Wax coating and Ag-TiO_2 nanoparticles as alternatives to preserve postharvest quality of the purple passion fruit (*Passiflora edulis* f. *edulis*)

Recubrimiento con ceras y nanopartículas de Ag-TiO_2 como alternativas para preservar la calidad poscosecha de frutos de gulupa (*Passiflora edulis* f. *edulis*)

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ABSTRACT

The purple passion fruit (*Passiflora edulis* f. *edulis*) is a highly sought climacteric fruit on the global market, but its short postharvest life makes international commercialization difficult. The objective of this study was to evaluate the implementation of wax coatings and silver-doped titanium dioxide nanoparticles (Ag-TiO_2-NPs) to preserve the postharvest quality parameters of the purple passion fruits. After the waxes and NPs synthesized using the combustion solution method were applied, the fruits were packed in plastic bags and cardboard boxes. Treatments were evaluated under two different storage conditions: room temperature (18°C, domestic market) and refrigeration (7°C, export market) + 1 week of shelf life. Physicochemical variables were measured periodically, and at the end of each storage condition, a consumer perception analysis was performed using natural language processing. The coating treatments did not favor postharvest behavior in the two experiments, and only increased brightness of the fruits was evident. In the refrigeration experiment, the application of Ag-TiO_2-NPs alone had a positive effect on the delaying parameters like respiration rate (decrease of up to 55% compared to the control), color (up to 80% less), total soluble solids (lower by ~ 10%), and titratable acidity (increased ~ 5%), with no effect on the perception of taste and visual characteristics identified by consumers. However, this treatment did not show consistent effects at room temperature (18°C). These findings support the viability of nanoparticle application as a strategy to preserve the postharvest quality of passion fruit destined for exportation and wax coatings to improve visual fruit perception.

Key words: respiration, ethylene, shelf life, natural language processing, consumer perception.

RESUMEN

La gulupa (*Passiflora edulis* f. *edulis*) es una fruta climatérica altamente deseada en el mercado global, pero con una corta vida poscosecha, lo que dificulta su comercialización en mercados internacionales. El objetivo del presente estudio fue evaluar la implementación de recubrimientos de ceras y nanopartículas de dióxido de titanio dopadas con plata (Ag-TiO_2-NPs) para preservar los parámetros de calidad poscosecha del fruto de gulupa. Después de aplicar las ceras y las NPs sintetizadas usando el método de combustión en solución, las frutas se empacaron en bolsas plásticas y luego en cajas de cartón. Posteriormente, se evaluaron los tratamientos bajo dos condiciones de almacenamiento diferentes, a temperatura ambiente (18°C, para el mercado doméstico) y refrigeración (7°C, para el mercado de exportación) + 1 semana de vida útil. Se midieron periódicamente variables fisicoquímicas y, al final del almacenamiento, se realizó un análisis de percepción del consumidor utilizando procesamiento de lenguaje natural. Los resultados indican que los tratamientos con encerado no tuvieron un efecto favorable en el comportamiento poscosecha en los dos experimentos, sólo se evidenció un mayor brillo de los frutos. Por otro lado, en el experimento de refrigeración, la aplicación de únicamente Ag-TiO_2 NPs tuvo un efecto positivo al ralentizar parámetros como la tasa de respiración (disminución hasta en un 55% comparado con el control), el color (hasta un 80% menos), los sólidos solubles totales (menores en ~ 10%) y la acidez titulable (aumentó ~ 5%), sin efecto en la percepción del sabor y las características visuales identificadas por los consumidores. Pero este tratamiento no mostró efectos consistentes a temperatura ambiente (18°C). Estos hallazgos apoyan la viabilidad de la aplicación de NPs como una estrategia para preservar la calidad poscosecha de la gulupa destinada a la exportación, y de los recubrimientos de cera para mejorar la percepción visual del fruto.

Palabras clave: respiración, etileno, vida en anaquel, lenguaje natural de procesamiento, percepción del consumidor.

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Introduction

The purple passion fruit (*Passiflora edulis* Sims f. *edulis*) is cultivated mainly in subtropical and tropical regions with an elevation between 1600 and 2300 m a.s.l. (De Armas Costa *et al*., 2022; Fischer *et al*., 2022). This Passifloraceae species is one of the most desired exotic fruits in the world and is adequately valued for its flavor, aroma, and presence of biofunctional compounds with medicinal potential (such as its high content of vitamin C, antioxidants, and fiber) that make it a healthy option for human consumption (Lozano-Montaña *et al*., 2021; Vuolo *et al*., 2019). Passion fruit is one of the most important exotic fruits in production in the tropics. Brazil is the world's largest producer of passion fruit, mainly cultivating the yellow variety (*Passiflora edulis* f. *flavicarpa*) and principally for the domestic market. Colombia is also a significant producer of these fruits, but Ecuador and Peru are major players in the international market (Fonseca *et al*., 2022). For this reason, the Colombian agro-industry has shown considerable interest in increasing crop production in recent years (Bernal Durán, 2022; Rincón Munar, 2020). For 2022, Colombia's national output of fruits reached 32,353.78 t in an area of 2,059.47 ha, with exports totaling 14,600 t (Agronet, 2023; ANALDEX, 2023).

The purple passion fruit is a berry with a spherical or ovoid shape, measuring 5.2 to 8.0 cm in length and 4.7 to 7.2 cm in diameter. It has a hard, smooth, and waxy skin (pericarp), about 3.0 to 4.5 mm thick, with a spongy, white mesocarp (Ocampo *et al*., 2020). The immature fruit is pale green and turns dark purple when ripe. The fruit weight ranges from 46 to 76 g (Ocampo *et al*., 2020). The maturity stage ideal for harvest corresponds to a fruit color of 40-50% green and 40-50% purple; at this point, the fruits reach the maximum total pulp fresh weight and the highest content of soluble solids (15.9 ºBrix) and decrease contents of titratable acidity to less than 4.65% (Pinzón *et al*., 2007). During the postharvest period, passion fruits experience loss of moisture and firmness, skin darkening, microorganism growth, nutrient degradation, cell wall rupture, wrinkling, and eventual senescence, resulting in a short shelf life (Nxumalo & Fawole, 2022; Zhou *et al*., 2022). Depending on the storage conditions, the storage time of purple passion fruit can range between 13 and 48 d (Herrera *et al*., 2024). Due to its climacteric behavior, passion fruit undergoes a physiological process characterized by a significant increase in the respiration rate during ripening accompanied by ethylene biosynthesis. While this promotes ripening of the fruits, it simultaneously accelerates its deterioration (Calderón-Martínez *et al*., 2021; De Armas Costa *et al*., 2022). Therefore, it is essential to develop appropriate preservation technologies to maintain fruit quality and improve shelf life.

It is necessary to control the rate of transpiration, respiration, ethylene production, and microbial infection, as these measures allow for prolonging the shelf life of the fruits and minimizing the losses during postharvest (Barsha *et al.,* 2021; Yahia & Carrillo-López, 2018). Among the various postharvest treatments, some techniques, such as the application of edible coatings based on oil, wax, and chemical products as microbial control agents (Gemail *et al*., 2023; Nxumalo & Fawole, 2022; Zhou *et al*., 2022), are used. In this way, the application of wax acts as a protective barrier against the entry of oxygen into the fruits and the loss of fruit moisture, thus obtaining a modified atmosphere allowing the control of the ripening process and postharvest quality of the fruits (Devi *et al*., 2022; Yahia & Carrillo-López, 2018). In purple passion fruit stored at room temperature, Zhou *et al.* (2022) found that a multifunctional coating based on chitosan and tannic acid delayed weight loss, firmness, shrinkage index, and prolonged postharvest life by 7 d.

