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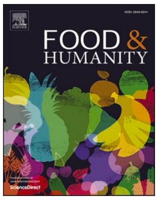

Levels of heavy metals in tropical fruits and soils from agricultural crops in Antioquia, Colombia. A probabilistic assessment of health risk associated with their consumption

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ABSTRACT

Heavy metals such as lead (Pb), mercury (Hg), cadmium (Cd), arsenic (As), and chromium (Cr) occur naturally in the environment and can be released through human activities such as mining and industry. These metals can accumulate in the biota and humans, furthermore, posing dangers through the consumption of contaminated foods, including fruits even at low levels. Therefore, the objective of this study was to evaluate the levels of these pollutants in tropical fruits and soils of Antioquia, Colombia. Furthermore, the health risk by consumption was estimated. 56 fruit samples (Hass avocado, cape gooseberry, and purple passion fruit) and 32 soil samples were collected from 8 farms between March 2023 and January 2024. The samples were digested/extracted and analyzed by inductively coupled plasma atomic emission spectrometry assisted by microwave. Levels above the maximum level of Hg (0.01 mg/kg), Pb (0.200 mg/kg), and As (0.500 mg/kg) were found in the three fruits of the study. Hass avocado had the highest Hg concentration (0.367 mg/kg); purple passion fruit had the highest Pb concentration (0.612 mg/kg), and cape gooseberry had the highest As concentration (0.179 mg/kg). Cd and Cr were not detected in fruits. In the soil, the mean levels of Hg and Cd were 3.46 mg/kg and 4.91 mg/kg, respectively. All samples exceeded the regulatory limits for these metals (Hg 0.450 mg/kg and Cd 1.00 mg/kg). The rest of the metals were below the regulatory limit in the soil. Irrigation water (groundwater) was identified as the main source of contamination because plants could uptake metals by roots due to its similarity with essential metals. The Hazard Quotient (HQ) in Hass avocado of Hg and Pb was 1.07 and 1.20; and in purple passion fruit to Pb was 1.28 in the 95th percentile. The above indicated a non-carcinogenic risk by consumption. It is worth noting that the risk was calculated considering the worse scenario for the population, such as high-rate intakes for a long term of exposure and high frequency of intake. Finally, the results indicated a high presence of these metals in fruits, contrary to expectations based on the matrix type. These highlight the need for ongoing monitoring to reduce exposure risks for the local population, as noncarcinogenic risks from Hg and Pb consumption were found. These findings encourage further research on this issue in the country and provide an overview of exposure that could be useful to environmental health policies and protect public health.

1. Introduction

Heavy metals are metallic elements with high density, known for their potential toxicity (Mawari et al., 2022a, 2022b). This classification includes elements such as lead (Pb), mercury (Hg), cadmium (Cd), arsenic (As), and chromium (Cr). While these metals are naturally occurring in the Earth's crust, they can also be released into the environment through human activities, such as industrial processes, mining, and the use of certain products (Briffa et al., 2020). Due to their persistence, heavy metals can remain in the environment for extended periods and may accumulate within living organisms, including humans, through a process known as bioaccumulation (Amini et al., 2014).

In recent years, the demand for tropical fruits has surged significantly. Fruits and vegetables are essential sources of nutrients and health-promoting phytochemicals, which play a crucial role in reducing

