. amazon web services, [online]. 2018. Disponible en: https://s3-us-west-2.amazonaws.com/openai-assets/research-covers/language-unsupervised/

[2] Manakitsa, N., Maraslidis, G.S., Moysis, L., and Fragulis, G.F., A review of machine learning and deep learning for object detection, semantic segmentation, and human action recognition in machine and robotic vision. Technologies, 12(2), art. 20015, 2024. DOI: https://doi.org/10.3390/technologies12020015

[3] Negro, P., and Pons, C., Artificial Intelligence techniques based on the integration of symbolic logic and deep neural networks: a systematic review of the literature. Inteligencia Artificial, 25(69), pp. 13-41, 2022. DOI: https://doi.org/10.4114/intartif.vol25iss69pp13-41

[4] Maroto-Gómez, M., Castro-González, Á., Castillo, J.C., Malfaz, M., and Salichs, M.A., An adaptive decision-making system supported on user preference predictions for human–robot interactive communication. User Modeling and User-Adapted Interaction, 33(2), pp. 359–403, 2023. DOI: https://doi.org/10.1007/s11257-022-09321-2

[5] Hooshyar, D., Azevedo, R., and Yang, Y., Augmenting deep Neural Networks with symbolic educational knowledge: towards trustworthy and interpretable AI for education. Machine Learning and Knowledge Extraction, 6(1), pp. 593-618, 2024. DOI: https://doi.org/10.3390/make6010028

[6] Wang, P., Fan, E., and Wang, P., Comparative analysis of image classification algorithms based on traditional machine learning and deep learning. Pattern Recognition Letters, 141, pp. 61–67, 2021. DOI: https://doi.org/10.1016/j.patrec.2020.07.042

[7] Yilmaz, A.A., Guzel, M.S., Bostanci, E., and Askerzade, I., A novel action recognition framework based on deep-learning and genetic algorithms. IEEE Access, 8, pp. 100631–100644, 2020. DOI: https://doi.org/10.1109/ACCESS.2020.2997962

[8] Page, M.J., McKenzie, J.E., Bossuyt, P.M., et al. Declaración PRISMA 2020: una guía actualizada para la publicación de revisiones sistemáticas. Revista panamericana de salud pública, 46, art. 112, 2020. DOI: https://doi.org/10.26633/RPSP.2022.112

[9] Ger, Y., Nachmani, E., Wolf, L. and Shahar, N., Harnessing the flexibility of neural networks to predict dynamic theoretical parameters underlying human choice behavior. PLOS Computational Biology, 20(1), art. 1011678, 2024. DOI: https://doi.org/10.1371/journal.pcbi.1011678

[10] Kuroki-Júnior, G.H., and Gottschalg-Duque, C., Information architecture applied on natural language processing: a proposal. Information Science contributions on data pre-processing for training and learning of artificial neural networks. Revista Digital de Biblioteconomia e Ciência da Informação, 21, art. 023002, 2023. DOI: https://doi.org/10.20396/rdbci.v21i00.8671396/30919

[11] Remaida, A., Abdellaoui, B., Lafraxo, M.A., Sabri, Z., Nouib, H., El Idrissi, Y.E.B., and Moumen, A., Application of artificial neural networks for personality traits prediction based on handwriting. Indonesian Journal of Electrical Engineering and Computer Science, 31(3), pp. 1534-1544, 2023. DOI: http://doi.org/10.11591/ijeecs.v31.i3.pp1534-1544

[12] Yu, Z., Li, S., Sun, L., Liu, L. and Haining, W., Multi-distribution noise quantisation: an extreme compression scheme for transformer according to parameter distribution. Connection Science, 34(1), pp. 990–1004, 2022. DOI: https://doi.org/10.1080/09540091.2021.2024510

[13] YíTao, Z., Natural language processing with improved deep learning neural networks. Scientific Programming, 2022, pp. 1-8, DOI: https://doi.org/10.1155/2022/6028693

[14] Jäger, G., and Reisinger, D., Can we replicate real human behaviour using artificial neural networks?. Mathematical and Computer Modelling of Dynamical Systems, 28(1), pp. 95-109, 2022. DOI: https://doi.org/10.1080/13873954.2022.2039717

[15] Guest, O., and Martin, A.E., On logical inference over brains, behaviour, and artificial neural networks. Computational Brain & Behavior, 6, pp. 213-227, 2023. DOI: https://doi.org/10.1007/s42113-022-00166-x

[16] Alamia, A., Gauducheau, V., Paisios, D., and VanRullen, R., Comparing feedforward and recurrent neural network architectures with human behavior in artificial grammar learning. Scientific Reports, 10(1), pp. 22172, 2020. DOI: https://doi.org/10.1038/s41598-020-79127-y

[17] Hasibuan, M.S., Nugroho, L.E. and Santosa, P.I., Model detecting learning styles with artificial Neural Network. Journal of Technology and Science Education, 9(1), pp. 85-95, 2019. DOI: https://doi.org/10.3926/jotse.540

[18] Costa-Jussà, M.R., Nuez, Á., and Segura, C., Experimental research on encoder-decoder architectures with attention for chatbots. Computación y Sistemas, 22(4), pp. 1233-1239, 2018. DOI: https://doi.org/10.13053/cys-22-4-3060