There are other postharvest management alternatives, such as the application of nanoparticles; this technology is up-and-coming and is arousing great interest in various fields due to its antifungal activity (Nevado-Velasquez *et al*., 2023; Sadek *et al*., 2022) in kiwifruit (Li *et al*., 2022) and mangosteen (Thammachote *et al*., 2023). Nanoparticles can be doped with certain elements that allow them to absorb or eliminate ethylene and extend the shelf life of fruits (Ali *et al*., 2020; Nevado-Velasquez *et al*., 2023). Titanium dioxide nanoparticles (Ag-TiO_2-NPs) are reported to inhibit ethylene biosynthesis by suppressing genes that encode enzymes of ACC synthase (ACS) and ACC oxidase (ACO) (Elatafi & Fang, 2022; Naing & Kim, 2020). Additionally, the combined use of waxes and nanoparticles is evaluated in several fruits (Cid-López *et al*., 2021; Taha *et al*., 2022) because their properties improve postharvest benefits. In this sense, in banana fruits, the addition of chitosan coating and zinc oxide nanoparticles (ZnO-NPs) generates better postharvest performance (La *et al*., 2021).

There is a trend for healthy foods like purple passion fruits to meet a series of basic parameters known as multidimensional quality (Ramirez-Gil *et al*., 2019). This includes sensory attributes, nutritional values, chemical constituents, mechanical properties, functional properties, defects, physical and visual appearance, safety, and additional aspects of consumer perception and preferences (Abbott, 1999; Ramirez-Gil *et al*., 2019; Saba *et al*., 2018). So, it is necessary to view quality from an integral perspective, emphasizing consumer perception and the analytical characteristics that determine it (Godrich *et al*., 2020; Nicolaï *et al*., 2014; Péneau *et al*., 2006).

Purple passion fruits show great potential for countries with emerging production systems, such as Colombia (Rincón Munar, 2020). However, the fruit's current export potential is limited by postharvest problems that significantly affect multidimensional quality criteria, especially visual parameters (color, shine, shape) easily detectable by consumers. This creates a technological gap that must be addressed with highly innovative technological tools such as nanoparticles and wax coatings. However, the role of waxes and nanoparticles in the quality of purple passion fruits has not been investigated. This research aimed to evaluate the effect of waxes and silver-doped titanium dioxide nanoparticles on postharvest quality parameters of purple passion fruits destined for two well-defined markets: national and international.

Materials and methods

The fruits and their initial characterization

High-quality purple passion fruits destined for exportation were acquired through the export company OCATI S.A. (Colombia). The chosen fruits had reached harvest maturity (50-80% of their peel with a purple color), with weight between 60-80 g. They were free of physical defects or phytosanitary problems. Before beginning the experiments, the fruits were disinfected with sodium hypochlorite (5%). The experiments were conducted at the Laboratorio de Calidad y Poscosecha de Productos Agrícolas de la Facultad de Ciencias Agrarias, Universidad Nacional de Colombia, Bogotá.

In the first part of the experiment, we characterized the fruits to establish a baseline for their physical, chemical, and biochemical qualities. We selected five random samples and measured the total titratable acidity, epidermis elasticity, firmness, color index, respiratory intensity, and contents of soluble solids. The protocols and quantification details are described in the following sections. This essential characterization at the start of the experiment is presented in Table 1.

TABLE 1. Physicochemical parameters of purple passion fruits at the start of the experiment.

Parameter	Value
Total titratable acidity (% citric acid)	3.1 ± 0.7
Epidermis elasticity (mm)	13.9 ± 0.6
Firmness (N)	23.1 ± 1.3
Color index	12.9 ± 4.4
Respiratory intensity (CO_2 cm^3 kg^{-1} h^{-1})	60.6 ± 4.3
Total soluble solids (° Brix)	14.9 ± 0.4

Experimental design and treatments

We carried out two experiments with the same treatments, one at room temperature (18°C and relative humidity (RH) of 75%) and the other in refrigerated storage (7°C and RH 90%) for 43 d + 1 week of shelf life (18°C), each with a specific market focus, with room temperature for the domestic market and low temperature for the export market. In each experiment, we used an completely randomized experimental design with 4 treatments; these were the application of wax (W), the combination of wax and Ag-TiO_2-NPs (W+N), the application of Ag-TiO_2-NPs (N), and a control treatment (C) where neither the wax nor the nanoparticles were applied. Each treatment had 4 replicates, and each experimental unit comprised 5 fruits. To store the fruits, we placed them in commercial plastic bags, packaging XtendR (coded B2) from StecPac (StePacPPC, Tefen, Israel), with dimensions of 53.6 × 40 cm^2, internal gussets of 9 cm, a thickness of 0.025 ± 0.002 mm^2, and 30 perforations of 0.62 ± 0.11 mm^2 in diameter (Herrera *et al*., 2024), which generated a modified atmosphere. After that we placed this plastic packaging in a 30x20x15 cm cardboard box, specifically for international trade.

Wax application

We conducted a preliminary test to establish the optimal dilution ratio for the wax application. This test determined that a 50% dilution in water (v/v) was most effective. The dilution allowed the wax to form a uniform layer on the surface of the fruits, significantly reducing dehydration during storage. The wax imparted a notorious shine to the fruits, enhancing their visual quality, a crucial factor for consumer appeal in domestic and international markets.

A microsprinkler was used to apply a uniform film over the entire surface of the fruits, guaranteeing the total coverage of each fruit. The wax was allowed to dry. The wax corresponded to a commercial product used after harvest, "Coatings Passiflora" (Coatings SAS®, Colombia), a natural resin solution developed especially for the coating of yellow passion fruits, granadilla fruits, and purple passion fruits, with the following characteristics: boiling point of 75 ± 5°C, pH of 7.8-8.2, with a medium viscous liquid appearance, brownish color, and compatibility to be dissolved in water.

Application of silver-doped titanium nanoparticles (Ag-TiO_2-NPs)

The Ag-TiO_2-NPs used were synthesized, characterized, and provided by the Ceramics and Glasses Group, Facultad de Ciencias, Universidad Nacional de Colombia, Medellín campus, and the Nanostructures and Applied Physics Group (NANOUPAR), Academic Directory, Universidad Nacional de Colombia, La Paz campus. Ag–TiO_2 nanoparticles were synthesized via the combustion solution method (Deganello & Tyagi, 2018; Sane *et al*., 2018) using titanium isopropoxide and silver nitrate as precursors and glycine as a reducing agent (Nevado-Velasquez *et al*., 2023). Titanium oxynitrate was formed through reactions with nitric acid. Silver doping (0-4.5 mol%) and glycine were added, followed by heating to 300°C, yielding a pale-yellow residue (Nevado-Velasquez *et al*., 2023). For this process, the combustion solution method was used to ensure size and synthesis, following the methodology and structural and morphological characterization through various techniques: XRD analysis and scanning electron microscopy. For particle size determination, approximately 400 particles were counted in 23 SEM photomicrographs for each of the TiO_2 samples with different concentrations of Ag (Nevado-Velasquez *et al*., 2023).

Ag-TiO_2-NPs were used at a dose of 400 mg kg^{-1} TiO_2 with 0.75% Ag; this was based on previous results in fruit trees, where no damage was observed to the epidermis and physical-chemical quality parameters improved along with antimicrobial activity (Nevado-Velasquez *et al*., 2023). Given the nature of the compound, the nanoparticles were applied by dissolving them in sterile distilled water, a process performed via ultrasound to ensure the correct and uniform dilution of the particles in the water. The fruits were then immersed in the solution. For the treatment of wax and nanoparticles, the fruits were immersed in the Ag-TiO_2-NPs solution as follows. After drying, the wax was applied, as explained above, mixing the nanoparticles in the wax solution and ensuring that the fruits were wholly dried to avoid any excess that could generate a spill or any section with poor coverage.