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the global incidence of nutritional deficiencies and providing protective antioxidants (Xiang et al., 2021). Among the key producers, Colombia stands out for its production and export of tropical fruits, such as cape gooseberry, purple passion fruit, and Hass avocado. These fruits are highly sought after in European and North American markets. As a result, Colombia has implemented international standards to ensure the safety and quality of its products. The National regulation in Colombia regarding levels of heavy metals in foods is the 4506/2013 (Resolucion, 4506,06, 2013) in which the maximum level for Cd is 0.02 mg/kg and to Pb is 0.200 mg/kg in fruits. National regulation does not include maximum level to As, Hg, and Cr in fruits. Likewise, the European regulation 915/2023 includes the same values to the same metals ((EU) 915, 2023) Moreover, includes As in rice (0.3 mg/kg). On the other hand, National Health and Family Planning Commission (NHFPC) and the China Food and Drug Administration (CFDA) released the National Food Safety Standard for maximum levels of contaminants in foods (GB 2762–2017) (USDA GB,62, 2017). In which are includes maximum levels for Hg, Cr and As in vegetables and vegetable products of 0.01 mg/kg, 0.5 mg/kg and 0.5 mg/kg, respectively. Given that soil is a potential source of contamination for crops (Chen et al., 2021), limits have been established for various metals based on the intended land use. For soils improvers designated for agricultural use, the established limits are 1.00 mg/kg, 0.45 mg/kg, 10 mg/kg, 100 mg/kg, and 100 mg/kg for Cd, Hg, As, Cr, and Pb, respectively (UE, 2022). Exposure to metals through food and beverages can lead to serious health issues, including kidney and lung damage, cancer, reduced Intelligence Quotient, birth defects, growth delays, nervous system effects, and reproductive toxicity. Therefore, measuring these contaminants in fruits is essential for protecting consumer health (Chen et al., 2021).

A study investigated metal pollution (Pb, Cd, As, and Hg) in 24 different types of vegetables and fruits cultivated in the industrialized city of Solapur, Maharashtra, India. Potential health risks due to the consumption of fruits and vegetables were evaluated. The average concentrations of selected heavy metals in analyzed fruits and vegetables were as follows: Pb (0.17 ± 0.38 mg/kg) > Hg (0.06 ± 0.09 mg/kg) > Cd (0.02 ± 0.007 mg/kg) > As (0.002 ± 0.003 mg/kg). Of the vegetables and fruits studied, garlic exhibited the highest levels followed by potatoes (Mawari et al., 2022a, 2022b). Furthermore, in 2014 a study in Nigeria revealed that avocados also can contain high levels of these pollutants. The study found that levels of Cd, Cu, Fe, Pb, Ni, Mn and Co in avocados ranged from 0.08 mg/kg to 0.22 mg/kg, 0.23 mg/kg to 5.29 mg/kg, 19.0 mg/kg to 29.6 mg/kg, 1.69 mg/kg to 5.80 mg/kg, 1.16 mg/kg to 5.87 mg/kg, 1.03 mg/kg to 12.6 mg/kg, and 1.43 mg/kg to 3.56 mg/kg, respectively (Ihesinachi & Eresiya, 2014).

Furthermore, a study conducted in several municipalities of the Pacific region in Colombia found Hg concentrations exceeding regulatory limits in some fruits. Concentrations were found in Bojayá of 1.55 ± 0.5 mg/kg for banana, 1.18 ± 0.3 mg/kg for lemon and 2.65 ± 0.3 mg/kg for lulo. In Vigía concentrations were found of 1.68 ± 0.4 mg/kg for lemon and 1.87 ± 0.2 mg/kg for lulo. In Murindó, concentrations were found of 7.33 ± 1.3 mg/kg for banana and 2.04 ± 0.8 mg/kg for borojó (Caicedo-Rivas et al., 2022). Moreover, a study in Sibaté, Colombia, reported mean concentrations of As, Cd, Co, Cr, Cu, Ni, Pb, and Zn of 2.36 mg/kg, 0.160 mg/kg, 0.430 mg/kg, 12.1 mg/kg, 13.1 mg/kg, 0.0200 mg/kg, 7.07 mg/kg, 3.97 mg/kg, respectively. Additionally, soils contain concentrations of Zn (1.90 mg/kg to 11.0 mg/kg), Pb (3.74 mg/kg to 6.42 mg/kg), Ni (0.650 mg/kg to 1.36 mg/kg), and Cd (0.0800 mg/kg to 0.270 mg/kg) (Lizarazo et al., 2020).

