Effect of phosphine dose and exposure time on postharvest quality of Hass avocado (*Persea americana* Mill.)

Efecto de dosis y tiempos de exposición a fosfina en la calidad poscosecha de aguacate Hass (*Persea americana* Mill.)

Santiago Benjumea-Orozco[1]*, Pedro Lizarazo-Peña[1,2], and Aníbal O. Herrera[1]

ABSTRACT

The Hass avocado in Colombia has great export potential, although its commercialization faces restrictions due to quarantine pests. Fumigation with magnesium phosphide has become a key postharvest strategy for pest control in refrigerated fruits. However, there is limited information regarding its impact on Hass avocados. This study evaluated the effect of treatments with phosphine at different concentrations (0, 200, 400, and 800 ppm) and exposure times (36 and 72 h) on postharvest quality in avocados refrigerated at 7°C. Fruit firmness, color of the exocarp and mesocarp, weight loss, and ethylene production were analyzed using a longitudinal multivariate analysis of variance. No direct damage to fruit quality was detected related to phosphine concentration or exposure time. Although significant differences in firmness and color were observed, these effects were attributed to variations in gas concentrations, such as CO_2, inside the barrels, and the fruit maturation process. Ethylene production increased with higher doses and longer exposure times, reaching a significant peak 72 h after harvest, coinciding with the climacteric point. These differences were related to the physiological maturation process of the avocados. Magnesium phosphide did not directly affect the quality of Hass avocados under the evaluated conditions. Magnesium phosphide is considered a viable option for phytosanitary pest control, although further studies are needed to assess its effectiveness against specific avocado pests.

Key words: phytosanitary management, postharvest treatment, magnesium phosphide, longitudinal analysis, avocado export.

RESUMEN

El aguacate Hass en Colombia tiene un gran potencial de exportación, aunque enfrenta restricciones comerciales debido a las plagas cuarentenarias. La fumigación con fosfuro de magnesio se ha considerado como una estrategia clave de poscosecha para el control de plagas en frutas refrigeradas. Sin embargo, hay poca información respecto a su impacto en la calidad de frutos de aguacate Hass. Este estudio evaluó el efecto de tratamientos con fosfina a diferentes concentraciones (0, 200, 400 y 800 ppm) y tiempos de exposición (36 y 72 h) sobre la calidad postcosecha en aguacates refrigerados a 7°C. Se analizaron la firmeza de fruto, color del exocarpo y mesocarpo, pérdida de peso y producción de etileno mediante un análisis de varianza multivariado longitudinal. No se detectaron daños directos en la calidad de la fruta relacionados con la concentración de fosfina ni el tiempo de exposición al gas. Aunque se observaron diferencias significativas en la firmeza y el color de los frutos, estos efectos fueron atribuibles a variaciones en la concentración de gases, como el CO_2, dentro de los barriles, y al proceso de maduración de los frutos. La producción de etileno aumentó con dosis más altas y tiempos de exposición más prolongados, alcanzando un pico significativo 72 h después de la cosecha, coincidiendo con el punto climatérico. Estas diferencias se vincularon con el proceso fisiológico de maduración de los aguacates. El fosfuro de magnesio no afectó directamente la calidad del aguacate Hass bajo las condiciones evaluadas. El fosfuro de magnesio es una opción viable para el control fitosanitario de plagas, aunque se requieren más estudios para evaluar su efectividad frente a algunas plagas específicas del aguacate.

Palabras clave: manejo fitosanitario, tratamiento poscosecha, fosfuro de magnesio, análisis longitudinal, exportación de aguacate.

Introduction

Avocado (*Persea americana* Mill.) is a tropical crop that grows across a wide range of thermal floors, with centers of origin for different races found both in the highlands of eastern Mexico and warm areas of southeastern Mexico and Guatemala (Guzmán *et al*., 2017; Williams, 1977). The fruits of Hass avocado have high nutritional value, with monounsaturated fatty acids making up 63.5% of total fats and containing 463 mg of potassium per 100 g of pulp (Bernal & Cartagena, 2017; Ferreyra *et al*., 2016). Therefore, in tropical countries, avocado has become an important

Received for publication: September 9, 2024. Accepted for publication: December 9, 2024. Doi: 10.15446/agron.colomb.v42n3.117960

[1] Universidad Nacional de Colombia, Facultad de Ciencias Agrarias, Bogotá (Colombia).
[2] Facultad de Ingeniería, Universidad El Bosque, Bogotá (Colombia).
* Corresponding author: sbenjumeao@unal.edu.co

crop due to its high international demand. By 2022, the total production was 9,114,135 t, with Mexico as the leading producer and exporter with 27.8%, followed by Colombia with 12% (FAO, 2022). In Colombia, avocado cultivation has become an important export product, with a growth in export volume from 44,570 t in 2019 to 124,930 t in 2024. This growth continues today with the expansion of avocado markets in the USA, Japan, and China (DIAN, 2024).

The fruit export market is characterized by high demand for quality, safety and phytosanitary standards; however, tropical crops have diverse organisms that generate phytosanitary problems, such as pests and diseases (ICA & ANDI, 2016). Quarantine pests (QP) are particularly limiting in export crops because QP are potentially dangerous species that are not present or are under strict control in the importing country (Heather & Hallman, 2008; IPPC, 2024). Consequently, importing countries enforce stringent detection policies that can lead to the interception, return, or destruction of shipments, thereby imposing additional costs on producers. In Colombia, significant quarantine pests affecting avocado cultivation include *Heilipus lauri* (Coleoptera: Curculionidae) and *Stenoma catenifer* (Lepidoptera: Elachistidae) (Carabalí Muñoz *et al*., 2021).

Various alternatives exist for postharvest pest management. Fumigants like methyl bromide have been commonly employed due to their efficacy and versatility; however, their use has been restricted due to adverse effects on the ozone layer (UNEP, 2020). As a result, alternative strategies were studied for postharvest pest management, including ionizing radiation, thermal treatments, and the application of other fumigants such as phosphine (Ma *et al.,* 2024). Phosphine gas, or hydrogen phosphide (PH_3), serves as the principal alternative to methyl bromide. This gaseous compound is commercially produced from metal phosphides, usually magnesium or aluminum, in conjunction with substances that control gas release (Kim *et al*., 2016; Zou *et al.,* 2025).

Aluminum phosphide has been used for approximately 80 years as a pest control for stored grains (Arora *et al*., 2021). In recent years, magnesium phosphide has been implemented as a phytosanitary treatment for agricultural products because, unlike aluminum phosphide, it does not contain ammonium carbamate. This means that the reaction product is phosphine gas without phytotoxic residues or ethylene stimulants that affect food quality (Agrafioti *et al.,* 2019; Restrepo Giraldo, 2019). Phosphine has rapid diffusion in the treated material, so it easily reaches pest insects, entering through the spiracles and the open circulatory system (Alzahrani & Ebert, 2019; Wang *et al*., 2006). Phosphine acts at the mitochondrial level, interrupting cellular respiration, acting on Complex IV of the electron transport chain of the mitochondria, preventing normal electron transport, generating energy insufficiency, and promoting the formation of reactive oxygen species that destroy the proteins through a redox effect (Nath *et al*., 2011).