Variables evaluated in purple passion fruits

We measured nondestructive variables every week, while we determined destructive variables at the beginning of the experiment and at the end of storage. In the case of the refrigeration experiment, they were also measured at the end of shelf life. A consumer perception analysis was performed at the end of each experiment to identify consumer perceptions of visual characteristics such as shape, color, firmness, presence of external damage, and parameters of taste and flavor.

Nondestructive variables

For respiratory intensity (RI, cm^3 CO_2 kg^{-1} h^{-1}) and ethylene production (μl C_2H_4 kg^{-1} h^{-1}), we followed the protocol step by step reported by Reyes *et al*. (2024). We placed each fruit inside an airtight glass chamber with a volume of 428.94 ml. After 1 h at the same storage temperature, we determined the CO_2 emission using a portable gas analyzer (Dansensor CheckPoint 3 Ametek-Mocon, Berwyn, PA, USA). After this, the fruits continued in the chambers for 2 h, and a 1 cm^3 sample of the gas was taken from the vessel's headspace. The gas sample was injected into an Agilent Technologies 7890A gas chromatograph (GC) (Agilent Technologies, Santa Clara, CA) equipped with a flame ionization detector (FID) and an HP-PLOT column (30 m x 0.55 mm x 40 μm; Castellanos *et al*., 2017).

We calculated weight loss (%) according to González *et al.* (2021) as the difference in weight of each sampling at the beginning of the experiment to a sample of approximately 60 g of fruits. We measured the fresh mass on a precision balance of 0.001 g (Ohaus-Pioneer, Colombia). We calculated the color index (CI) of the epidermis according to Cepeda *et al.* (2021), measuring the chromatic coordinates L* (lightness), a* (green/red), and b* (blue/yellow) of the CIELab color space using a Minolta CR 400 digital colorimeter (Konica Minolta, Chiyoda, Tokyo, Japan). We took three measurements in the equatorial fruit zone.

Destructive variables

We determined fruit firmness (N), and elasticity (mm) using a Lloyd Instrument LS1 digital material tester with a 1 kN load cell, a cylindrical punch of 3 mm, and Nexygen plus software. For total titratable acidity (TTA, % of citric acid), we carried out an acid-base titration with NaOH (0.1 N). Total titratable acidity was determined by incorporating 2 ml of juice in 25 ml of distilled water and proceeding to potentiometric titration until reaching pH 8.2 with a 916 Food Ti-Touch 120 automatic titrator (Metrohm, Herisau, Switzerland) (Gutiérrez-Villamil *et al*., 2023). We obtained the contents of total soluble solids (TSS) from approximately 1 ml of juice by reading in a Hanna digital refractometer with a range of 0 to 85% (Hanna Instruments, Spain).

We determined electrolyte leakage (EL, %; Eq. 1) as the electrical conductivity ratio according to Gutiérrez-Villamil *et al*. (2023), by which 10 disks of 0.5 cm in diameter were cut from the epidermis of each fruit. The disks were inserted into a plastic tube with 10 ml of deionized water and left at room temperature for 30 min. We measured electrical conductivity (EC_1) using an EC electrode. After measurement, the sample was heated at 90°C in a water bath for 15 min, allowed to cool, and the second EC (EC_2) was estimated.

$$EL(\%) = EC1/EC2 \times 100 \quad (1)$$

Consumer perception analysis

The perception of a product has been traditionally approached in two ways. The first was through expert panels, and the second was through consumer surveys. The first method is costly and presents logistical challenges, making it less viable for widespread use in these tests (Nicolaï *et al.*, 2014). On the other hand, consumer surveys traditionally require a large sample size and include specific intrinsic characteristics of the population being estimated (age, gender, race, economic income, social strata). This makes the process time-consuming and logistically demanding (Nicolaï *et al.*, 2014).

To incorporate consumer perception into our study, we designed a survey method based on ranking the importance of various quality characteristics such as appearance (internal-external), color, shine, aroma, texture (internal-external), flavor, and purchase criteria. We used an open-ended question format to capture the sensations, perceptions, and feelings generated by the fruits subjected to different treatments. We also focused on visual and taste characteristics upon consumption. We implemented a natural language processing method to extract as much information as possible and compensate for the number of respondents (n). This method analyzes the words used in open responses to find patterns and identify the emotions evoked by the fruits (positive, negative, or neutral) (Chong *et al.*, 2014; Hamilton & Lahne, 2020; Sun *et al.*, 2017).

The evaluated population consisted of students, professors, and administrative personnel from the Facultad de Ciencias Agrarias of the Universidad Nacional de Colombia, Bogotá campus. We randomly selected participants (n=25), avoiding any type of bias in selection, to ensure a diverse and plural representation. This methodology ensured that the sample adequately reflected fruit consumption, similar to how it is observed in an everyday market. We performed a sensory profile test based on a descriptive analysis, using a survey in which we characterized the fruit aroma, flavor, texture, and visual perception. We neutralized fruit flavors with soda crackers. The survey structure was implemented via Google Forms. We conducted the survey only for academic research purposes, with a commitment to the noncommercial use of the collected data. Participants were informed of the nature of the study and provided their consent before proceeding.

Statistical analysis

We used open software R 4.3.1 in which a multivariate approach analysis was implemented, using a PERMANOVA (P<0.05), except for the weight loss percentage, respiratory intensity, and ethylene rate variables that were analyzed employing a repeated measures model over time, and a *post hoc* analysis using Fisher's least significant difference test (LSD, P<0.05). For both methods, all assumptions were corroborated. The sensory perception analysis was developed using the Wordcloud libraries, and the Sentiment Intensity Analyzer tool from the nltk library using the Python programming environments.

Results

Physical parameters

Fruit weight loss had a continuous and significant increase at room temperature. Control fruits exhibited the lowest weight loss, whereas fruits treated with nanoparticles experienced a weight loss exceeding 20% (Fig. 1A). Under refrigeration, weight loss was minimal, with similar

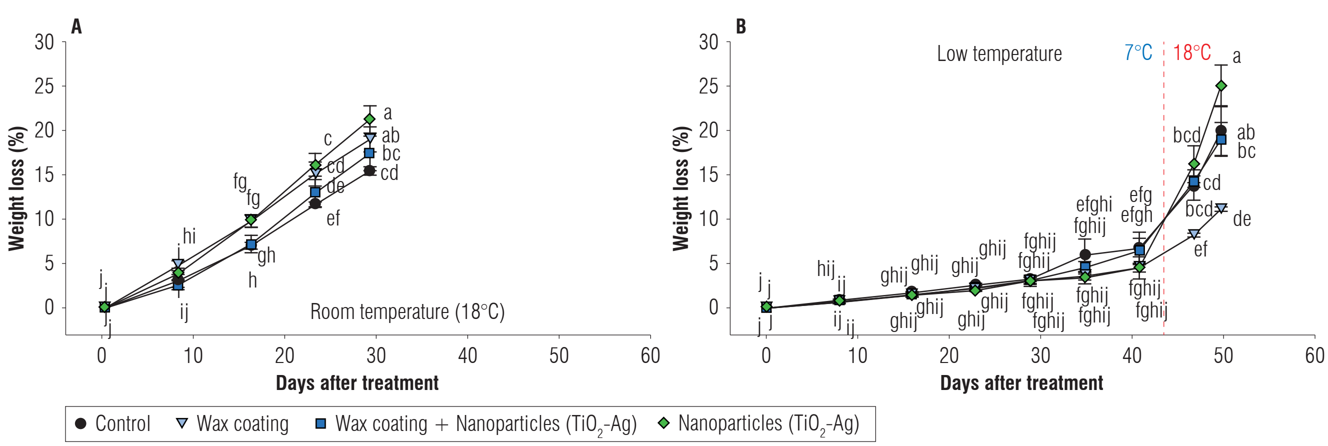

FIGURE 1. Effect of the application of wax and Ag-TiO_2-NPs on the fruit weight loss under room temperature storage (A) and refrigerated conditions of purple passion fruits stored at 7°C for 43 d and then transferred to 18°C for 7 d (B). Repetitive measures analysis was performed as a function of time. Different letters indicate significant differences according to the LSD test (P<0.05). The vertical bars represent the standard error (n=4). Control: fruits without wax or Ag-TiO_2-NPs application.