Recent research has highlighted the health risks posed by dietary exposure to toxic metals, which can lead to both noncarcinogenic and carcinogenic health concerns for local populations. Health risk assessment used Hazard Quotient (HQ) values to evaluate non-carcinogenic risks. An HQ value greater than 1 indicates a potential health risk from exposure to a particular toxic metal through the diet. The results showed high non-carcinogenic risks, especially associated with toxic metals in cereals (HQ = 1.2104), followed by solanaceous fruits (HQ = 0.9134), vegetables (HQ = 0.8726), fruits (HQ = 0.8170), meat (HQ = 0.7269), drinking water (HQ = 0.6139), beans (HQ = 0.2991) and potatoes (HQ = 0.1573).). For carcinogenic risks, the assessment calculates the Increase Lifetime Cancer Risk (ILCR), with values above 1.0×10^{-4} considered indicative of elevated cancer risk. The total carcinogenic risk from toxic metal intake was found to be 9.98×10^{-4}, which exceeds the acceptable threshold and points to an increased risk of cancer, particularly from drinking water (ILCR = 2.34×10^{-4}), meat (ILCR = 2.11×10^{-4}), and various fruits and vegetables (Wang et al., 2023).

Similarly, another study in China reported that daily dietary intake of As, Cd and Pb surpassed the provisional tolerable daily intake levels for local residents, with children especially affected by high vegetable consumption. Target hazard quotients above the safe value of one were observed in approximately 95 %, 50 %, and 25 % of local residents for As, Cd, and Pb, respectively. In particular, the values of the 95th percentile hazard index were 15.71 for children, 11.15 for adolescents, and 9.34 for adults, highlighting significant health risks, particularly for children (Guo et al., 2019).

According to data from Analdex (National Association of Foreign Trade), in 2023, exports of Hass avocado increased by 12.5 %, reaching 114,535 tons. Similarly, exports of cape gooseberry reached 153,000 tons, and those of purple passion fruit amounted to 8541 tons (ANALDEX, 2023). Therefore, the objective of this study was to evaluate metal levels in cape gooseberry (*Physalis peruviana*), purple passion fruit (*Passiflora pinnatistipula*), and Hass avocado (*Persea americana L. Hass*), as well as in the soils used for their cultivation. Additionally, health risk due to consumption was estimated. Monte Carlo simulations were conducted to evaluate the potential carcinogenic and non-carcinogenic risks associated with the concentrations of metals present in the fruits. The results could be useful to environmental health policies to protect public health.

2. Materials and methods

2.1. Study area

The samples were collected in the municipality of La Unión, Antioquia, Colombia. The municipality has a total area of 198 km^2, with urban areas covering 62 km^2 and rural areas covering 136 km^2. The population is 21,475 inhabitants. La Unión is notable for its significant agricultural production of potatoes, cape gooseberry, avocado, purple passion fruit, and strawberries. Its economy also includes mining and livestock farming. This study included three Hass avocado farms (A1, A2, A3), three purple passion fruit farms (G4, G5, G6), and two cape gooseberry farms (U7, U8) (Figure S1).

2.2. Fruits sampling

Between March 2023 and January 2024, seven campaigns of sampling were conducted every 45 days taking samples from all farms as follows: 21 samples of Hass avocado, 14 samples of cape gooseberry, and 21 samples of purple passion fruit. The weight of the sample taken was 500 g per bag. The samples were transported at 25 ± 5 °C to the laboratory of the Contamination and Diagnosis Control Group (GDCON) of the University of Antioquia. Homogenization of the samples was done with 200 g of dry ice using a Hobart GmbH, model CC34 (Offenburg, Germany). The homogenized samples were dried at 25 °C ± 5 for 15 days over aluminum foil. Afterwards, they were hermetically sealed in bags and stored at −20 ± 2 °C until analysis. The sampling and pretreatment of the samples were carried out in accordance with the protocol of European Commission UE 333/2007 (CE N° 333, 2007). The time between campaigns of sampling corresponds to the harvest period of the crops.

2.3. Soils sampling

Between March 2023 and January 2024, four campaigns of sampling were conducted every 90 days, enabling the monitoring of changes in soil metal levels across different stages of plant growth. Two of these sampling campaigns took place during the wet season and two during the rainy season, allowing for an evaluation of precipitation effects on soil metal levels. In total 32 samples of soil were collected from the agricultural farms, distributed as follows: 12 samples of Hass avocado soil, 12 samples of Cape gooseberry soil, and 8 samples of purple passion fruit soil. Soil samples were collected by drilling at a depth of 0–40 cm using a soil auger suitable for soil extraction. The samples were then disaggregated and foreign materials such as clasts, glass fragments and/or debris were removed. The weight of the sample taken was 1000 g per bag and the samples were transported at 25 ± 5 °C to the GDCON laboratory. The samples were dried at 25 °C ± 5 for 15 days over aluminum foil. The samples were stored at 25 °C ± 5.