Treatments involving magnesium phosphide for fresh agricultural products are conducted in sealed environments, typically under refrigeration, where the concentration of phosphine and exposure time play critical roles (Ahmed *et al*., 2018). The volatilization rate of magnesium phosphide diminishes at lower temperatures, which may affect treatment efficacy; therefore, increasing the dosage or extending the exposure time can be necessary (Zhang *et al*., 2013). An appropriate exposure duration is essential, as sufficient time can achieve effective control even at lower concentrations (Zhang *et al*., 2015). Wason and Selladurai (2023) found that phosphine was effective in mitigating fruit fly eggs in fruits of *Syzygium samarangense*, and the color and texture of the fruits were not significantly affected at concentrations up to 0.69 mg L^{-1} of PH_3 for 24 h. However, prolonged exposure may disrupt export logistics. Conversely, utilizing high concentrations of phosphine can negatively impact control efficacy, as it may induce narcosis in certain insects, thereby limiting respiration and reducing mortality (Lampiri *et al*., 2021). Likewise, its low concentrations or insufficient exposure times increase the selection pressure on pest insects, inducing the development of resistance (Kyung *et al*., 2018; Liu & Liu, 2014). On the other hand, high concentrations of fumigants can cause phytotoxic damage in agricultural products, affecting quality (Cato *et al*., 2019). It is important to establish concentration ranges and exposure times that can control pests without affecting the quality of the agricultural products.

The objective of this research was to assess the impact of different doses and exposure times of phosphine on the postharvest quality of Hass avocados, thereby supporting future studies of insect pest management.

Materials and methods

Location and plant material

This experiment was conducted in the first semester of 2019 at the postharvest laboratory of the Faculty of Agricultural Sciences at the Universidad Nacional de Colombia, Bogotá campus. The avocados were sourced from an orchard located in the municipality of Granada, Cundinamarca

(Vereda Santa Helena) (4°30'10.9" N, 74°20'45.3" W, altitude 2500 m a.s.l.). Harvest was carried out based on visual criteria, which were subsequently validated through the measurement of the fruit dry mass percentage, reported as optimal at around 23%, serving as an indicator of harvest maturity (Carvalho *et al*., 2014; Cerdas Araya *et al*., 2014). From the total harvested fruits, those exhibiting uniform size and free from damage or abnormalities were selected for the study.

Experiment design and treatments

The experiment was designed as a bifactorial arrangement, with the first factor representing five levels of phosphine concentration (D) (0, 200, 400, 600, and 800 ppm) and the second factor comprising two exposure times (E) (36 and 72 h). Treatments were conducted under refrigerated conditions in cold rooms maintained at 7±1°C, using ten 200 L metal barrels that were placed and used as treatment chambers. Each treatment contained six avocados as the experimental unit, with six replicates. Magnesium phosphide (Fumicel placa®, ANASAC, Chile) was added to each barrel based on a commercial dosage of 3.4 g m^{-3}, which approximates a concentration of 200 ± 20 ppm. Additionally, according to the Andean standard for pesticide registration, two control treatments were included: the first without phosphine (0 ppm), and the second with a double dose (400 ppm) (ICA & ANDI, 2016; Lizarazo-Peña *et al*., 2024). The barrels were hermetically sealed, and the presence of phosphine leaks was monitored with a portable meter (PAC-7000, Drager, Lübeck, Germany). Treatments were applied starting with 72 h of exposure, followed by 36 h. Then the fruits were kept refrigerated for 30 d to simulate the export transport process, which served as the postharvest evaluation period.

Measurement of fruit variables

During the application of treatments in each barrel, the phosphine concentration was measured using colorimetric tubes based on silver salts (Detia®, Degesch, Laudenbach, Germany) with a detection range of 50 to 2000 ppm. The first measurement was taken two h after the application of each treatment and, from then on, every 12 h until the end of the exposure periods. During this period, and with the same frequency, the CO_2 concentration was monitored in the cold room and inside the barrels with treatments 0 ppm – 36 h (phosphine concentration – exposure time) and 0 ppm – 72 h using an electronic atmosphere meter (Oxybaby, Witt-Gasetechnik GmbH & Co. KG, Witten, Germany).

Destructive-type variables of fruit firmness and color (exocarp and mesocarp) were evaluated on days 0, 7, 14, 21, and 28 after the application of the treatments (DAT). In each of the samples, the following variables were evaluated in six fruits per experiment unit:

Firmness (F) measurement was made using a Universal Test Machine penetrometer with a cylindrical Magness-Taylor probe of 8 mm diameter. Following the methodology of Castellanos *et al*. (2016), the firmness was determined as the force (Newtons) necessary to penetrate the fruit; a single measurement was taken per fruit at a random point on its equatorial contour, using a speed of 10 mm s^{-1} and a maximum depth of penetration of 12 mm from the surface of the fruit.

Color was measured on the exocarp and mesocarp of the fruits with a Minolta CR-400 colorimeter (Minolta Camera Co., Osaka, Japan) using the L*, a*, and b* coordinates of the CIELAB color space. For each fruit, three points were taken in the exocarp, then the fruit was immediately cut transversely and three points were taken again in the mesocarp.

For the exocarp, a color index (ICe) was determined with a principal component analysis (PCA), integrating the standardized values of L, a and b that explained 88% of the variation and were defined by:

$$ICe = 0.546*a - 0.600*b - 0.584*L \quad (1)$$

The resulting value was used as a variable to identify differences between treatments.

For the mesocarp, the PCA generated a color index that explained 64% of the variation; therefore, it was not considered, and the values of L*, a*, and b* were analyzed independently.

Weight loss and ethylene production were estimated with non-destructive sampling, for which samples of two fruits were placed in a plastic mesh with three repetitions and evaluated on days 0, 3, 6, 10, 14, 19, 23, and 26 after the application of treatments.

For ethylene production (ET) analysis, ethylene samples were taken by drawing 1 ml of gas with a syringe through the rubber seal of the container where the avocados were stored for 1 h, and the samples were injected into a gas chromatograph (Agilent 7890A, Agilent Technologies Inc., Santa Clara, CA, USA) following the methodology proposed by Castellanos *et al*. (2017).

Weight loss (WL) was measured with the fresh mass of the fruit samples described above, using a balance (Scout

Pro® RS232, OHAUS, Mexico) with a precision of 0.01 g, calculating the percentage of weight lost between the initial weight (0 DAT) and the weight of the subsequent samples.

Statistical analysis

The experiment was designed with a bifactorial structure in complete and generalized blocks, where the blocking factor (B) represented fruit maturity at harvest. For the variables with longitudinal structure (evaluated over time) including F, WL, ET, and color L*, a*, b* of the exocarp and mesocarp, the days after treatment (DAT) was considered as a factor in repeated measurements to account for the correlational structure in temporal measurements. The effect of the factors and the differences between treatments in variables with longitudinal structure were estimated from a longitudinal multivariate analysis of variance with a permutational (non-parametric) approach as proposed by Friedrich *et al*. (2018), using the MANOVA.RM library (2019) of the R statistical software (Version 1.2.1335), along with the library's confidence intervals, to assess differences between the factor levels. The graphics were created with the package "ggplot2" (Wickham, 2016). For interpreting and discussing the interval, we refer to the confidence interval criteria outlined by Cumming *et al*. (2007).