[19] Cleeremans, A., Servan-Schreiber, D., and McClelland, J.L., Finite state automata and simple recurrent networks. Neural Computation, 1, pp. 372-381, 1989. DOI: https://doi.org/10.1162/neco.1989.1.3.372

[20] Servan-Schreiber, D., Cleeremans, A., and McClelland, J.L., Graded state machines: the representation of temporal contingencies in simple recurrent networks. Machine Learning, [online]. 7, pp. 161-193, 1991. Available at: https://link.springer.com/article/10.1007/BF00114843

[21] Cleeremans, A., and McClelland, J.L., Learning the structure of event sequences. Journal of Experimental Psychology: General, 120(3), pp. 235-253, 1991. DOI: https://doi.org/10.1037/0096-3445.120.3.235

[22] Giles, C.L., Miller; C.B., Chen, D., Chen, H.H., Sun, G.Z. and Lee, Y.C., Learning and extracting finite state automata with second-order recurrent neural networks. Neural Computation, 4, pp. 393-405, 1992. DOI: https://doi.org/10.10.1162/neco.1992.4.3.393

[23] Dienes, Z., Connectionist and memory-array models of artificial grammar learning. Cognitive Science, 16, pp. 41–79, 1992. DOI: https://doi.org/10.1207/s15516709cog1601_2

[24] Bodén, M., and Wiles, J., Context-free and context-sensitive dynamics in recurrent neural networks. Connection Science. 12(3/4), pp. 197-210, 2000. DOI: https://doi.org/10.1080/095400900750060122

[25] Kinder, A., and Shanks, D.R., Amnesia and the declarative/nondeclarative distinction: a recurrent network model of classification, recognition, and repetition priming. Journal of Cognitive Neuroscience, 13(5), pp. 648–669, 2001. DOI: https://doi.org/10.1162/089892901750363217

[26] Tunney, R.J., and Shanks, D.R., Subjective measures of awareness and implicit cognition. Memory & Cognition, 31, pp. 1060–1071, 2023. DOI: https://doi.org/10.3758/BF03196127

[27] Petersson, K.M., Grenholm, P. and Forkstam, C., Artificial grammar learning and neural networks. Proceedings of the 27th Annual Conference of the Cognitive Science Society, [online]. 2005, pp. 1726–1731. Available at: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=1bef0e63cefc9eefce22c32ae676350b714f6aca

[28] Wierzchon, M., and Barbasz, J.A., Wierzchoń, M., and Barbasz, J., A connectionist model of artificial grammar learning: simulations based on Higham (1997) Indexes of Knowledge Representation. 29th Annual Conference of the Cognitive Science Society, 2008.

[29] Cohen, M., Caciularu, A., Rejwan, I., and Berant, J., Inducing regular grammars using recurrent Neural Networks. Computation and Language, pp. 1-5, 2018. DOI: https://doi.org/10.48550/arXiv.1710.10453

[30] Alamia, A., Gauducheau, V., Paisios, D., and VanRullen, R., Which Neural Network Architecture matches Human Behavior in Artificial Grammar" Learning? Neurons and Cognition, 2019. DOI: https://doi.org/10.48550/arXiv.1902.04861

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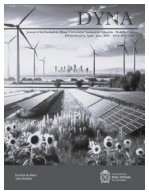

UNIVERSIDAD NACIONAL DE COLOMBIA

Compressive strength and diagonal compression in masonry made with artisanal brick in the province of Manabí

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Abstract
In Ecuador, masonry made with artisanal brick is widely used in buildings as a non-structural element in walls, which can be used as infill in portal frame systems. Recent earthquakes have shown that masonry influences the behavior of portal frames, highlighting the importance of understanding the mechanical properties of masonry to study the joint behavior of portal frames and masonry. This article presents the results of compression strength tests, diagonal compression strength tests, and modulus of elasticity tests on masonry elements made with artisanal brick from the province of Manabí. 27 prisms were subjected to compression loads and 27 walls were subjected to diagonal compression loads. The prisms failed due to vertical cracking or crushing of the piece, with an average compression strength of 3 MPa recorded, while the walls failed due to shear and displacement, and adhesive failures between the unit and mortar were observed, with an average shear strength of 0,61 MPa recorded.

Keywords: compression stress; diagonal compression stress; artisanal masonry; wall; prism.

Resistencia a compresión y compresión diagonal en mampostería elaborada con ladrillo artesanal en la provincia de Manabí

Resumen
En Ecuador, la mampostería elaborada con ladrillo artesanal se utiliza ampliamente en edificaciones como elemento no estructural en paredes, que pueden estar como relleno de los pórticos en sistemas aporticados. Sismos recientes han demostrado que la mampostería influye en el comportamiento de los pórticos, lo que resalta la importancia de conocer las propiedades mecánicas de la mampostería para estudiar el comportamiento conjunto pórtico-mampostería. Este artículo presenta los resultados de los ensayos de resistencia a compresión, resistencia a compresión diagonal y módulo de elasticidad de elementos de mampostería elaborados con ladrillo artesanal de la provincia de Manabí. Se sometieron a esfuerzos de compresión a 27 prismas y a esfuerzos de compresión diagonal a 27 muretes. Los prismas experimentaron fallas por agrietamiento vertical o trituración de la pieza y se registró una resistencia a la compresión promedio de 3 MPa, mientras que los muretes fallaron por corte y desplazamiento, y se observaron fallas de adherencia entre la unidad y el mortero, y una resistencia promedio al corte de 0,61 MPa.