2.4. Standards and reagents

The standards for the metals Pb, Hg, Cd, Cr, As, and Au, as well as the acids used for the digestions (HCl, HNO_3) and hydrogen peroxide (H_2O_2), were purchased from Merck (Darmstadt, Germany). Working solutions were prepared from individual solutions of each metal, each with a concentration of 1000 mg/L in water acidified to 5 % with HNO_3. Calibration solutions were prepared by appropriately diluting the working mixtures in water acidified to 5 % with HNO_3. The working mixtures and stock solutions were stored at room temperature.

2.5. Sample digestion procedure

The samples of fruit and soil were analyzed in the same way. A homogenized fruit or soil sample weighing 5.0 ± 0.1 g was placed into a 250 ml Erlenmeyer flask. Subsequently, 50 μL of a 50 mg/L gold solution was introduced to mitigate potential interference during analysis. Following this, 2 ml of 30 % hydrogen peroxide and 8 ml of 65 % nitric acid were added to the sample. Digestion was conducted for 45 minutes at 150 °C heating plate. Leachable metals were digested considering that hydrogen peroxide and nitric acid cannot digest silicone bound metals. Upon completion of the digestion process, the sample was allowed to cool, and 2.5 ml of 65 % hydrochloric acid was incorporated. The resultant extract underwent filtration using cellulose filter paper and was diluted to 25 ml with deionized water. The concentration of leachable metals in soils and fruits was measured using an atomic emission spectrophotometer.

2.6. Instruments and equipment

The hydrides for As and Hg were produced using an Agilent 4100 MIP OES microwave plasma-atomic emission spectrophotometer (Agilent, Santa Clara, CA). For the other metals, a two- way chamber inert OneNeb nebulizer equipped with an Agilent 4107 nitrogen generator (Agilent, Santa Clara, CA) was employed. A Shimadzu AUW120D balance (Shimadzu, Kyoto, Japan) was utilized for the weighing procedure.

2.7. Validation and uncertainty

All methods used were validated, and the uncertainty of the measurement was estimated. The validation parameters evaluated were linearity, matrix effect, method detection limit (MDL), method quantification limit (MQL), precision, and trueness (Chavan & Desai, 2022).

The linearity in both matrices was evaluated with three calibration curves using seven concentration levels in the range of 0.050–0.500 mg/kg As; 0.020–0.250 mg/kg Cd; 0.200–2.500 mg/kg Cr; 0.005–0.100 mg/mg Hg; and 0.150 mg-1.50 mg/kg Pb in fruits and soils. The regression hypothesis was evaluated using an analysis of variance (ANOVA) and the coefficients of determination (R^2) (SANTE/11312, 2021). The matrix effect (ME) was evaluated by comparing the ratio between the slopes of calibration curves in solvent (water) and matrix using the following equation ((a/b)-1) x100, where a and b correspond to the slope in matrix and solvent, respectively. The acceptance criterion was ± 20 % (Zhou et al., 2022). MDLs and MQLs were estimated using the t_{99}SLLMV approximation (Corley, 2003). The precision and trueness were evaluated with spiked samples at MQLs ($n = 20$) and 10xMQLs ($n = 20$) levels for metal in fruits. Precision and trueness in soil were evaluated by analyzing ($n = 20$) the certified reference material (metals in soil - PT; Sigma-Aldrich; SPE001–30G) (Lot # LRAB6031). The acceptance criteria were the HORRATr value (the ratio of the standard deviation of the repetitions to the square root of the mean of the test results) should be less than 2 for both parameters, and recovery percentages between 50 % and 120 % ((EC) No 333/2007, 2006). Below is (Eq. 1) for HORRATr.

$$\text{HorRatR} = \text{RSDr} \,/\, \text{PRSDR} \tag{1}$$

Where RSDR is the relative standard deviation due to reproducibility, $PRSDR = 2\,C^{-0.15}$. Where C is expressed as mass fraction.