Results and discussion

Table 1 summarizes the MANOVA results for the evaluated postharvest variables. The analysis revealed no significant effects from the blocking factor or the dose factor on any variables. However, exposure time significantly influenced all variables, except for the L* color coordinate in the exocarp, WL, and ET. The duration of the test in days after treatment (DAT) also showed significant differences across all parameters. Notable interactions were observed, including the effect of phosphine dose and exposure time (D x E) on weight loss and ethylene production, as well as the impact of exposure time and days after treatment (E x DAT) on firmness and the b* component of color in both exocarp and endocarp. Additionally, the triple interaction involving dose, exposure, and DAT demonstrated differences in the L* and a* components of mesocarp color. Given the interactions observed, the highest degree of interaction was analyzed according to Montgomery (2017), with differences interpreted through graphical representations.

The evaluated variables showed no adverse effects from the application of phosphine at different doses (D) compared to the control group (Tab. 1), indicating that magnesium phosphide concentration does not significantly impact fruit quality (Güncan *et al*., 2023; Liu *et al*., 2018). However, firmness (F), exocarp color (ICe), and mesocarp color (values a* and b*) were influenced by the duration of exposure to phosphine (E), regardless of the concentration used. Notably, these affected variables may be directly related to the CO_2 content inside the barrels at the time of applying the treatments, which reached values of 2.8% in the barrels with an exposure time of 36 h and 4.4% in barrels with 72 h exposure compared to a value of 0.8% outside the barrels in the cold storage room (Espinosa-Cruz *et al*., 2014). Avocado fruits, when interacting in confined spaces (such as hermetic barrels), experience a sharp reduction in O_2 and an increase in CO_2 (Rojas-Graü *et al*., 2009). The rate of O_2 consumption decreases with increasing CO_2 levels; thus, high CO_2 concentrations may activate both the alternative respiratory pathway and anaerobic pathways simultaneously. Considering that Hass avocado fruits cannot tolerate environments with O_2 concentrations lower than 2% without undergoing fermentation (El-Shafei, 2020; Hertog *et al*., 2003), the reduction in O_2 availability induces fermentation, resulting in the production of ethanol and acetaldehyde, which can negatively affect fruit quality, reflected in the increased production of volatile compounds in the fruits (Perotti *et al*., 2014).

TABLE 1. Summary of the *P*-values from the MANOVA.RM analysis for the main factors and interactions between factors for each of the longitudinal response variables evaluated in Hass avocado fruits treated with phosphine at different exposure times.

Variation factor	F	Exocarp color			Mesocarp color			WL	ET
		L*	a*	b*	L*	a*	b*		
B	ns	ns	ns	ns	ns	ns	ns	ns	ns
D	ns	ns	ns	ns	ns	ns	ns	ns	ns
E	**	***	***	**	ns	***	**	ns	ns
DxE	ns	ns	ns	ns	ns	ns	ns	***	***
DAT	***	***	***	***	***	***	***	***	*
DxDAT	ns	ns	ns	ns	ns	ns	ns	ns	ns
ExDAT	*	ns	ns	*	ns	ns	*	ns	ns
DxExDAT	ns	ns	ns	ns	*	*	ns	ns	ns

Abbreviations: ns: not significant, B: blocking factor (point of maturity at harvest), D: dose (effect of the phosphine used), E: exposure time to phosphine, DAT: days after treatment (effect over time), D×E: interaction between the dose and the exposure time to phosphine, F: firmness, WL: weight loss, ET: ethylene production. MANOVA. *, **, *** represents the significant differences at probability levels 0.05, 0.01, 0.001, respectively.

Fruit firmness was influenced by both exposure duration and evaluation time, with reductions observed in firmness for all durations. However, the decrease was more significant in fruits exposed for 72 h. At 21 DAT, similar reductions in firmness were noted, but by 28 DAT fruits exposed for 72 h demonstrated a significantly greater loss of firmness (Fig. 1). The avocado is classified as a climacteric fruit, and the production of ethylene is intricately linked

to the ripening process during storage (Pedreschi *et al.*, 2019). Thus, firmness, color, and weight loss are affected by chlorophyll degradation and increased enzymatic activity in pectin degradation and hemicellulose hydrolysis induced by maturation (Liu *et al.*, 2018). Firmness was affected mainly at 72 h exposure, possibly because the fruits were mostly at consumption maturity (Fig. 1), and a few were at physiological maturity, which led to greater enzymatic degradation of polysaccharides (Goulao & Oliveira, 2008; Walse & Jimenez, 2021). Similar to Garcia *et al.* (2021), a shelf-life study on avocados was conducted to assess the effects of biopolymer coatings on post-harvest parameters. Hass avocados were refrigerated at 4°C and 79% relative air humidity. Initially, the avocados had a firmness greater than 70 Newtons. By 24 d, the firmness of fruits in the control group had decreased to below 10 Newtons, demonstrating a similar trend in firmness reduction.

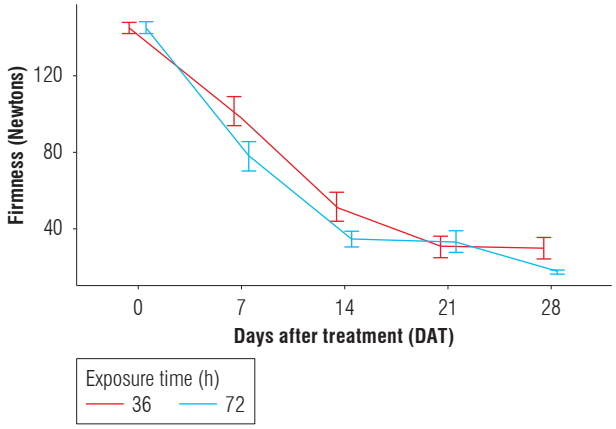

FIGURE 1. Effect of phosphine exposure time on the firmness of Hass avocado fruits. Vertical bars represent confidence intervals for the MANOVA.RM model ($P<0.05$), n = 180.

The exocarp color was significantly affected by exposure duration and days post-treatment, as shown in the L*, a*, and b* components. The L* value darkened over time, particularly with the 72-h exposure. Meanwhile, the a* component indicated a reduction in the fruit's green hue, with higher values observed from 7 d post-treatment for the 72 h exposure. Additionally, the b* component showed a decrease, reflecting a loss of yellow color, especially after the 72 h exposure (Fig. 2).

The mesocarp color was significantly influenced by the triple interaction between dose (D), exposure time (E), and days after treatment (DAT), particularly in the L* and a* components. The L* component showed a darker tone over time, which was more noticeable with 72-h exposures. The changes were subtle, making it difficult to identify clear trends. The a* component increased over time, indicating