Palabras clave: resistencia a compresión; resistencia a compresión diagonal; mampostería artesanal; murete; prisma.

1. Introducción

La mampostería elaborada con ladrillos artesanales de arcilla cocida ha sido tradicionalmente usada en el Ecuador para las paredes en edificaciones aporticadas. Los sistemas estructurales basados en pórticos de hormigón armado o basados en columnas de hormigón armado con losas planas han sido acompañados con paredes de mampostería que sirven para separar ambientes y/o dar seguridad al perímetro de las construcciones. Sismos recientes, y de gran magnitud, como el del 16 de abril del 2016, de 7,8 Mw., cuyo epicentro se ubicó cercano a la ciudad de Pedernales, en la provincia de

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Manabí [1], evidenció la poca rigidez de estos sistemas estructurales, los cuales presentaron gran daño en elementos no estructurales, estructurales e incluso colapsos de edificaciones [2], y que las paredes de mampostería (de relleno) condicionan el comportamiento de los sistemas estructurales debido a su aporte de rigidez y resistencia en pórticos que se asumen libres para los cálculos estructurales.

Investigaciones recientes han destacado el interés en evaluar la influencia de las paredes en el comportamiento de estructuras de pórticos [3–6]. En la literatura se han propuesto varios modelos para incluir la presencia de las paredes de mampostería en los análisis de comportamiento de pórticos. Estos modelos incluyen macromodelos como los expuestos por Asteris et al. [7], y micromodelos, como los indicados por Asteris et al. [8]. Para incluir la mampostería en los análisis de estructuras, independientemente del modelo propuesto, es necesario conocer las propiedades mecánicas de la mampostería construida con los materiales específicos a cada edificación. Esto implica la necesidad de realizar ensayos experimentales de la mampostería local. Los resultados de estos ensayos permiten caracterizar la mampostería y son útiles tanto para la evaluación de estructuras existentes que cuenten con este tipo de mampostería como para el diseño de nuevas estructuras con sistemas estructurales a base de mampostería.

El ladrillo de arcilla cocida es una pieza moldeada y cocida, en forma de paralelepípedo o de prisma regular, utilizada en albañilería. Existe ladrillos cerámicos fabricados a máquina, que siguen el proceso de amasado, moldeo y presión de la masa de arcilla, y ladrillos cerámicos artesanales, que no incluyen la etapa de prensado de la masa de arcilla. En la provincia de Manabí, Ecuador, se utilizan principalmente los ladrillos artesanales.

En este documento se presentan los resultados de ensayos experimentales realizados en probetas de prismas y muretes de mampostería elaboradas con ladrillos artesanales de la provincia de Manabí. Estas probetas fueron sometidas, respectivamente, a ensayos de compresión y compresión diagonal.

1.1 Fabricación de ladrillos artesanales de arcilla cocida

En la provincia de Manabí, Ecuador, aún se conserva la tradicional forma de elaboración de ladrillos artesanales de arcilla cocida. Existen varias fábricas de ladrillos artesanales que aprovechan la cercanía a las fuentes de materia prima en la provincia de Manabí. El proceso de fabricación de los ladrillos, mostrado en la Fig. 1, comienza con la obtención de la materia prima: arcilla, aserrín, cáscara de arroz y agua. Durante la selección de la arcilla, como se muestra en la Fig. 1a, los fabricantes evalúan su color y evitan el uso de arcilla de tonalidad oscura, ya que esta no asegura una cocción adecuada. Todos los materiales se mezclan hasta lograr una composición homogénea, como se observa en la Fig. 1b. La masa resultante se expone al sol para luego ser colocada en moldes con las dimensiones deseadas del ladrillo. La masa en los moldes se deja secar durante tres días hasta que pierda humedad, tal como se muestra en la Fig. 1c. Posteriormente

Figura 1. Proceso de fabricación de ladrillos.
Fuente: Fotografías tomadas por los autores

los ladrillos se apilan verticalmente y se trasladan al horno construido con otros ladrillos para iniciar el proceso de cocción, mostrado en la Fig. 1d. Este proceso continúa hasta obtener el ladrillo final. Si bien cada ladrillera tiene sus particularidades en cuanto a la adquisición de la materia prima, la dosificación de los materiales y el proceso de cocción, en general, el proceso es similar.

1.2 Propiedades de la mampostería

Entre las propiedades mecánicas de la mampostería, necesarias tanto para la evaluación de estructuras existentes como para el diseño de nuevas estructuras con mampostería estructural, se incluyen el esfuerzo máximo a la compresión, el módulo de elasticidad, el esfuerzo máximo a corte, y el módulo de corte, entre otros. Estas propiedades deben ser evaluadas mediante ensayos experimentales.