behavior across treatments. During shelf life, weight loss increased notably, especially in nanoparticle-treated fruits. In contrast, waxed fruits had significantly (P<0.05) lower weight loss (Fig. 1B).

Under room temperature conditions, no significant differences in the color index (CI) were observed between treatments (Fig. 2A). However, at the end of refrigeration and during the shelf life, statistical differences (P<0.05) were seen. Control fruits consistently showed the highest CI in both samples, while the lowest CI was recorded in fruits treated with nanoparticles. Additionally, the CI was higher during the shelf life than during the refrigeration stage (Fig. 2B).

There were statistical differences (P<0.05) in the elasticity of the fruits in the experiment under room temperature conditions, with increased elasticity in the control fruits

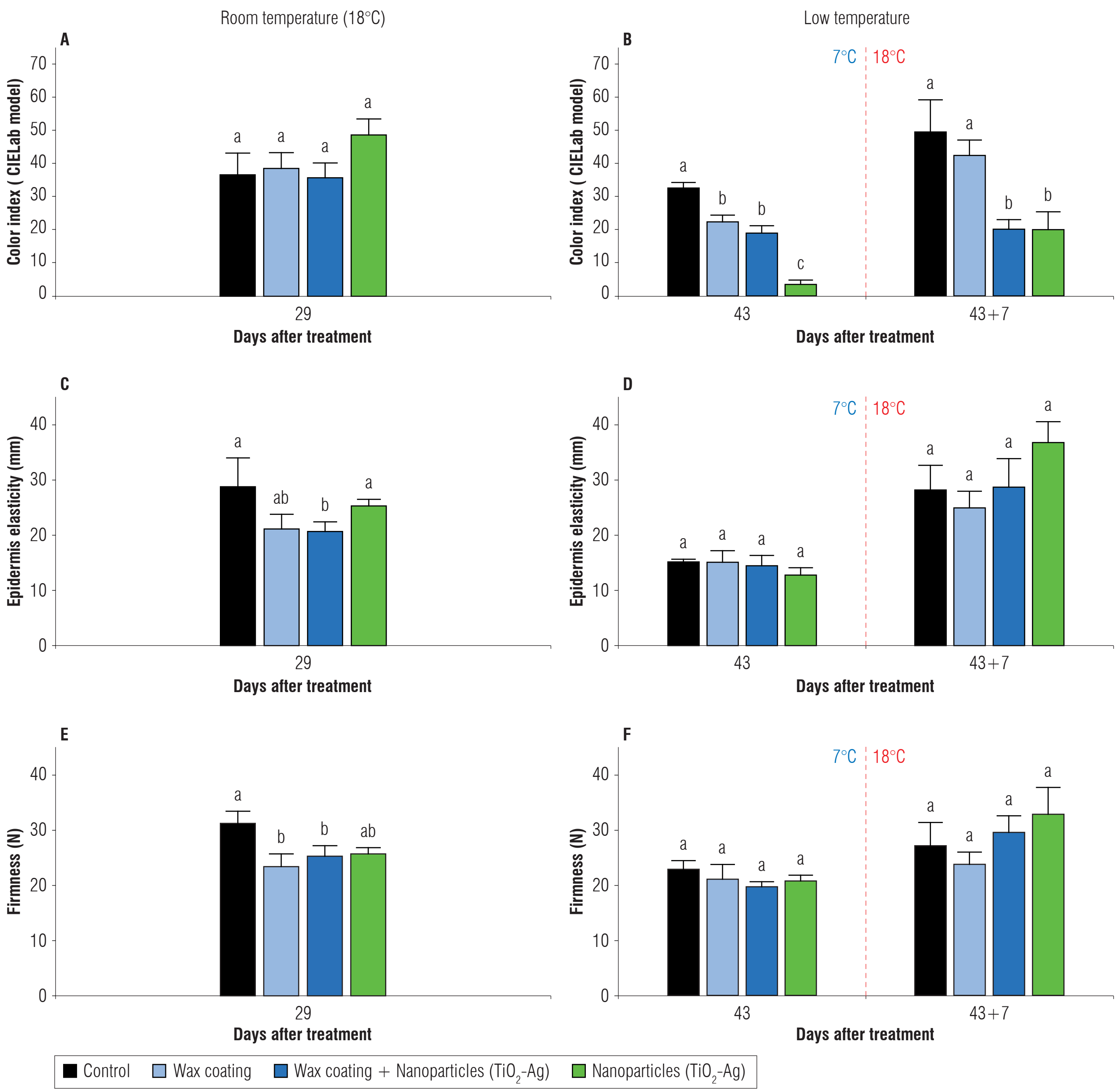

FIGURE 2. Effect of the application of wax and Ag-TiO_2-NPs on fruit color index, elasticity, and firmness during room temperature storage (A, C, and E) and refrigerated conditions of purple passion fruits stored at 7°C for 43 d and then transferred to 18°C for 7 d (B, D, and F). Repetitive measures analysis was performed as a function of time. Different letters indicate significant differences according to the LSD test (P<0.05). The vertical bars represent the standard error (n=4). Control: fruits without wax or Ag-TiO_2-NPs application.

and less in the fruits with wax + nanoparticles (Fig. 2C). Elasticity increased from the end of refrigerated storage to the end of shelf life. Still, there were no significant differences between treatments in either sampling (Fig. 2D). The control fruits had a higher (P<0.05) firmness at the end of room temperature storage (Fig. 2E). From the end of refrigerated storage to the end of shelf life there was an increase in firmness. Still, the treatments were statistically similar in both cases (Fig. 2F).

Biochemical parameters

In-room temperature storage, all fruits had similar acidity values (Fig. 3A). A similar situation was observed at the end of refrigerated storage. In contrast, at the end of shelf life, there were statistical differences when the highest acidity was achieved in fruits treated only with nanoparticles and the lowest value in fruits with waxing only (Fig. 3B).

There were no significant differences in treatments under room temperature conditions (Fig. 3C) for total soluble solids (TSS); however, at the end of refrigeration, there were differences (P<0.05): the NPs treatment showed the lowest TSS value, and the opposite occurred in the control fruits. For shelf life, there was a decrease in TSS in all treatments, but there were no significant differences between them (Fig. 3D). Under room temperature conditions, the fruit ripening process was rapid, so much so that the evaluated technologies apparently did not affect carbohydrate metabolism and, consequently, TSS were not affected. This also indicates that these treatments do not negatively impact this quality parameter related to sensory perception.