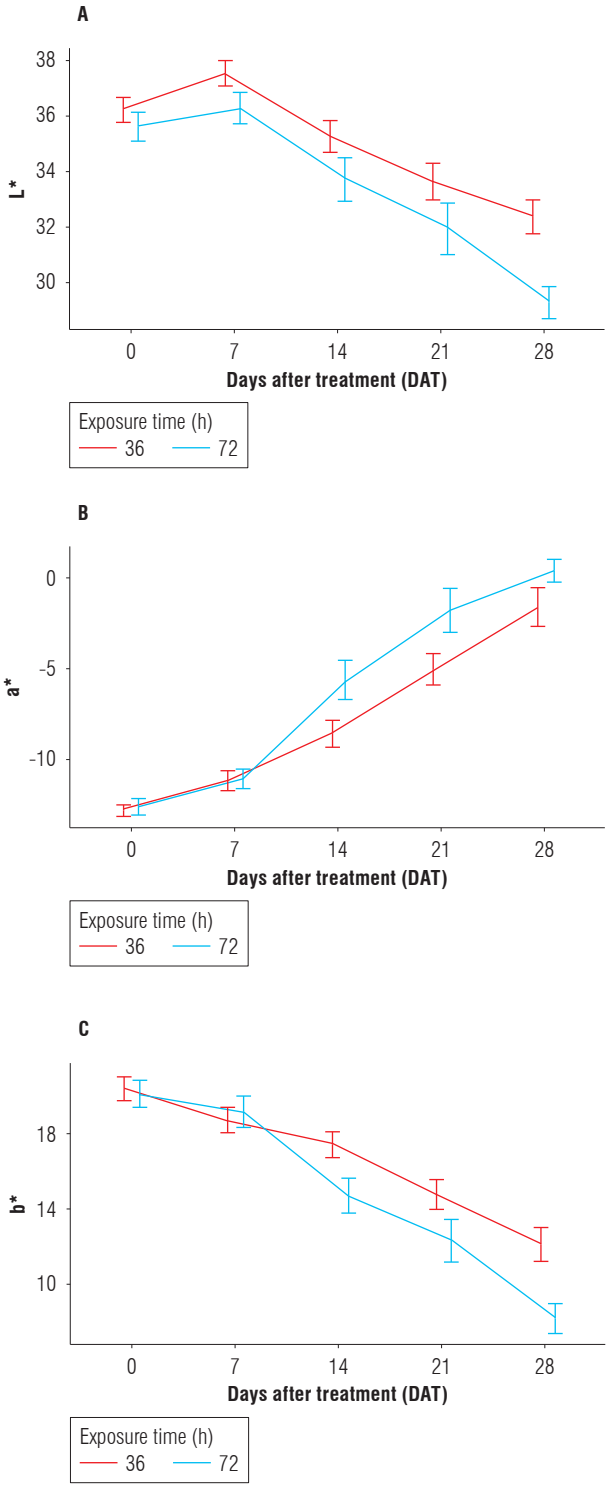

FIGURE 2. Effect of phosphine exposure time on color components (CIELAB) of the exocarp in Hass avocado fruits. The blue line represents the exposure time of 72 h, and the red line shows the 36 h. (A) component L*, (B) component a*, (C) component b*. Vertical bars represent confidence intervals for the MANOVA.RM model ($P<0.05$), n = 180.

a transition from dark green to light green, with significant differences at 21 d for 36 h exposures and at 14 d for 72 h exposures; the treatment with the least effect was 800 ppm.

The b* component was significantly influenced by the interaction between exposure time (E) and days after treatment (DAT). It decreased, reflecting a loss of yellow color, especially in the 72 h exposures. The differences between exposure times were more pronounced at the start and diminished as the experiment progressed.

The previously mentioned changes, such as the alteration in mesocarp color, are associated with changes in the exocarp. These alterations may be closely related to water loss and the subsequent dehydration of the fruit during the ripening process in storage (Pidakala *et al*., 2024; Shikwambana *et al*., 2021). Furthermore, exocarp luminosity

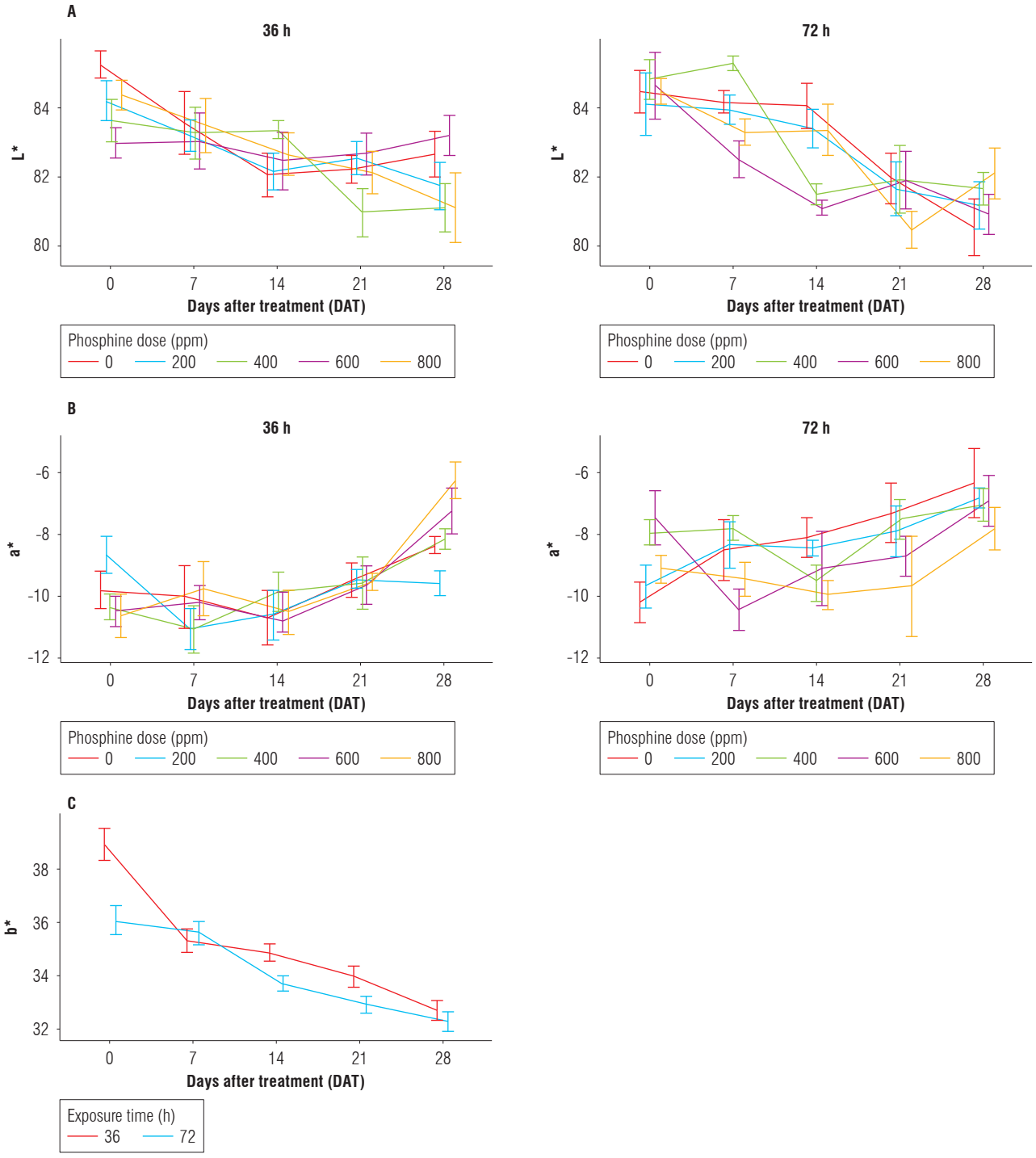

FIGURE 3. Effect on the color components (CIELAB) of the mesocarp of Hass avocado fruits from the interactions between dose, exposure time, and test time for (A) component L* and (B) component a* and (C) the interaction between exposure time and test time (DAT) for component b*. Vertical bars represent confidence intervals for the MANOVA.RM model ($P<0.05$), n = 180.