1.2.1. Esfuerzo máximo a compresión, $f_m^{'}$

El esfuerzo máximo a compresión de la mampostería típicamente se determina mediante ensayos de compresión de prismas, los cuales se someten a carga axial de compresión hasta el fallo a los 28 días de edad, de acuerdo con los lineamientos de ASTM C1314 [9, 10]. Los prismas se definen como una construcción de unidades de mampostería y mortero apiladas verticalmente, siendo la forma más común la construida como una columna de ladrillos macizos. En la Fig. 2 se muestra un esquema de un prisma utilizado para realizar el ensayo a compresión. En el esquema se definen el espesor *t*, el ancho *b*, y la altura *h*, como las dimensiones del prisma.

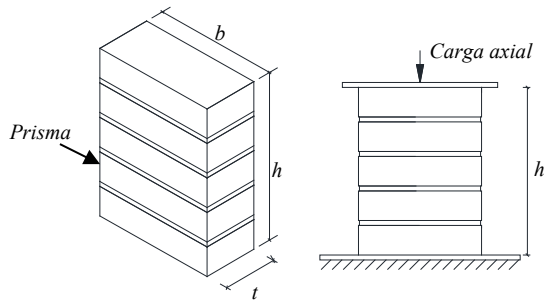

Figura 2. Esquema de prismas de mampostería a compresión
Fuente: Elaboración propia

El ensayo a compresión se realiza de manera que se controle adecuadamente la carga aplicada hasta el fallo del prisma ensayado. La carga debe aplicase en el eje del prisma, y la carga máxima aplicada, P_{max}, se divide entre el área de la sección transversal, $t \cdot b$, para obtener el esfuerzo a compresión. El esfuerzo a compresión así obtenido debe multiplicarse por un factor de corrección debido a la esbeltez del prisma, h/b, para obtener el esfuerzo máximo del prisma, $f_m^{'}$, como se indica en la ecuación 1. El factor de corrección por esbeltez se muestra en la Tabla 1.

$$f_m^{'} = \frac{P_{max}}{t \cdot b} \cdot C \quad (1)$$

Tabla 1.
Factor de corrección de esbeltez, *C*.

Relación h/b	1,3	1,5	2,0	2,5	3,0	4,0	5,0
C	0,75	0,86	1,00	1,04	1,07	1,15	1,22

Fuente: Norma ASTM C 1314-22

Los prismas se construyen de acuerdo con los objetivos del programa de ensayos en el caso de investigación y deben fabricarse de manera que reflejen la calidad de los materiales y la mano de obra que tendría la construcción en el caso de control de obras [10]. Una vez construidos los prismas en laboratorio deben almacenarse y cubrirse con polietileno durante los primeros 14 días; después de ese periodo deben ser expuestos a las condiciones ambientales del laboratorio hasta el ensayo, de acuerdo con las recomendaciones de ASTM C 1314 [9]. Antes del ensayo, los extremos de los prismas deben ser refrentados para garantizar una correcta transmisión de esfuerzos en toda la sección transversal, y todas las dimensiones del prisma deben registrarse para el posterior procesamiento de datos.

1.2.2 Módulo de elasticidad

El módulo de elasticidad de la mampostería, E_m, se puede determinar de manera experimental a partir de la curva esfuerzo-deformación obtenida en los ensayos de compresión de prismas. Se define como la pendiente de la secante desde $0{,}05\, f_m^{'}$ hasta $0{,}33\, f_m^{'}$. En ausencia de valores experimentales, o de información de la curva esfuerzo-deformación, puede empelarse la ecuación 2 para su cálculo.

$$E_m = 750\, f_m^{'} \leq 20000\, MPa \quad (2)$$

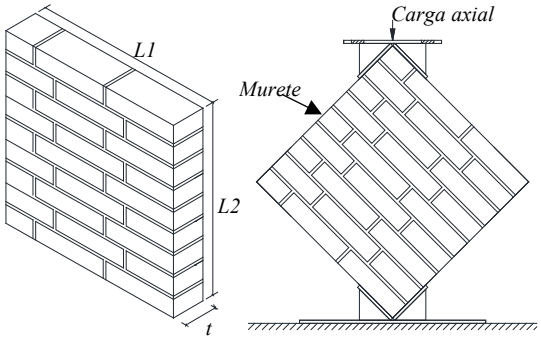

Figura 3. Esquema de muretes de mampostería a compresión diagonal
Fuente: Elaboración propia

1.2.3 Esfuerzo máximo a corte, compresión diagonal en muretes

La resistencia a corte de la mampostería se evalúa en términos de esfuerzos máximos ante ensayos de muretes sometidos a cargas de compresión diagonal, el cual se efectúa aplicando una carga de compresión sobre una diagonal de un murete hasta llevarlo al fallo, típicamente usando la norma ASTM E519/E519 M [11]. La Fig. 3 muestra un esquema de murete y el esquema del ensayo de compresión diagonal. Se definen el espesor *t*, el ancho *L1*, y la altura *L2*, como las dimensiones del murete.

2. Materiales y métodos

Se realizaron ensayos en prismas y muretes de mampostería, sometidos a cargas de compresión y compresión diagonal, respectivamente. Antes de la construcción de estos elementos, se caracterizó el mortero y los ladrillos utilizado en la fabricación de los prismas y muretes mediante ensayos estandarizados de esfuerzo de compresión. El esfuerzo a compresión del mortero se calculó como el promedio del esfuerzo máximo obtenido en seis probetas cúbicas de 50 x 50 x 50 mm, ensayadas según ASTM C109 [12].