In-room temperature conditions, statistical differences were observed (P<0.05). The most significant loss of electrolytes occurred in the control fruits. In contrast, waxed fruits were characterized by the lowest loss of electrolytes (Fig. 4A). In refrigeration, there were no statistical differences. A marked increase in shelf life was observed, with significant differences (P<0.05). The fruits with only nanoparticles had the most crucial loss of electrolytes (Fig. 4B).

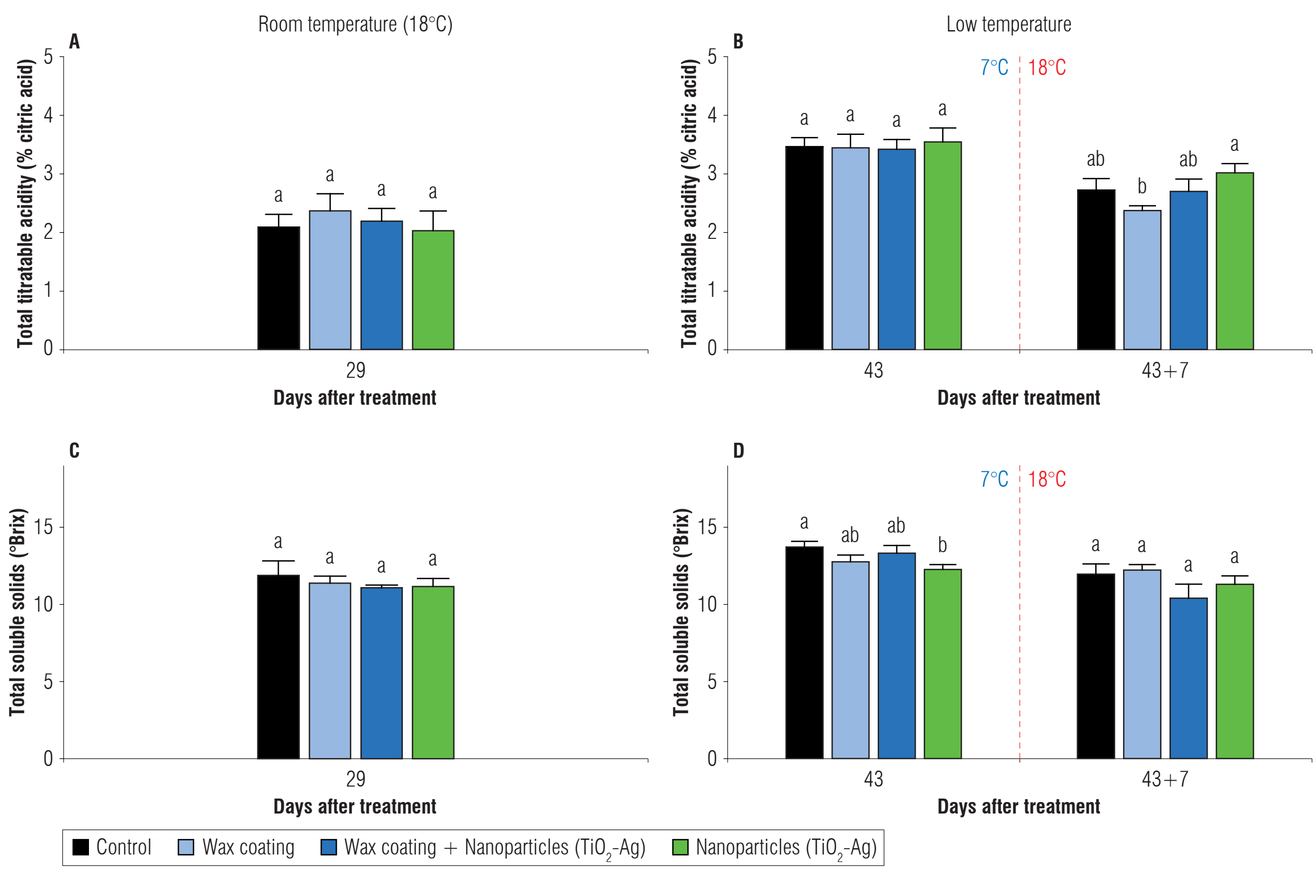

FIGURE 3. Effect of the application of wax and Ag-TiO_2-NPs on the titratable acidity and total soluble solids of purple passion fruits under room-temperature storage conditions (A and C) and refrigerated conditions of fruits stored at 7°C for 43 d and then transferred to 18°C for 7 d (B and D). Repeated measure analysis was performed as a function of time. Different letters indicate significant differences according to the LSD test (P<0.05). The vertical bars represent the standard error (n=4). Control: fruits without wax or Ag-TiO_2-NPs application.

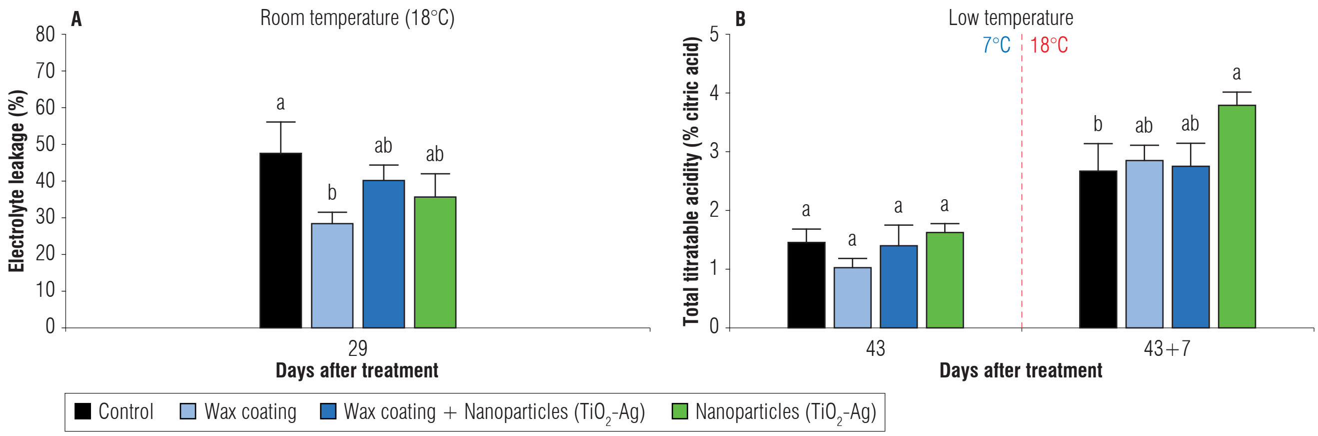

FIGURE 4. Effect of the application of wax and Ag-TiO_2-NPs on electrolyte loss from the epidermis of purple passion fruits under room temperature storage (A) and refrigerated conditions of fruits stored at 7°C for 43 d and then transferred to 18°C for 7 d (B). Repeated measure analysis was performed as a function of time. Different letters indicate significant differences according to the LSD test ($P<0.05$). The vertical bars represent the standard error (n=4). Control: fruits without wax or Ag-TiO_2-NPs application.