(L*) decreased in the days following treatment, indicating a reduction in brightness. Meanwhile, the exocarp color value a*, which describes the shift in color from red (positive) to green (negative), increased during the same period (Fig. 2). Since no significant differences were observed between the treatments applied at different doses (Tab. 1), color changes in the a* and L* coordinates could be associated with the fruit ripening process, which induces the degradation of chlorophyll through the enzymatic action of chlorophyllases, red chlorophyll catabolite reductases (RCCR), and pheophorbide oxygenases (PAOy). This process promotes the synthesis of cyanidin-3-O-glucoside during the ripening of Hass avocados, resulting in lower L* values and higher a* values in both the exocarp and mesocarp (Castellanos *et al*., 2016; Pathare *et al.,* 2013; Wason & Selladurai, 2023). Regarding the b* coordinate (Fig. 3), which describes changes between yellow (positive) and blue (negative), a decrease in the yellow hue of the avocado pulp (mesocarp) was observed. Although an increase in b* was expected, indicating a shift towards more yellow tones due to the synthesis of carotenoids during ripening, this observed behavior in b* is consistent with findings reported by Sierra *et al.* (2019) when modeling the ripening effect in Hass avocados. Lu *et al.* (2009) reported variations in carotenoid levels in the pulp of avocado cv. Hass at its consumption ripeness stage, with a range from 5 μg g^{-1} to 40 μg g^{-1} total carotenoids. Similarly, Rosas Flores *et al.* (2021) found carotenoid content in Hass avocado to be 17.60±1.61 μg g^{-1}, compared to a chlorophyll content of 56.85±19.41 μg g^{-1}. This suggests that, when evaluating color, the b* coordinate could be influenced by the content of these pigments, masking the effect of secondary metabolites such as carotenoids (Li *et al*., 2020).

Ethylene production was affected by the interaction of phosphine doses and exposure time. Ethylene is a signaling hormone in the ripening processes, which leads to the degradation of complex sugars that serve as a source of carbon and energy for enzymatic processes and changes in fruit color, facilitating the ripening process (Astudillo-Ordóñez & Rodríguez, 2018). Figure 4A shows that the interaction of phosphine doses and exposure times affected ethylene production; however, the interaction with the highest ethylene production was at 800 ppm at 36 h exposure, and the lowest production of ethylene occurred at 400 ppm at 36 h exposure and not at 0 ppm. Fluctuations in ethylene levels were observed, but they were not associated with the concentration of phosphine (Obenland *et al*., 2021). Instead, it is suggested that these fluctuations may have been generated by the fruit's production of carbon dioxide, a phenomenon akin to findings reported by Liu (2012), where doses of up to 2,200 ppm phosphine were evaluated for 3 d and there was no evidence of damage to fresh products, but there was damage due to accumulated CO_2. Subsequently, Liu and Liu (2014) evaluated the use of CO_2 and ethylene absorbents to reduce damage to lettuce.

For the production of ethylene over time, a decrease was observed; however, an abrupt increase was observed at 3 DAT as a result of the climacteric peak, reflecting the overproduction of ethylene in the maturation process (Fig. 4B). This behavior coincides with the report by Gwanpua *et al.* (2018) and Rosas Flores *et al.* (2016), who stated that Hass avocado fruits are sensitive to ethylene after the first 72 h after harvest, where there is an increase in the rate of ethylene production that subsequently stabilizes.

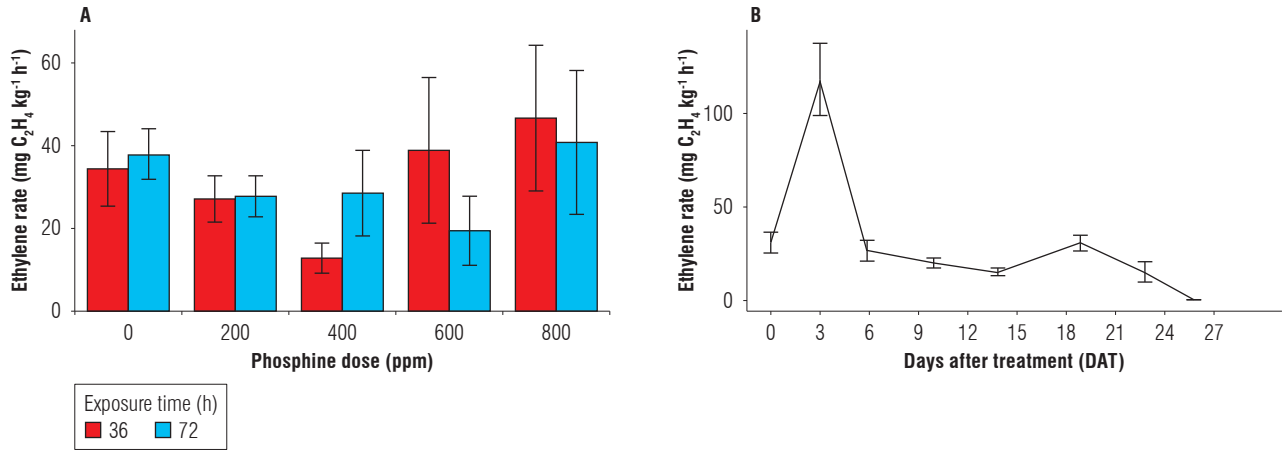

FIGURE 4. Effect of phosphine on the rate of ethylene produced by Hass avocado fruits. (A) Interaction effect of phosphine dose and exposure time, (B) effect of days after treatment (storage period). Vertical bars represent confidence intervals for the MANOVA.RM model ($P<0.05$), n = 180.

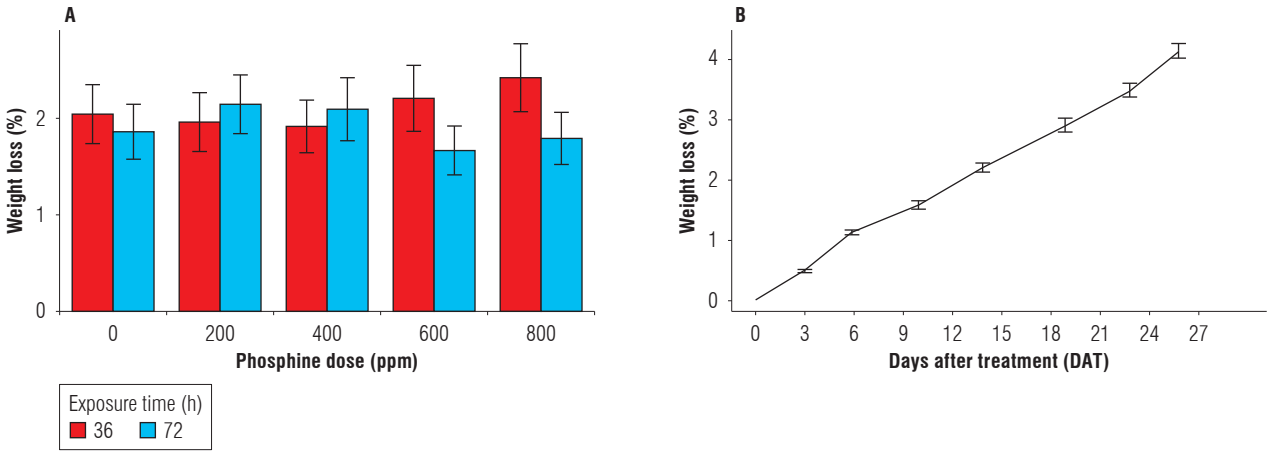

FIGURE 5. Effect of phosphine on weight loss in Hass avocado fruits. (A) Interaction effect of doses and exposure length to phosphine, (B) effect of trial evaluation days. Vertical bars represent confidence intervals for the MANOVA.RM model ($P<0.05$), n = 180.