En este estudio, se seleccionaron nueve fábricas de ladrillo de arcilla cocida en la provincia de Manabí, Ecuador. Se eligieron tres fábricas en la ciudad de Rocafuerte, tres en la ciudad de Santa Ana y tres en la ciudad de Montecristi. Para cada fábrica de ladrillo se construyeron y ensayaron tres prismas y tres muretes, resultando en un total de 27 prismas y 27 muretes. Los prismas tuvieron dimensiones promedio de 110 x 280 x 440 mm, y los muretes, dimensiones promedio de 110 x 575 x 575 mm, con un espesor de junta de mortero entre 15 y 20 mm. Las dimensiones de prismas y muretes fueron variables debido a la irregularidad de los ladrillos.

Una vez confeccionadas las probetas, estas fueron curadas según el procedimiento indicado en la norma ASTM E519/E519 M [11], que consiste en envolver las probetas en polietileno a las 24 horas de su confección. Luego de 14 días, se retira el polietileno, dejando las probetas expuestas a las condiciones climáticas del laboratorio hasta el día del ensayo, el cual se realizó entre los 30 y 35 días desde la confección de las probetas. Antes de los ensayos se refrentaron las

superficies de las probetas que estarían en contacto con las placas de acero que aplican la carga, para asegurar una correcta transferencia de carga de las placas a la probeta.

Los ensayos se realizaron en el Laboratorio de Estructuras de la Universidad Técnica de Manabí, utilizando un actuador hidráulico con bomba manual y una celda de carga de 300 kN de capacidad. La velocidad de carga promedio fue de 30 kN/min hasta el fallo de las probetas. Se registró la deformación vertical de las probetas mediante un transductor potenciométrico lineal (LVDT) con un recorrido máximo de 200 mm. Sin embargo, en este artículo solo se reportan los valores de cargas y esfuerzos máximos obtenidos en los ensayos. Para los prismas, se reporta el esfuerzo máximo a compresión, y para los muretes, el esfuerzo máximo a corte.

Para el análisis estadístico se utilizó la prueba ANOVA de un solo factor, empleando el método de comparaciones múltiples MCB de Hsu para identificar los mejores niveles de los factores, definiendo como "mejor" la media más alta. Este es el procedimiento generalmente utilizado.

3. Resultados y Discusión

Se muestran los resultados referentes a la resistencia a la compresión del mortero, la resistencia a la compresión de los prismas y los resultados de la resistencia a compresión diagonal de los muretes para las diferentes ladrilleras analizadas.

3.1 Resistencia a la compresión de mortero y ladrillos

En la Tabla 2 se presenta el esfuerzo de compresión de las muestras de mortero, cumpliendo con lo especificado en la NEC-15 para un mortero tipo M15. Los resultados de a 28 días superaron los 15 MPa, con un esfuerzo promedio de 16,10 MPa y una desviación estándar del 10 %.

3.2 Esfuerzo a la compresión de prismas

La Tabla 3 presenta los resultados de los ensayos a compresión realizados en los prismas, en los que se ha aplicado el factor de corrección por esbeltez. Los resultados están agrupados según el lugar de origen de los ladrillos. Los prismas provenientes de la ciudad de Rocafuerte alcanzaron una carga máxima de compresión de 124,0 kN y un esfuerzo máximo de 3,8 MPa; los prismas de Santa Ana alcanzaron una carga máxima de 145,1 kN y un esfuerzo máximo de 4,7 MPa; y los de Montecristi una carga máxima de 102,7 kN y un esfuerzo máximo de 3,8 MPa. El promedio de esfuerzo de compresión normalizado de los prismas de Rocafuerte fue de 3,6 MPa, para los prismas de Santa Ana de 3,9 MPa y para los de Montecristi de 2,7 MPa.

Tabla 2.
Esfuerzo a compresión del mortero.

Muestra	Esfuerzo a compresión MPa
M1	16,13
M2	16,09
M3	15,35
M4	16,53
M5	19,92
M6	15,74

Fuente: Elaboración propia

Tabla 3.
Esfuerzo a compresión de prismas.

Procedencia.	Muestra	Área cm²	Carga kN	Resistencia MPa	Rel. h/t	f´m MPa
	R 1.1	331,9	92,9	2,8	4,4	3,3
	R 1.2	303,7	109,5	3,6	4,7	4,3
	R 1.3	323,4	61,4	1,9	4,4	2,2
	R 2.1	327,0	124,0	3,8	3,9	4,3
Rocafuerte	R 2.2	295,3	54,2	1,8	4,1	2,1
	R 2.3	317,3	103,3	3,3	3,8	3,7
	R 3.1	309,4	90,3	2,9	4,2	3,4
	R 3.2	278,3	104,8	3,7	4,4	4,4
	R 3.3	295,6	107,4	3,6	4,3	4,2
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	S 1.1	327,3	97,5	3,0	3,5	3,3
	S 1.2	317,1	57,6	1,8	3,5	2,0
	S 1.3	321,8	89,7	2,8	3,4	3,1
	S 2.1	309,1	143,9	4,7	3,4	5,1
Santa Ana	S 2.2	310,8	145,1	4,7	3,4	5,1
	S 2.3	312,7	125,6	4,0	3,4	4,4
	S 3.1	304,7	98,3	3,2	3,7	3,6
	S 3.2	309,2	101,5	3,3	3,7	3,7
	S 3.3	299,8	123,6	4,1	3,6	4,6
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	M 1.1	322,9	58,3	1,8	3,2	2,0
	M 1.2	311,6	51,0	1,6	3,3	1,8
	M 1.3	305,3	40,4	1,3	3,3	1,5
	M 2.1	267,3	82,6	3,1	3,7	3,5
Montecristi	M 2.2	270,3	102,7	3,8	3,6	4,2
	M 2.3	272,7	79,5	2,9	3,7	3,3
	M 3.1	296,7	71,7	2,4	3,4	2,7
	M 3.2	289,4	86,1	3,0	3,3	3,3
	M 3.3	287,0	54,7	1,9	3,3	2,1