Finally, the uncertainty was estimated using (Eq. 2), combining the contributions of u_{cal}, u_{vol}, u_{um}, u_{treat}, and u_{tru}. Where U is the expanded uncertainty; k is the coverage factor ($K = 2$); u_{cal} is the relative standard uncertainty regarding the calibration curve; u_{vol} is the relative standard uncertainty regarding the final volume; um is the relative standard uncertainty regarding sample mass; u_{treat} is the relative standard uncertainty regarding the sample treatment factor; and u_{tru} is the trueness estimation for relative standard uncertainty (Mohamed et al., 2020).

$$U = k\sqrt{u_{cal}^2 + u_{vol}^2 + u_{um}^2 + u_{treat}^2 + u_{tru}^2} \tag{2}$$

2.8. Probabilistic risk assessment (PRA)

The risk due to consumption of these metals in fruits was estimated using a strategy of probabilistic risk assessment (PRA) with Monte Carlo simulation (MCS). The risk was estimated in two scenarios; non-carcinogenic risk which is expressed as the hazard quotient (HQ) (Eq. 3) and a carcinogenic risk which is expressed as the Increased Lifetime Cancer Risks (ILCR) (Eq. 4).

$$\text{HQ} = \frac{EDI}{RfD} \tag{3}$$

$$\text{ILCRs} = \text{EDI*OSF} \tag{4}$$

Where EDI, RfD, and OSF correspond to the estimated daily intake, the oral reference dose, and the oral slope factor, respectively. The EDI (mg/kg/day of body weight) was calculated using (Eq. 5), in which Cn represents the mean concentration of metals in the fruits on a fresh weight basis (mg/kg) (log-normal distribution); IR is ingestion rate (200 g/person by day) (log-normal distribution) (U.S. EPA, 1990); EFr is exposure frequency (365 days/year)(normal distribution (U.S. EPA, 1990); ED is exposure duration (70 years)(normal distribution) (U.S. EPA, 1990); BW is the body mass, adult (70 kg) (log-normal distribution (U.S. EPA, 1990);and AT is averaging time for noncarcinogens (365 days / year× number of exposure years (U.S. EPA, 1990).

$$\text{EDI} = \frac{Cn * IR * EFr * ED}{BW * AT} * 0.001 \tag{5}$$

The RfD was taken from IRIS for metal. The RfD used was 1×10^{-4} mg/kg/day of Hg and 5×10^{-4} mg/kg/day of Pb (IRIS, 1987). When the HQ value was less than 1 at the 95 % percentile, it indicated that the risk of non-carcinogenic effects was at a safe level. In contrast, when HQ was greater than 1, there was a probability of non-carcinogenic effects, with the probability increasing as this value increases (IRIS, 1987). The values of OSF used to Pb was 8.50×10^{-4} per $(\text{mg/kg} \times \text{day})^{-1}$ y, As 1.5

$(mg/kg \times day)^{-1}$, In the case of Hg, a specific value is not found as it is not considered carcinogenic (IRIS, 1987). ILCRs result is considered normal in the range between 10^{-6} and 10^{-4} (U.S. EPA, 1990). Values higher than 10^{-4} indicate a carcinogenic risk. The MCS was performed with the package mc2d version 0.2.1 using 10,000 iterations in the variables and 5000 iterations in the uncertainty.

2.9. *Metal transfer factor from soil to plant*

The metal transfer factor (MTF), also known as the bioconcentration factor (BF), quantifies how metals move from soil into plants. It is computed by comparing the metal concentration in the edible parts of the plant to that in the soil (Eq. 6). This calculation helps to determine the extent to which metals are taken up by plants from the soil (Zunaidi et al., 2021).

$$MTF = \frac{C_{fruit}}{C_{soil}} \quad (6)$$

where C_{fruit} and C_{soil} represent the concentrations of metals in the extracts of the vegetable and soil samples, respectively.