Weight loss exhibited a linear trend throughout the trial, increasing with the number of days post-treatment, ultimately resulting in a 4% loss of initial weight by 27 DAT (Fig. 5B). The interaction between phosphine dose and exposure time significantly influenced weight loss. The highest weight loss was observed at an 800 ppm phosphine dose with 36 h exposure, which differed significantly from the combination of 600 ppm and 72 h. However, none of these interactions showed significant differences compared to the control (Fig. 5A). The greater weight loss at 800 ppm and 36 h of exposure was possibly attributed to increased respiration in the avocados subjected to high concentrations of phosphine (Fig. 5A), which led to a greater vapor pressure deficit of the avocado compared to the reduced and saturated environment of phosphine molecules, resulting in increased water loss (Espinosa-Cruz *et al.*, 2014; Kim *et al.*, 2022). However, the high concentrations of phosphine exposed for 72 h did not show marked differences with respect to the weight loss of the control (0 ppm). Similarly, the weight loss overtime was less than 5% (Fig. 5B) attributed to the ripening process. This is consistent with reports by Escobar *et al.* (2019), who noted a weight loss due to maturation of 3.84% at 5°C. Likewise, Aguirre-Joya *et al.* (2017) reported a weight loss of up to 5.56% at 7°C in fruits of 190±20 g stored for 28 d.

Conclusions

Considering the postharvest variables evaluated in this study, the applied treatments indicate that the phosphine concentrations tested did not produce adverse effects on the postharvest quality of Hass avocado fruits. This finding suggests that concentrations up to 800 ppm could be viable for future studies on the efficacy of pest management, without compromising fruit quality. Notably, exposure duration did not show a direct impact on fruit quality, nor were there significant interactions between exposure time and phosphine concentration affecting fruit quality. However, it is important to note that prolonged exposure times, such as 72 h, may lead to the accumulation of respiratory by-products, which could inadvertently accelerate fruit ripening. Therefore, it is crucial to implement strategies within the treatment containers to mitigate this effect and ensure optimal fruit preservation.

Acknowledgments

The authors express their gratitude to the Universidad Nacional de Colombia for the invaluable assistance, including access to staff, equipment, facilities, and support throughout the setup and logistics of the trials. The authors also thank Mariam Vasquez for her support in establishing the trial and collecting the data.

Conflict of interest statement

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

Author's contributions

PALP carried out the functions of conceptualization, research, data curation, formal analysis, validation, visualization and writing the original draft. SBO contributed to research, data curation, formal analysis, visualization and writing the original draft. AOHA contributed to funding acquisition, project administration, supervision, validation, writing review & editing. All authors approved the final version of the manuscript.

Literature cited

Agrafioti, P., Athanassiou, C. G., & Subramanyam, B. (2019). Efficacy of heat treatment on phosphine resistant and susceptible populations of stored product insects. *Journal of Stored Products Research*, *81*, 100–106. https://doi.org/10.1016/j.jspr.2018.11.007

Aguirre-Joya, J. A., Ventura-Sobrevilla, J., Martínez-Vazquez, G., Ruelas-Chacón, X., Rojas, R., Rodríguez-Herrera, R., & Aguilar, C. N. (2017). Effects of a natural bioactive coating on the quality and shelf-life prolongation at different storage conditions of avocado (*Persea americana* Mill.) cv. Hass. *Food Packaging and Shelf Life*, *14*(Part B), 102–107. https://doi.org/10.1016/j.fpsl.2017.09.003

Ahmed, Q., Ren, Y., Emery, R., Newman, J., & Agarwal, M. (2018). Evaluation of ethyl formate, phosphine, and their combination to disinfest harvested celery against purple scum springtails. *HortTechnology*, *28*(4), 492–501. https://doi.org/10.21273/HORTTECH04030-18

Alzahrani, S. M., & Ebert, P. R. (2019). Oxygen and arsenite synergize phosphine toxicity by distinct mechanisms. *Toxicological Sciences*, *167*(2), 419–425. https://doi.org/10.1093/toxsci/kfy248

Arora, S., Stanley, J., & Srivastava, C. (2021). Temporal dynamics of phosphine fumigation against insect pests in wheat storage. *Crop Protection*, *144*, Article 105602. https://doi.org/10.1016/j.cropro.2021.105602

Astudillo-Ordóñez, C. E., & Rodríguez, P. (2018). Physicochemical parameters of avocado *Persea americana* Mill. cv. Hass (Lauraceae) grown in Antioquia (Colombia) for export. *Corpoica Ciencia y Tecnología Agropecuaria*, *19*(2), 383–392. https://doi.org/10.21930/rcta.vol19_num2_art:694

Bernal-Estrada, J., & Cartagena-Valenzuela, J. (2017). Contenido de lípidos y composición relativa de los ácidos. *Memorias del V Congreso Latinoamericano del Aguacate* (pp. 389–400). Ciudad Guzmán, Jalisco, México. https://www.avocadosource.com/Journals/Memorias_VCLA/2017/Memorias_VCLA_2017_PG_389.pdf

Carabalí Muñoz, A., Caicedo Vallejo, A. M., & Holguín, C. M. (2021). *Guía para el reconocimiento y manejo de las principales plagas de aguacate cv. Hass en Colombia*. Agrosavia. https://editorial.agrosavia.co/index.php/publicaciones/catalog/view/226/208/1422-1

Carvalho, C. P., Velásquez, M. A., & Van Rooyen, Z. (2014). Determination of the minimum dry matter index for the optimum harvest of 'Hass' avocado fruits in Colombia. *Agronomía Colombiana*, *32*(3), 399–406. https://doi.org/10.15446/agron.colomb.v32n3.46031

Castellanos, D. A., Mendoza, R., Gavara, R., & Herrera, A. O. (2017). Respiration and ethylene generation modeling of "Hass" avocado and feijoa fruits and application in modified atmosphere packaging. *International Journal of Food Properties*, *20*(2), 333–349. https://doi.org/10.1080/10942912.2016.1160921

Castellanos, D. A., Polanía, W., & Herrera, A. O. (2016). Development of an equilibrium modified atmosphere packaging (EMAP) for feijoa fruits and modeling firmness and color evolution. *Postharvest Biology and Technology*, *120*, 193–203. https://doi.org/10.1016/j.postharvbio.2016.06.012

Cato, A., Afful, E., Nayak, M. K., & Phillips, T. W. (2019). Evaluation of knockdown bioassay methods to assess phosphine resistance in the red flour beetle, *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae). *Insects, 10*(5), Article 140. https://doi.org/10.3390/insects10050140

Cerdas Araya, M. D. M., Montero Calderón, M., & Somarribas Jones, O. (2014). Verificación del contenido de materia seca como indicador de cosecha para aguacate (*Persea americana*) cultivar Hass en zona intermedia de producción de Los Santos, Costa Rica. *Agronomía Costarricense*, *38*(1), 207–214. https://doi.org/10.15517/rac.v38i1.15205

Cumming, G., Fidler, F., & Vaux, D. L. (2007). Error bars in experimental biology. *Journal of Cell Biology*, *177*, 7–11. https://doi.org/10.1083/jcb.200611141

Dirección de Impuestos y Aduanas Nacionales (DIAN). (2024, July). *Tablero de Información Estadística de Comercio Exterio*r. Dirección de Impuestos y Aduanas Nacionales. https://www.dian.gov.co/dian/cifras/Paginas/Tablero-de-estadisticas-de-comercio-exterior.aspx