Physiological parameters

Under room temperature storage conditions, fruits showed increased respiration at 14 d, at which point climacteric occurred; there was a marked decrease until 21 d, and the fruits remained almost stable until the end of the experiment. The lowest respiration was obtained in fruits with nanoparticle application, and, curiously, the highest respiration was obtained with waxing (Fig. 5A). In refrigerated storage, respiration decreased progressively until 21 d, then began to increase until the end of storage and also

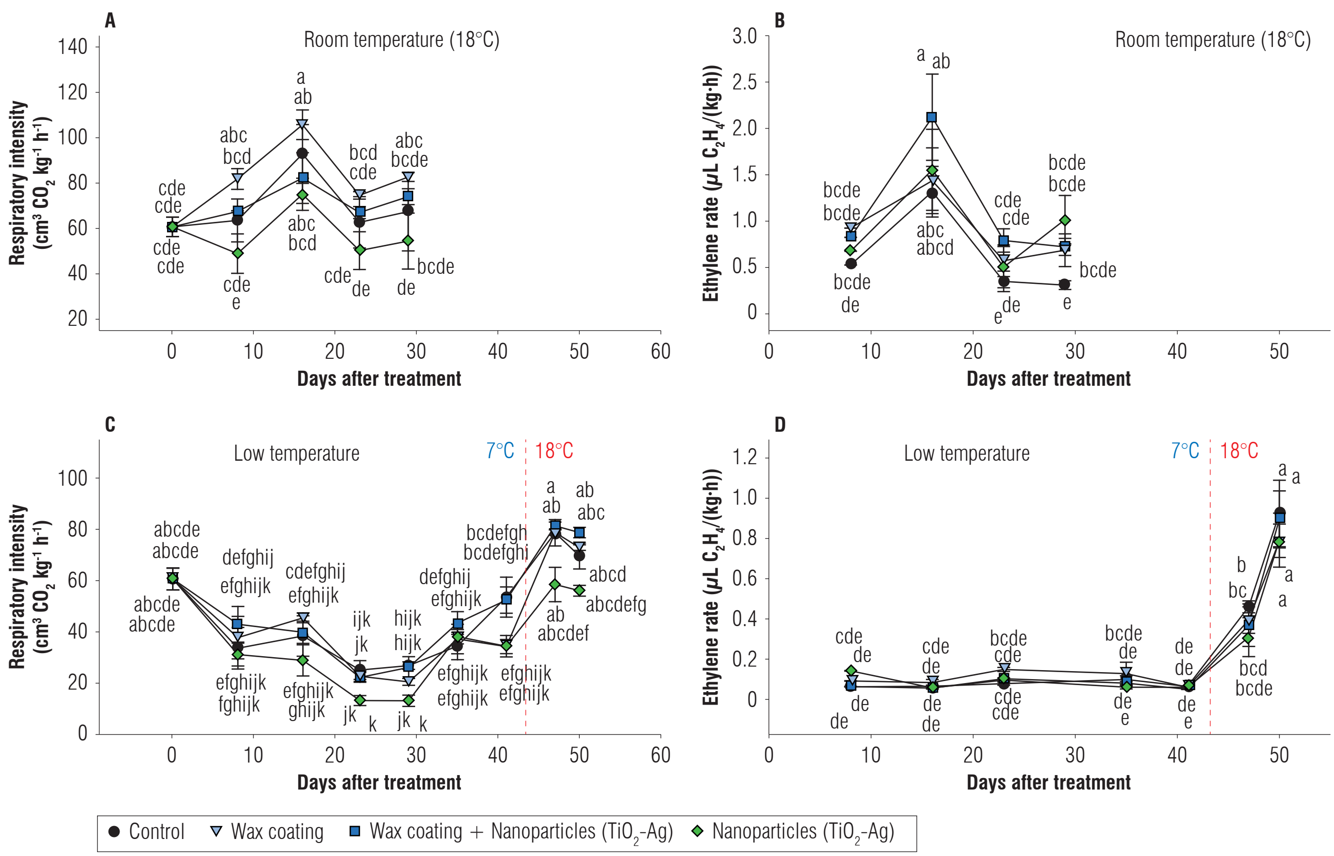

FIGURE 5. Effects of the application of wax and Ag-TiO2-NPs on the respiratory intensity and ethylene production rate of purple passion fruits during room temperature storage (A, B) and refrigerated conditions of fruits stored at 7°C for 43 d and then transferred to 18°C for 7 d (C, D). Repetitive measures analysis was performed as a function of time. Different letters indicate significant differences according to the LSD test ($P<0.05$). The vertical bars represent the standard error (n=4). Control: fruits without wax or Ag-TiO_2-NPs application.

increased during the shelf-life period. Here, it was also observed that the fruits with the lowest respiration were those treated with only nanoparticles. Respiration in the other fruits behaved similarly (Fig. 5C).

At room temperature, ethylene production increased markedly up to 18 d and then decreased. Fruits with nanoparticles and waxes had higher ethylene production during most of the experiment, while control fruits were characterized by the lowest ethylene values (Fig. 5B). Under refrigeration, ethylene remained stable as well as between treatments, but in the shelf-life period, there was a drastic increase but no differences between treatments (Fig. 5D).

Responses to sensorial analysis

The perception of purple passion fruit storaged at room temperature was mostly positive in all treatments (Fig. 6). However, there is a general lack of knowledge or low consumption of these fruits among the participants in the survey. Among the external physical characteristics of the control treatment, texture, coloration, and integrity stand out, especially of the epidermis, which is positively appreciated when smooth, shiny, and dark purple. The fruit flavor is described between acid and sweet notes with a gelatinous, soft, and smooth pulp texture similar to the same sensation that the consumption of sweet granadilla fruit gives. Another appreciated characteristic consists of the aroma of the fruits, which is considered fresh and pleasant with a citric touch (Fig. 6).

The appearance of the wax-coated fruits was more attractive as they were shiny, mostly smooth, with striking colors and aromas, and with an epidermis preserved in better conditions (Fig. 7), unlike treatments with nanoparticles, which showed a dull epidermis, mostly dehydrated, with a rough or powdery texture, and more significant visible damage, but without significantly affecting their flavor, internal texture or aroma (Fig. 7). The rough or uneven appearance of the fruit epidermis, the lightweight or low quantity of pulp, and the size of the fruit are the main undesirable characteristics when purchasing or consuming this product.

Discussion

Physical parameters of the fruits

During room temperature storage, purple passion fruits exhibited considerable weight loss with values exceeding 15% at the end of storage (Fig. 1A). This was likely due to the climacteric nature of the fruits and their high transpiration rate, given that water constitutes 90% of the fruit weight (Gemail *et al*., 2023). Surprisingly, the use of nanoparticles led to more significant weight loss (>20%), possibly due to increased ethylene production, as observed in other fruits such as mangosteen (Thammachote *et al*., 2023). This finding contrasts with results for loquats, where nanoparticle coatings reduced weight loss (Ali *et al*., 2020). In contrast, wax coatings consistently minimized water loss by reducing cuticular transpiration, particularly during shelf life (Fig. 1B) (Devi *et al*., 2022; Zhou *et al*., 2022). Gemail *et al.* (2023) also report the effectiveness of combining wax and Ag-TiO_2-NPs in reducing weight loss in refrigerated mandarins. These conflicting results highlight the need for further research on the role of nanoparticles in managing postharvest water loss, as their effects may vary depending on the fruit species and storage conditions.

The color of the fruit epidermis, a critical indicator of ripening and quality, was also affected by nanoparticle and wax treatments. Nanoparticles, especially during low-temperature storage, delayed color changes, and the CI was approximately 4 (Fig. 2B). This result was probably because of inhibiting flavonoid biosynthesis, which influences the color of the purple fruit epidermis (Xin *et al*., 2021). This finding is consistent with the results for mangosteen, where nanoparticles delayed anthocyanin synthesis and color changes (Thammachote *et al*., 2023). However, the rapid ripening process at room temperature may have obscured these effects, preventing noticeable color changes. Peel shrinkage, an essential quality indicator for purple passion fruit, was significantly reduced in wax-treated fruits in correlation with increased epidermis elasticity and improved resistance to penetration (Zhou *et al*., 2022). This observation explains the differences in the firmness of the fruits under ambient conditions, where wax treatments offered superior physical protection.