Fuente: Elaboración propia

Figura 4. Prismas de la ciudad de Rocafuerte. Antes y después del ensayo.
Fuente: Fotografías tomadas por los autores

Figura 5. Prismas de la ciudad de Santa Ana. Antes y después del ensayo
Fuente: Fotografías tomadas por los autores

Figura 6. Prismas de la ciudad de Montecristi. Antes y después del ensayo
Fuente: Fotografías tomadas por los autores

Los tipos de falla más comunes observados fueron el agrietamiento vertical y diagonal. También se observaron fallas por aplastamiento y trituración de las piezas de mampostería. En la Fig. 4 se muestra uno de los prismas ensayados de Rocafuerte, en Fig. 5 los de Santa Ana y en la Fig. 6 se muestra los de Montecristi.

3.3 Esfuerzo a la compresión diagonal en muretes

La tabla 4 presenta los resultados obtenidos de los ensayos a compresión diagonal en los muretes. Los muretes elaborados con ladrillos de la ciudad Rocafuerte alcanzaron una carga máxima de 96,6 kN y un esfuerzo máximo de 1,1 MPa; los muretes de Santa Ana alcanzaron una carga máxima de 71,9 kN y un esfuerzo máximo de 0,8 MPa; y los de Montecristi una carga máxima de 47,4 kN y un esfuerzo de 0,5 MPa. El promedio del esfuerzo a compresión diagonal obtenido de los muretes de Rocafuerte fue de 0,8 MPa, en los de Santa Ana de 0,6 MPa y en los de Montecristi de 0,4 MPa.

Tabla 4.
Esfuerzo a compresión diagonal de muretes.

Procedencia	Muestra	Área cm²	Carga kN	f´v MPa
	R 1.1	943,0	81,9	0,9
	R 1.2	981,1	65,6	0,7
	R 1.3	950,6	84,1	0,9
	R 2.1	1050,0	63,0	0,6
Rocafuerte	R 2.2	954,5	70,3	0,7
	R 2.3	918,0	96,6	1,1
	R 3.1	933,8	71,4	0,8
	R 3.2	939,4	71,6	0,8
	R 3.3	943,0	68,6	0,7
--	--	--	--	--
	S 1.1	946,0	55,3	0,6
	S 1.2	973,1	47,9	0,5
	S 1.3	946,0	38,6	0,4
	S 2.1	935,0	66,9	0,7
Santa Ana	S 2.2	929,5	62,0	0,7
	S 2.3	882,0	62,5	0,7
	S 3.1	903,0	71,9	0,8
	S 3.2	900,5	64,3	0,7
	S 3.3	875,5	29,6	0,3
--	--	--	--	--
	M 1.1	929,5	30,0	0,3
	M 1.2	918,5	34,1	0,4
	M 1.3	954,9	32,8	0,3
	M 2.1	832,1	37,4	0,4
Montecristi	M 2.2	850,2	43,3	0,5
	M 2.3	809,8	40,5	0,5
	M 3.1	917,4	37,4	0,4
	M 3.2	902,0	45,7	0,5
	M 3.3	918,4	47,4	0,5

Fuente: Elaboración propia

En algunos casos, los muretes ensayados a compresión diagonal exhibieron fallas escalonadas a través de las juntas de mortero y fallas por deslizamientos debido a la poca adherencia entre la unidad y el mortero, lo que ocasionó el desprendimiento de ladrillos. La Figs. 7, 8 y 9 muestran muretes de las ciudades de Rocafuerte, Santa Ana, y Montecristi, respectivamente, antes y después del ensayo; permitiendo observar los modos de falla característicos.

3.4 Análisis estadístico de los ensayos

Se aplicó la prueba ANOVA a los resultados obtenidos en las pruebas de resistencia a la compresión presentados en la Tabla 3. Como resultado se utilizó la columna “f’m” y como factores la columna “Procedencia”. Se obtuvieron los resultados que se presentan en la Tabla 5.