El-Shafei, W. K. M. (2020). Comparison between using phosphine and/or carbon dioxide for controlling *Plodia interpunctella* and *Oryzaephilus surinamensis* in stored date fruits. *Middle East Journal of Applied Sciences*, *10*(4), 657–664. https://doi.org/10.36632/mejas/2020.10.4.56

Escobar, J. V., Rodríguez, P., Cortés, M., & Correa, G. (2019). Influencia de la materia seca como índice de madurez de cosecha y tiempo de almacenamiento en frío sobre la calidad del aguacate cv. Hass producido en la región del trópico alto. *Información Tecnológica*, *30*(3), 199–210. https://doi.org/10.4067/S0718-07642019000300199

Espinosa-Cruz, C. C., Valle-Guadarrama, S., Ybarra-Moncada, M. C., & Martínez-Damián, M. T. (2014). Comportamiento postcosecha de frutos de aguacate "Hass" afectado por temperatura y atmósfera modificada con microperforado. *Revista Fitotecnia Mexicana*, *37*(3), 235–242. https://doi.org/10.35196/rfm.2014.3.235

FAO – Food and Agriculture Organization. (2022, July). *FAOSTAT*. https://www.fao.org/faostat/en/#data

Ferreyra, R., Sellés, G., Saavedra, J., Ortiz, J., Zúñiga, C., Troncoso, C., Rivera, S. A., González-Agüero, M., & Defilippi, B. G. (2016). Identification of pre-harvest factors that affect fatty acid profiles of avocado fruit (*Persea americana* Mill) cv. "Hass" at harvest. *South African Journal of Botany*, *104*, 15–20. https://doi.org/10.1016/j.sajb.2015.10.006

Friedrich, S., Konietschke, F., & Pauly, M. (2018). Analysis of multivariate data and repeated measures designs with the R package MANOVA.RM. arXiv preprint. https://doi.org/10.48550/arXiv.1801.08002

Garcia, F., Lin, W., Mellano, V., & Davidov-Pardo, G. (2021). Effect of biopolymer coatings made of zein nanoparticles and ε-polylysine as postharvest treatments on the shelf-life of avocados (*Persea americana* Mill. Cv. Hass). *Journal of Agriculture and Food Research*, *7*, Article 100260. https://doi.org/10.1016/j.jafr.2021.100260

Goulao, L. F., & Oliveira, C. M. (2008). Cell wall modifications during fruit ripening: When a fruit is not the fruit. *Trends in Food Science & Technology*, *19*(1), 4–25. https://doi.org/10.1016/j.tifs.2007.07.002

Güncan, A., Altunç, Y. E., Karayar, Ş., Bahat, T. N., & Yüksel, E. S. (2023). Optimizing phosphine fumigation efficiency in hazelnut industry: Determining optimal exposure time for stored product pest control. *International Journal of Agriculture Environment and Food Sciences*, *7*(3), 540–549. https://doi.org/10.31015/jaefs.2023.3.8

Guzmán, L. F., Machida-Hirano, R., Borrayo, E., Cortés-Cruz, M., Espíndola-Barquera, M. del C., & García, E. H. (2017). Genetic structure and selection of a core collection for long term conservation of avocado in Mexico. *Frontiers in Plant Science*, *8*, Article 243. https://doi.org/10.3389/fpls.2017.00243

Gwanpua, S. G., Qian, Z., & East, A. R. (2018). Modelling ethylene regulated changes in 'Hass' avocado quality. *Postharvest Biology and Technology*, *136*, 12–22. https://doi.org/10.1016/j.postharvbio.2017.10.002

Heather, N. W., & Hallman, G. J. (2008). *Pest management and phytosanitary trade barriers* (1st ed.). CABI Digital Library. https://doi.org/10.1079/9781845933432.0000

Hertog, M. L. A. T. M., Nicholson, S. E., & Whitmore, K. (2003). The effect of modified atmospheres on the rate of quality change in "Hass" avocado. *Postharvest Biology and Technology*, *29*(1), 41–53. https://doi.org/10.1016/S0925-5214(02)00211-9

ICA, & ANDI. (2016). *Manual para la elaboración de protocolos para ensayos de eficacia con PQUA*. https://www.andi.com.co/Uploads/Manual_Protocolos_Ensayos_Eficacia_PQUA_REV_08_09_2016%20(2).pdf

IPPC – International Plant Protection Convention. (2024). Secretaría de la CIPF. 2024. *Glosario de términos fitosanitarios.* Norma internacional para medidas fitosanitarias n.º 5. Roma. FAO en nombre de la Secretaría de la Convención Internacional de Protección Fitosanitaria. https://assets.ippc.int/static/media/files/publication/es/2024/07/ISPM_05_2024_Es_Glossary_PostCPM-18_InkAmdts_2024-07-28.pdf

Kim, B. S., Hong, K. J., Kwon, T. H., Lee, K. Y., Lee, B. H., & Lee, S. E. (2022). Phosphine fumigation followed by cold treatment to control peach fruit moth, *Carposina sasakii*, larvae on "Fuji" apples intended for export. *Applied Sciences*, *12*(15), Article 7514. https://doi.org/10.3390/app12157514

Kim, B. S., Park, C. G., Moon, Y. M., Sung, B. K., Ren, Y., Wylie, S. J., & Lee, B. H. (2016). Quarantine treatments of imported nursery plants and exported cut flowers by phosphine gas (PH_3) as methyl bromide alternative. *Journal of Economic Entomology*, *109*(6), 2334–2340. https://doi.org/10.1093/jee/tow200

Kyung, Y., Kim, H. K., Lee, J. S., Kim, B. S., Yang, J. O., Lee, B. H., Koo, H. N., & Kim, G. H. (2018). Efficacy and phytotoxicity of phosphine as fumigants for *Frankliniella occidentalis* (Thysanoptera: Thripidae) on Asparagus. *Journal of Economic Entomology*, *111*(6), 2644–2651. https://doi.org/10.1093/jee/toy218

Lampiri, E., Agrafioti, P., & Athanassiou, C. G. (2021). Delayed mortality, resistance and the sweet spot, as the good, the bad and the ugly in phosphine use. *Scientific Reports*, *11*(1), Article 3933. https://doi.org/10.1038/s41598-021-83463-y

Li, L., Zhang, G., Li, B., Yang, J. O., Park, M. G., & Liu, T. (2020). Postharvest treatment of mandarin fruit using a combination of methyl bromide and phosphine against *Bactrocera dorsalis* (Diptera: Tephritidae). *Pest Management Science*, *76*(5), 1938–1943. https://doi.org/10.1002/ps.5726

Liu, S. S., & Liu, Y. B. (2014). Reducing injury of lettuce from phosphine fumigation. *HortTechnology*, *24*(2), 188–195. https://doi.org/10.21273/horttech.24.2.188

Liu, T., Li, L., Li, B., Zhan, G., & Wang, Y. (2018). Evaluation of low-temperature phosphine fumigation for control of oriental fruit fly in loquat fruit. *Journal of Economic Entomology*, *111*(3), 1165–1170. https://doi.org/10.1093/jee/toy029

Liu, Y. B. (2012). Oxygenated phosphine fumigation for control of *Nasonovia ribisnigri* (Homoptera: Aphididae) on harvested lettuce. *Journal of Economic Entomology*, *105*(3), 810–816. https://doi.org/10.1603/EC11328