In contrast, nanoparticles had limited impacts on these physical attributes under refrigeration, suggesting that their primary action could be biochemical. This contrasts with studies on mandarins and mangoes, where nanoparticle treatments improved fruit firmness under refrigerated and ambient conditions (Chi *et al*., 2019; Gemail *et al*., 2023). This discrepancy underscores the need for refinement of nanoparticle and wax applications to optimize postharvest physical properties in purple passion fruit with particular attention to species-specific and environmental factors.

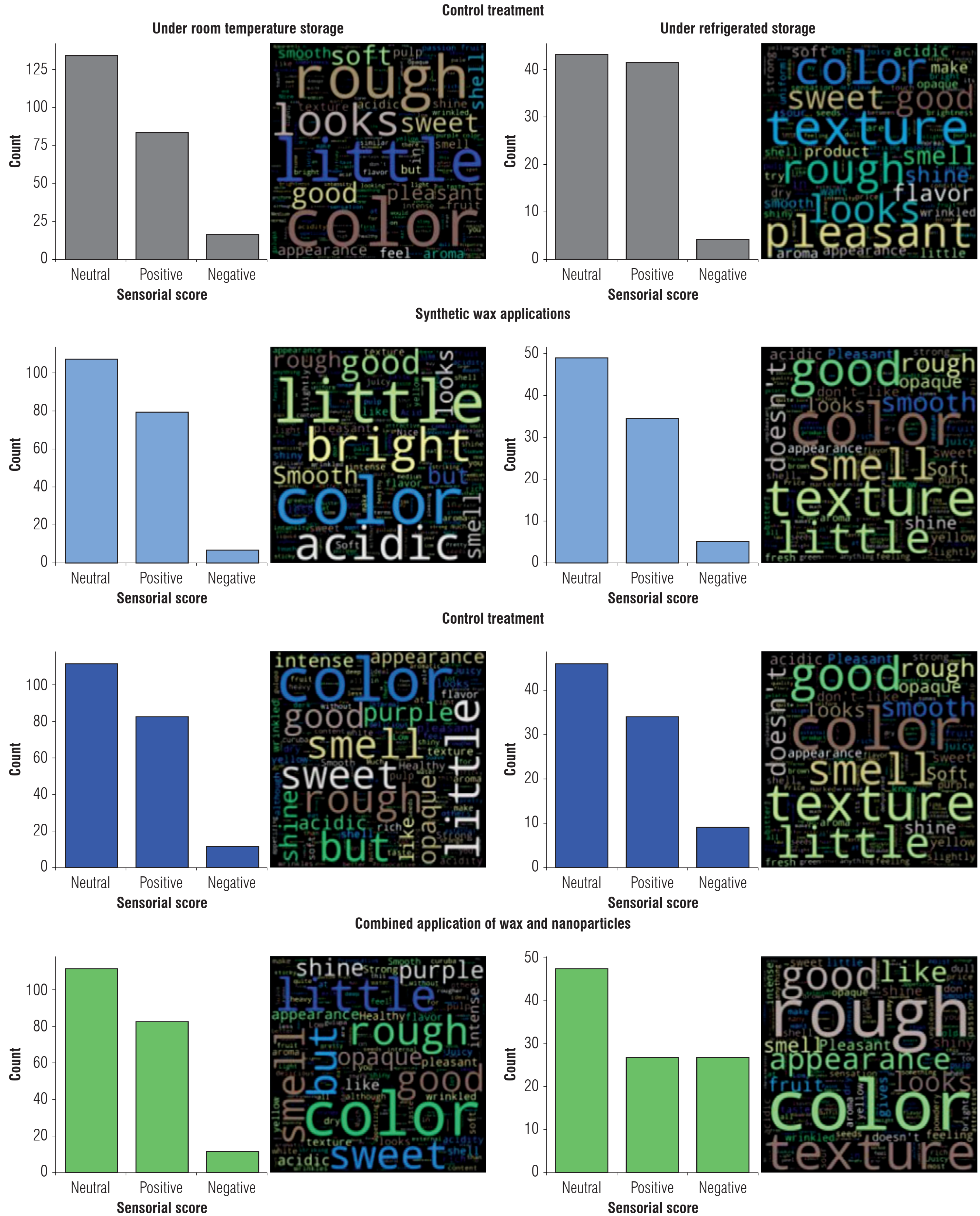

FIGURE 6. Sensory analysis corresponding to purple passion fruits with an application of wax and Ag-TiO_2-NPs and under room-temperature storage (left) and refrigerated storage (right) at the end of the shelf-life period, with their respective text analysis (word cloud). Control: fruits without wax or Ag-TiO_2-NPs application.

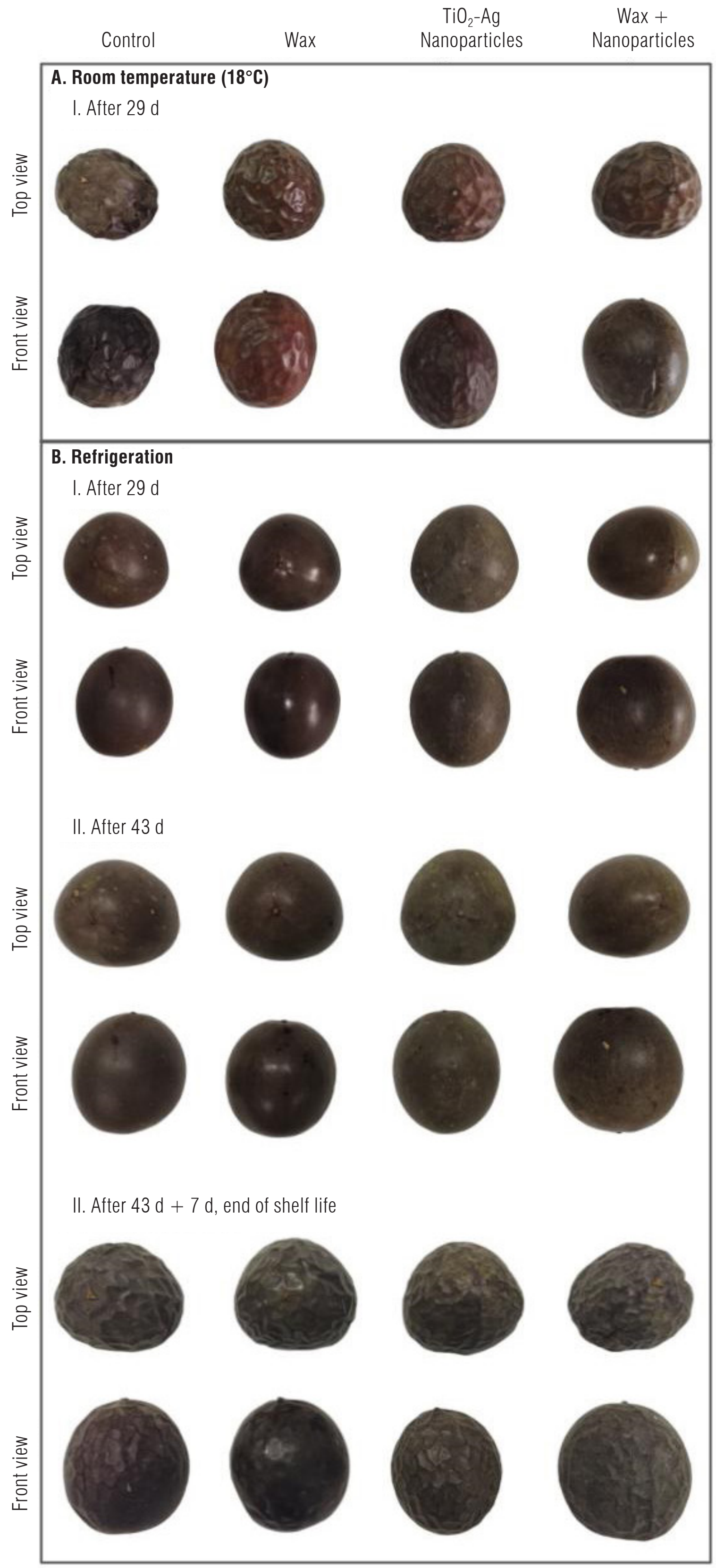

FIGURE 7. Epidermis of purple passion fruits: A) at room temperature at 18°C and B) refrigeration at 7°C with wax and Ag-TiO_2-NPs. Control: fruits without wax or Ag-TiO_2-NPs application.