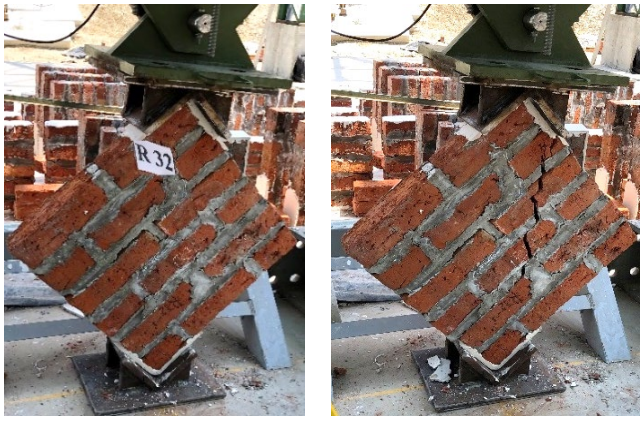

Figura 7. Murete de la ciudad de Rocafuerte. Antes y después del ensayo
Fuente: Fotografías tomadas por los autores


Figura 8. Murete de la ciudad de Santa Ana. Antes y después del ensayo
Fuente: Fotografías tomadas por los autores

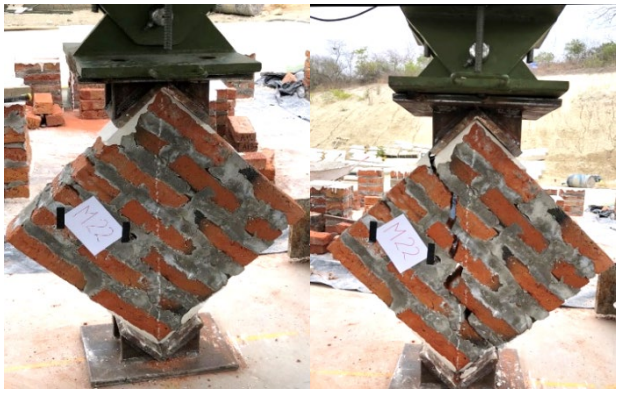

Figura 9. Murete de la ciudad de Montecristi. Antes y después del ensayo
Fuente: Fotografías tomadas por los autores

Tabla 5.
Resultados de la prueba ANOVA para la resistencia a la compresión.

Fuente	GL	SC Ajust.	MC Ajust.	Valor F	Valor p
Procedencia	2	6,500	3,2500	3,65	0,041
Error	24	21,367	0,8903		
Total	26	27,867			

Fuente: Elaboración propia

Como se observa en la Tabal 5, el valor p obtenido en la Tabla 5 es menor a 0,05. Con lo cual se rechaza la hipótesis nula y se acepta la hipótesis de investigación de que existe una diferencia en las medias de las muestras. Mediante el gráfico de intervalos mostrado a continuación en la Fig. 10, se puede verificar que la mejor resistencia a la compresión la obtuvieron las muestras de la región de Santa Ana.

Para los resultados obtenidos en la Tabla 4 sobre resultados de esfuerzo a la compresión en diagonal, se realizó la misma prueba. Se tomaron como resultado la columna "f'v" y como factores la columna "Procedencia". Se obtuvieron, los resultados que se presentan en la Tabla 6.

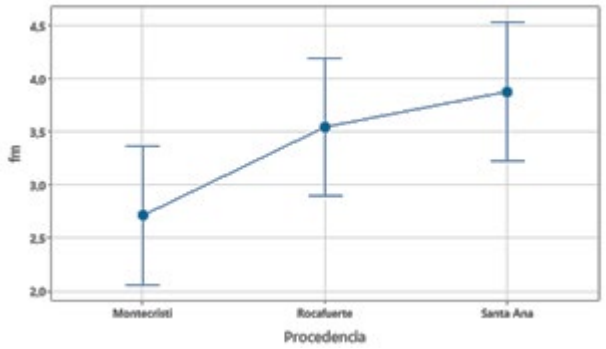

Figura 10. Gráfica de intervalos de f'm vs Procedencia (95 % IC para la media)
Fuente: Elaboración propia

Tabla 6.
Resultados de la prueba ANOVA para el esfuerzo a la compresión diagonal.

Fuente	GL	SC Ajust.	MC Ajust.	Valor F	Valor p
Procedencia	2	0,6430	0,32148	16,94	0,000
Error	24	0,4556	0,01898		
Total	26	1,0985			

Fuente: Elaboración propia

Como se observa en la Tabla 6, el valor p obtenido en la Tabla 5 es menor a 0,05, lo que permite rechazar la hipótesis nula y aceptar la hipótesis de investigación que sostiene que existe una diferencia en las medias de las muestras. El gráfico de intervalos, mostrado en la Fig. 11, confirma que las muestras de la ciudad de Rocafuerte obtuvieron los mayores esfuerzos a la compresión diagonal.

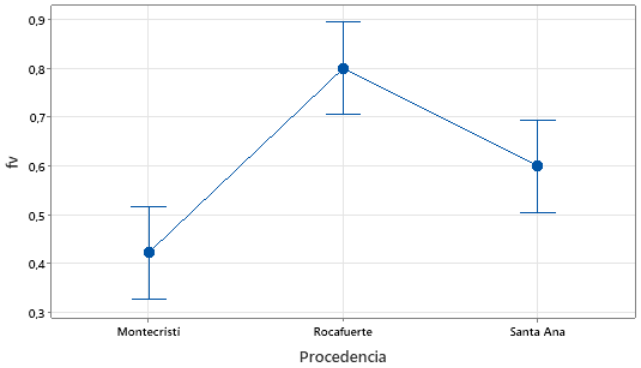

Figura 11. Gráfica de intervalos de f'v vs Procedencia (95 % IC para la media)
Fuente: Elaboración propia

4. Conclusiones

El esfuerzo promedio de compresión normalizado fue de 3,6 MPa para los prismas de Rocafuerte, 3,9 MPa para los de Santa Ana y 2,7 MPa para los de Montecristi. Los esfuerzos a compresión diagonal (corte) promediaron 0,8 MPa en los muretes de Rocafuerte, 0,6 MPa en los de Santa Ana y 0,4 MPa en los de Montecristi.