Lizarazo-Peña, P., Benjumea-Orozco, S., & Herrera Arévalo, A. O. (2024). Effects of phosphine and plant extracts on flower thrips mortality and the quality of cut flowers. *Agronomía Colombiana, 42*(1), Article 112909. https://doi.org/10.15446/agron.colomb.v42n1.112909

Lu, Q. Y., Zhang, Y., Wang, Y., Wang, D., Lee, R., Gao, K., & Heber, D. (2009). California Hass avocado: Profiling of carotenoids, tocopherol, fatty acid, and fat content during maturation and from different growing areas. *Journal of Agricultural and Food Chemistry*, *57*, 10408–10413. https://doi.org/10.1021/jf901839h

Ma, Y., Li, L., Li, B., Liu, Q., Ren, Y., Wang, P., & Liu, T. (2024). Phosphine fumigation followed by forced hot-air treatment for postharvest control of *Bactrocera dorsalis* in dragon fruit. *Journal of Pest Science*, 1–12. https://doi.org/10.1007/s10340-024-01848-0

Montgomery, D. (2017). *Diseño y análisis de experimentos* (9th ed.). Limusa S. A.

Nath, N. S., Bhattacharya, I., Tuck, A. G., Schlipalius, D. I., & Ebert, P. R. (2011). Mechanisms of phosphine toxicity. *Journal of Toxicology*, *2011*, Article 494168. https://doi.org/10.1155/2011/494168

Obenland, D., Cranney, J. R., Tebbets, S., Walse, S., & Arpaia, M. L. (2021). Fumigating citrus with phosphine does not impact marketability or eating quality. *Plant Health Progress*, *22*(4), 516–523. https://doi.org/10.1094/PHP-03-21-0053-RS

Pathare, P. B., Opara, U. L., & Al-Said, F. A. J. (2013). Colour measurement and analysis in fresh and processed foods: A review. *Food and Bioprocess Technology*, *6*(1), 36–60. https://doi.org/10.1007/s11947-012-0867-9

Pedreschi, R., Uarrota, V., Fuentealba, C., Alvaro, J. E., Olmedo, P., Defilippi, B. G., Meneses, C., & Campos-Vargas, R. (2019). Primary metabolism in avocado fruit. *Frontiers in Plant Science*, *10*, Article 795. https://doi.org/10.3389/fpls.2019.00795

Perotti, V. E., Moreno, A. S., & Podestá, F. E. (2014). Physiological aspects of fruit ripening: The mitochondrial connection. *Mitochondrion*, *17*, 1–6. https://doi.org/10.1016/j.mito.2014.04.010

Pidakala, P. P. B., Esfandi, K., Afsar, S., Baldassarre, C., Ortiz, G. I., Page-Weir, N., & Woolf, A. B. (2024). Effects of phosphine (ECO2FUME®) on 'Hass' avocado fruit quality and target pest mortality. *New Zealand Journal of Crop and Horticultural Science*, *52*(2), 159–169. https://doi.org/10.1080/01140671.2022.2111446

Restrepo Giraldo, P. A. (2019). *El fosfuro de magnesio como alternativa para el control de plagas en pos-cosecha de flores tipo exportación* [Specialization thesis, Corporación Universitaria Lasallista].

Rojas-Graü, M. A., Oms-Oliu, G., Soliva-Fortuny, R., & Martín-Belloso, O. (2009). The use of packaging techniques to maintain

freshness in fresh-cut fruits and vegetables: A review. *International Journal of Food Science and Technology*, *44*(5), 875–889. https://doi.org/10.1111/j.1365-2621.2009.01911.x

Rosas Flores, N., Saucedo Veloz, S., García Osorio, C., & Saucedo Reyes, D. (2016). Producción de etileno y cambios asociados a la maduración de frutos de aguacate "Hass" y "Carmen Hass". *Revista Iberoamericana de Tecnología Postcosecha*, *17*(1), 24–29. https://www.redalyc.org/pdf/813/81346341004.pdf

Rosas Flores, N., Saucedo Veloz, C., Saucedo Reyes, D., López Jiménez, A., Valle Guadarrama, S., Ramírez Guzmán, M. E., & Chávez Franco, S. H. (2021). Maduración en poscosecha de frutos de aguacate cultivares Hass y Méndez tratados con etefón. *Acta Agronómica*, *69*(4), 275–284. https://doi.org/10.15446/acag.v69n4.89994

Shikwambana, K., Mafeo, T. P., & Mathaba, N. (2021). Effect of postharvest glucose infusion on exocarp colour of Hass' avocado (*Persea americana* Mill) during ripening. *Journal of Horticulture and Postharvest Research*, *4*(4), 439–452. https://doi.org/10.22077/jhpr.2021.4254.1202

Sierra, N. M., Londoño, A., Gómez, J. M., Herrera, A. O., & Castellanos, D. A. (2019). Evaluation and modeling of changes in shelf life, firmness and color of 'Hass' avocado depending on storage temperature. *Food Science and Technology International*, *25*(5), 370–384. https://doi.org/10.1177/1082013219826825

UNEP. (2020). *Handbook for the montreal protocol on substances that deplete the ozone layer* (14th ed.). UN Environment Programme. Ozone Secretariat. https://ozone.unep.org/sites/default/files/Handbooks/MP-Handbook-2020-English.pdf

Walse, S. S., & Jimenez, L. R. (2021). Postharvest fumigation of fresh citrus with cylinderized phosphine to control bean thrips (Thysanoptera: Thripidae). *Horticulturae*, *7*(6), Article 134. https://doi.org/10.3390/horticulturae7060134

Wang, D., Collins, P. J., & Gao, X. (2006). Optimising indoor phosphine fumigation of paddy rice bag-stacks under sheeting for control of resistant insects. *Journal of Stored Products Research*, *42*(2), 207–217. https://doi.org/10.1016/j.jspr.2005.02.001

Wason, S., & Selladurai, M. (2023). Is phosphine an ideal candidate for fruit fly disinfestation in Java apple, *Syzygium samarangense*?. *Food and Humanity*, *1*, 662–669. https://doi.org/10.1016/j.foohum.2023.07.011

Wickham, H. (2016). *ggplot2. Elegant graphics for data analysis* (2nd ed.). Springer. https://doi.org/10.1007/978-3-319-24277-4

Williams, L. O. (1977). The avocados, a Synopsis of the genus *Persea*, subg. *Persea*. *Economic Botany*, *31*(3), 315–320. https://doi.org/10.1007/BF02866883

Zhang, F., Wang, Y., Li, L., & Liu, T. (2013). Effects of phosphine fumigation on postharvest quality of four Chinese cut flower species. *Postharvest Biology and Technology*, *86*, 66–72. https://doi.org/10.1016/j.postharvbio.2013.06.016

Zhang, F., Wang, Y., Liu, B., Ren, L., Gong, S., & Liu, T. (2015). Low temperature phosphine fumigation for postharvest control of western flower thrips, *Frankliniella occidentalis* (Thysanoptera: Thripidae) on oriental lily. *Postharvest Biology and Technology*, *100*, 136–141. https://doi.org/10.1016/j.postharvbio.2014.09.011

Zou, H., Li, L., Li, B., Ren, Y., & Liu, T. (2025). Phosphine and phosphine plus ethyl formate for controlling papaya mealybug (Hemiptera: Pseudococcidae) on succulents. *Journal of Economic Entomology*, *118*(1), 152–159. https://doi.org/10.1093/jee/toae270