2.10. *Data treatment and statistics*

All results are presented in mg/kg for fruits and mg/kg for soils. The values in which the results were <MQL were replaced by $\frac{1}{2}$MQL for descriptive analysis (Antweiler & Taylor, 2008). All statistical analysis and graphs were performed using R 4.3.3 and RStudio 2024.04.2 + 764 software. In most cases, the Kruskal-Wallis nonparametric test (KW) using correction of the Benjamini-Hochbergar method (BH) was used. When a KW-BH test was significant ($p\text{-value} < 0.05$) a post hoc Dunn test was performed as a pairwise comparison method. Finally, an analysis of variance (ANOVA) was performed to evaluate the regression hypothesis, and the Spearman method was performed to evaluate the correlation and relationships between the data.

2.11. *Quality assurance and control (QA/QC)*

In each batch of samples analyzed, a control was carried out using a method blank that consisted of a matrix of fruit and soil to verify possible cross-contamination during extraction. In addition, an analytical control of the method was carried out by adding a blank sample of fruit and soil with concentrations at the level of the limit of quantification for each metal (0.05 mg/kg of As, 0.02 mg/kg of Cd, 0.2 mg/kg Cr, 0.005 mg/kg of Hg and 0.15 mg/kg of Pb). The recovery percentages obtained from the analytical controls of the method varied between 83 % (Cd) and 111 % (Pb) in fruits, and between 72 % (Pb) and 116 % (As) in soils. Furthermore, a sample that was spiked in duplicate at concentrations within the range of the calibration curve for each metal in fruits and soils, respectively, was randomly selected to evaluate the performance of the method in terms of recovery and precision during the analysis of the samples. The recovery percentages for the spiked samples ranged between 72 % (Hg) and 112 % (As) in fruits and between 73 % (Cd) and 104 % (As) in soils. The relative percentage difference (RPD) of the spiked samples was in the range of 13 % (Cd) to 18 % (As) in fruits, and 5.7 % (Cr) to 19 % (Pb) in soils.

2.12. *Results and discussion*

The methods developed and used for the determination of the concentration of metals (Pb, Hg, Cd, As, and Cr) in fruit and soil samples collected from La Unión Antioquia, Colombia, had adequate performance, given that the results obtained during the validation were within the acceptance criteria for linearity, precision, trueness, MDL and MQL established by the reference method of European Commission (EU) 2016/582 of April 15, 2016. The summary of the validation results is presented in Table S1.

The linearity was evaluated considering the coefficients of determination (R^2) and the regression hypothesis through the ANOVA. The R^2 for all compounds of the study were ≥ 0.990 in both solvent and matrix (Table S1). Additionally, the linear regression hypothesis ($p < 0.05$) was demonstrated in solvent and matrix within the working range of all metals. The compounds did not show significant ME as all slope ratios were below 20 %.

In fruits, the MDL ranged from 0.00135 mg/kg (Hg) to 0.0413 mg/kg (Pb), and the MQL ranged from 0.0045 mg/kg (Hg) to 0.138 mg/kg (Pb). In soil, the MDL ranged from 0.00126 mg/kg (Hg) to 0.0403 mg/kg (Pb), and the MQL ranged from 0.0042 mg/kg (Hg) to 0.134 mg/kg (Pb). The recovery percentages ranged from 75.3 % (Hg) to 110 % (As) in fruits and from 73.8 % (Cr) to 111 % (Cd) in soils. The MQL values in this study were similar in magnitude to those reported in other studies on fruits and soils (Ezeilo et al., 2020; Khan et al., 2024; Scutarașu & Trincă, 2023; Tahir et al., 2001). Furthermore, MQL were at least at the regulatory level. Finally, the RSDs were ≤ 20 % in both matrices. Therefore, the methods were accurate because they had adequate precision and trueness (Wood, 1999).

2.13. *Metals in fruits*

Table 1 summarizes the results of the levels of metals in fruits. Individual results of all analyzed samples with their associate uncertainty are shown in Table S2.

Hg was detected in the three fruits of the study. The higher values were found in Hass avocado and the highest concentration was 0.367 ± 0.0660 mg/kg. In purple passion fruit the highest concentration was 0.0270 ± 0.00620 mg/kg, and in cape gooseberry was 0.0150 ± 0.00280 mg/kg. The 915/2023 regulation does not include a maximum level for Hg in this type of food, because the regulation is focused on levels of Hg in fish products, since fruits are not expected to contain mercury. However, the National Health and Family Planning Commission (NHFPC) and the China Food and Drug Administration (CFDA) released the National Food Safety Standard for maximum levels of contaminants in foods (GB 2762–2017) which include a maximum level of Hg in fruit of 0.0100 mg/kg (USDA GB,62, 2017). Considering the above, 38.1 % (8/21) of the Hass avocado, 28.6 % (6/21) of purple passion fruit and 28.6 % (4/14) of cape gooseberry samples had levels equal or higher than maximum level (Fig. 1).