Fruit biochemical parameters

The total titratable acidity (TTA) in the shelf life decreased by about 5% compared to the control (Fig. 3B). Our findings were consistent with previous studies on purple passion fruit, where the application of chitosan coatings fused with medicinal plant extracts led to a reduction in acidity (Nxumalo & Fawole, 2022). This observation aligns with similar results in loquat fruits, where coatings and Ag-NPs treatments also reduced TTA, potentially contributing to lower weight loss during shelf life (Ali *et al.*, 2020). The lack of statistical differences in other conditions may be attributed to the effects of the modified atmospheric packaging on the ripening process, which could diminish the impact of different treatments.

The beneficial effects of NPs observed at the end of refrigeration were likely due to their role in reducing the respiration rate (Fig. 5). This decrease in respiration resulted in a slower increase in TSS (lower by approximately 10% for control) as a result of reduced hydrolysis of structural and reserve carbohydrates. For example, in mangoes, wax coatings, and Ag-NPs led to lower TSS than controls (Hmmam *et al.*, 2021). Similarly, Ali *et al.* (2020) report a reduction in TSS in loquat fruits treated with NPs and coatings, which is attributed to the slower metabolic processes induced by these treatments.

Nxumalo and Fawole (2022) find that purple passion fruit coatings effectively prevent cell degradation and control electrolyte leaching by providing an additional protective layer. This finding was supported by our results with wax treatments, which maintained fruit quality under room-temperature storage conditions, with a value <30% of electrolyte leakage (Fig. 4). In contrast, Tavakoli *et al.* (2019) report that the application of Ag-NPs in lemon fruits control the leakage of electrolytes. This result differs from our findings in purple passion fruit, where NPs alone increased the leakage of electrolytes. Although NPs were associated with more significant weight loss, indicating possible membrane damage, they did not adversely affect quality parameters such as firmness, color, TSS, or acidity.

These results suggested that coatings and NPs can influence various postharvest attributes, but their effects are complex and vary depending on the specific fruit and storage conditions. More research is needed to refine these treatments and understand their mechanisms in different fruit species.

Fruit physiological parameters

The observed reduction in fruit respiration rate (a decrease of up to 55%, compared to the control) with the application of nanoparticles in both experiments may be attributed to the release of silver ions from Ag-NPs, which probably obstructed the Krebs cycle by disrupting intracellular ion flux and altering the respiratory electron transport system (Elatafi & Fang, 2022). In support of this, Ortiz-Duarte *et al.* (2019) reported that nanoparticles can inhibit enzyme activity in the respiratory chain. This finding is corroborated by studies of mangoes, where nanoparticles were shown to inhibit respiration during refrigerated storage and throughout shelf life (Kassem *et al.*, 2022). Similarly, the application of Ag-NPs in mangosteen also significantly reduces respiration rates (Thammachote *et al.*, 2023).

Our results indicate that neither nanoparticles nor wax coatings effectively inhibit ethylene production in purple passion fruit. In some cases, these treatments even led to a slight increase in ethylene levels (Fig. 5). This finding contradicts expectations based on their known roles in ethylene inhibition reported in mangoes and avocados (Kassem *et al.*, 2022; Nevado-Velasquez *et al.*, 2023). In the refrigerated storage experiment, the ineffectiveness of these treatments ($P>0.05$) may be attributed to the combined effects of low temperature and modified atmosphere packaging, which mimic the inhibitory effects on enzymatic activity related to ethylene synthesis.

These results suggest that while nanoparticles and wax coatings can affect respiration rates, their influence on ethylene production may be more complex and depend on specific storage conditions. More research is needed to elucidate these interactions and optimize the use of these technologies for the postharvest management of purple passion fruit.

Responses to sensorial analysis

The limited consumption of purple passion fruit, compared to more widely consumed varieties such as yellow passion fruit and sweet granadilla can be attributed to several factors. The lower commercial trajectory and limited market presence of purple passion fruit primarily contribute to its reduced availability and consumer familiarity (De Armas Costa *et al.*, 2022; Franco *et al.*, 2014; Gomes *et al.*, 2021). Additionally, its distinctive physicochemical properties, acidity, and unique flavor profile further restrict its appeal. Many consumers in Colombia are accustomed to the milder flavors of yellow passion fruit or the sweeter taste of sweet granadilla, positioning purple passion fruit as a niche product.

Consumer perception is critical in the potential expansion of the purple passion fruit market domestically and internationally. Sensory attributes such as taste, aroma, and appearance influence consumer preference. In this study, the application of wax coatings (application of 50% diluted wax coating) and nanoparticles (400 mg kg^{-1} TiO_2 with 0.75% Ag) positively impacted the visual appeal of the fruits by providing a bright and glossy finish. However, these treatments did not significantly affect the taste or aroma of the fruits, which are key factors in consumer acceptance.

Applying coatings and nanoparticles significantly improves the fruit external appearance and shelf life, including attributes such as color retention and reduced weight loss. However, these interventions have limited influence on enhancing the sensory qualities of taste and aroma, critical factors influencing consumer preferences and purchase decisions. To achieve successful market expansion for purple passion fruits, it is essential to focus on external quality improvements and invest in strategies to enhance its organoleptic properties. These include optimizing sweetness, acidity balance, and aromatic profile through cultivation practices, postharvest handling, and product development. Additionally, highlighting the fruit nutritional benefits and versatility in marketing campaigns can further boost its appeal and acceptance among consumers.

Our study did not evaluate the potential impact of nanoparticles on human health, as this falls beyond the scope of our research. This topic has generated extensive debate, yet current findings remain inconclusive. Future studies are expected to provide more substantial evidence to clarify the potential risks and implications (Chaud *et al*., 2021; Iavicoli *et al*., 2017).

Conclusions

These findings emphasize optimizing postharvest treatments for purple passion fruits, balancing consumer appeal with internal quality preservation. Wax coatings improve the fruit visual appearance but offer limited protection for key quality attributes, particularly under refrigeration. In contrast, Ag-TiO_2-NPs demonstrated superior effectiveness in maintaining fruit quality at 7°C by stabilizing key parameters such as respiratory rate, color, and acidity. However, both wax and nanoparticle treatments were less effective at room temperatures. Further research is needed to refine nanoparticle formulations, assess long-term safety, and explore commercial applications, with an emphasis on consumer education and a holistic approach to quality characterization.

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Conflict of interest statement

The authors declare that there is no conflict of interests regarding the publication of this article.

Author´s contributions

EDSS: conceptualization, research, writing - original draft, visualization, writing, and editing. HEBL: conceptualization, writing - original draft, and editing. JGRG: conceptualization, writing - original draft, and editing. All authors have read and approved the final version of the manuscript.

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