Las fallas predominantes en los prismas fueron el agrietamiento vertical del prisma y la trituración de las unidades, atribuibles al proceso de fabricación del ladrillo. Los muretes ensayados a compresión diagonal presentaron fallas escalonadas a través de las juntas de mortero, y deslizamientos por baja adherencia unidad-mortero, lo que provocó el desprendimiento del mampuesto.

Se encontraron diferencias estadísticamente significativas entre las resistencias a la compresión y a la compresión en diagonal, siendo las mejores muestras las de Santa Ana y las de Rocafuerte, respectivamente.

La resistencia a compresión y corte en paredes de relleno de pórticos es significativa debido a la resistencia del ladrillo artesanal combinado con la gran área transversal de las paredes en relación con las columnas, lo que explica que muchas estructuras con columnas que no cumplen la normativa resistieron el sismo. Lo anterior también da perspectivas de utilizar las paredes de esas estructuras para utilizarlas en el reforzamiento de estructuras consideradas vulnerables ante sismos.

Referencias

[1] IG-EPN., Observaciones del sismo del 16 de abril de 2016 de magnitud Mw 7.8, Intensidades y aceleraciones, IG-EPN. 2016.
[2] Aguiar, R., y Mieles, Y., Análisis de los edificios que colapsaron en Portoviejo durante el terremoto del 16 de abril de 2016, Revista Internacional de Ingeniería de Estructuras, 21(3), pp. 257-282, 2016.

[3] Aşikoğlu, A., Vasconcelos, G., Lourenço, P., and Pantò B., Pushover analysis of unreinforced irregular masonry buildings: lessons from different modeling approaches, Engineering Structures. (218), art. 110830, 2020. DOI: https://doi.org/10.1016/j.engstruct.2020.110830
[4] Mehrabi, A., Benson-Shing, B., Michael, P. Schuller, P., and James L.-N., Experimental evaluation of masonry-infilled RC frames, Journal of Structural Engineering. 122(3), pp. 228–237, 1996. DOI: https://doi.org/10.1061/(ASCE)0733-9445(1996)122:3(228)
[5] Kakaletsis, D., and Karayannis, C.-G, Influence of masonry strength and openings on infilled R/C frames under cycling loading, Journal of Earthquake Engineering. 12(2), pp. 197–221, 2008. DOI: https://doi.org/10.1080/13632460701299138
[6] Pokharel, S., Biswal, D.R., Sahoo K.K., and Dhir, P.K.P., Seismic performance of masonry-infilled RC frames and its implications in design approach: a review. Practice Periodical on Structural Design and Construction, 29(2), art. 03124001, 2024. DOI: https://doi.org/10.1061/PPSCFX.SCENG-1337
[7] Asteris, P.G., Antoniou S.T., Sophianopoulos, D.S., and Chrysostomou, C.Z., Mathematical macromodeling of infilled frames: state of the art, Journal of Structural Engineering, 137(12), art. 0000384, 2011. DOI: https://doi.org/10.1061/(asce)st.1943-541x.0000384
[8] Asteris, P.G., Cotsovos, D.M., Chrysostomou, C.Z., Mohebkhah, A., and Al-Chaar., G.K., Mathematical micromodeling of infilled frames: state of the art. Engineering Structures [online]. (56), pp. 1905–1921, 2013. DOI: https://doi.org/10.1016/J.ENGSTRUCT.2013.08.010
[9] ASTM C1314-22, Standard test method for compressive strength of masonry prisms, ASTM International. 2022.
[10] Cuza-Bayón, E., Reyes-Viñas, O., Fundora-Sautié, N., y Martínez-Cid, J.O., Revisión bibliográfica sobre ensayos a compresión en prismas de mampostería, Revista Ciencia y Construcción., 3(1), pp. 90–109, 2022.
[11] ASTM E519/E519M-21, Standard test method for diagonal tension (shear) in masonry assemblages, B.M.: ASTM International West Conshohocken, PA, USA. 2021
[12] ASTM C109/C109M, Standard test method for compressive strength of hydraulic cement mortars (using 2-in, or [50 mm] cube specimens), ASTM International, 04(2), 2020.

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- MetS: an interactive application to identify metabolites in Liquid chromatography-mass spectrometry experiments with data independent acquisition.
- Emerging trends in retail analytics: a bibliometric analysis of the last decade.
- A new thin-film solar cell prototype based on Na-doped $BiFeO_3$.
- Peace and Region Semester, a strategy for comprehensive university training and contribution to regional development.
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- Resistencia a compresión y compresión diagonal en mampostería elaborada con ladrillo artesanal en la provincia de Manabí.