Although Hg is not expected to be found in vegetables and fruits, there are several reports around the world of Hg in these matrices. Indeed, in India, they found maximum concentrations of Hg in garlic (0.123 mg/kg), okra (0.17 mg/kg), fenugreek (0.235 mg/kg), sugar cane (0.035 mg/kg), tamarind (0.147 mg/kg) and sorghum (0.356 mg/kg) which exceed regulatory limits (Mawari et al., 2022a, 2022b). Moreover, In China, the highest value of Hg in fruit samples was found in apple (0.0122 mg/kg), followed by banana (0.0103 mg/kg), peach (0.00882 mg/kg) and cherry (0.00821 mg/kg) (Zhang et al., 2021). Furthermore, a study conducted in several municipalities of the Pacific region in Colombia found Hg concentrations exceeding regulatory limits in some fruits. In Bojayá, concentrations were found in banana of 1.55 ± 0.5 mg/kg, lemon of 1.18 ± 0.3 mg/kg, and lulo of 2.65 ± 0.3 mg/kg. In Vigía del Fuerte, concentrations were found in lemon of 1.68 ± 0.4 mg/kg and in lulo of 1.87 ± 0.2 mg/kg. Meanwhile, in Murindó, concentrations in banana were 7.33 ± 1.3 mg/kg and in borojó 2.04 ± 0.8 mg/kg (Caicedo-Rivas et al., 2022). These levels raise concerns about the presence of Hg in fruits from these tropical regions. Considering the above, it is essential that the country adopt and implement strategies and regulations that include the monitoring of Hg in fruits and vegetables to reduce the exposure to this pollutant in the country. Furthermore, identifying the sources of this metal in the region should be an important issue to guarantee the innocuity of the foods distributed in the region and to protect the health of the population.

Table 1
Results of metals in fruits (mg/kg).

	Hass Avocado		Purple Passion Fruit		Cape gooseberry	
Metal	Mean (Median)	min - max (Percentile 95th)	Mean (Median)	min - max (Percentile 95th)	Mean (Median)	min - max (Percentile 95th)
Hg	0.0386 (<0.00450)	< 0.00450–0.367 (0.342)	0.00664 (<0.00450)	< 0.00450–27.0 (0.026)	0.00601 (<0.00450)	< 0.00450–0.0150 (0.0137)
Cd	< 0.015 (<0.015)	< 0.015-< 0.015 (<0.015)	< 0.015 (<0.015)	< 0.015 - < 0.015 (<0.015)	< 0.015 (<0.015)	< 0.015-< 0.015 (<0.015)
Pb	0.149 (<0.138)	< 0.138–372 (0.365)	0.194 (<0.138)	< 0.138–612–0.486	0.120 (<0.138)	< 0.138–0.499–0.356
As	< 0.044 (<0.044)	< 0.0440–154 (0.148)	0.0417 (<0.044)	< 0.0440–154 (0.147)	44.8 (<0.044)	< 0.0440–0.179 (0.159)
Cr	< 0.136 (<0.136)	< 0.136- < 0.136 (<0.136)	< 0.136 (<0.136)	< 0.136 - < 0.136 (<0.136)	< 0.136 (<0.136)	< 0.136- < 0.136 (<0.136)

min: minimum concentration, **max:** maximum concentration.

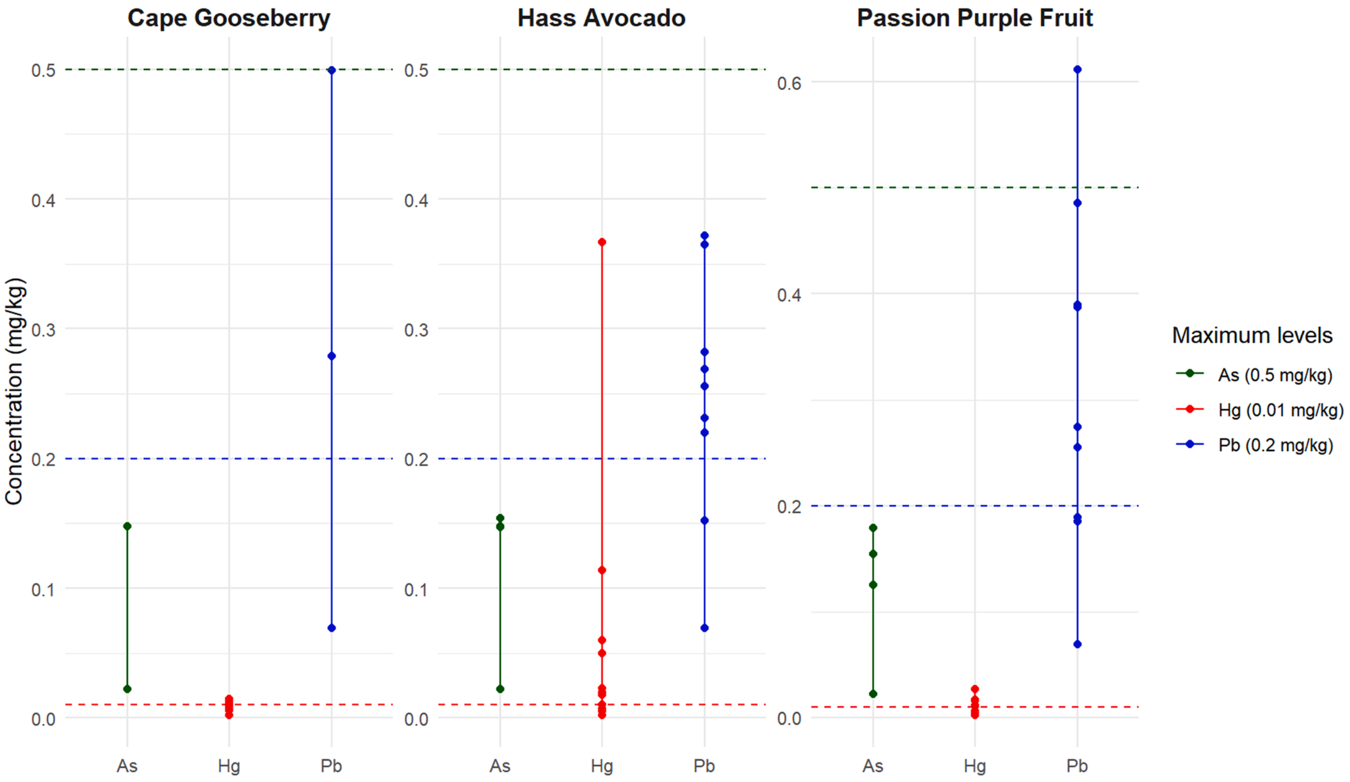

Fig. 1. Metal concentrations in fruits.

Regarding Pb, higher levels were found in purple passion fruit with the highest value of 0.612 ± 0.129 mg/kg. 33.3 % (7/21) of samples had levels above maximum limit (0.200 mg/kg). The highest level in Hass avocado was 0.372 ± 0.0745 mg/kg with a 33.3 % (7/21) of the sample's levels above the maximum limit. Finally, 14.3 % (2/14) of cape gooseberry samples had levels about regulation limit. The highest value was 0.499 ± 0.0998 mg/kg (Fig. 1).

These results were consistent with other studies that have reported concentrations above the regulatory limit to Pb. For instance, in India, maximum concentrations of up to 0.170 mg/kg were found in fruits (Mawari et al., 2022c). In China maximum values of Pb were found in sugar cane with a value of 1.74 mg/kg. Furthermore, in Nigeria it was revealed that avocados can contain high levels of heavy metals. The study found that the levels of Cd, Cu, Fe, Pb, Ni, Mn and Co in avocados ranged from 0.08 mg/kg to 0.22 mg/kg, 0.23 mg/kg to 5.29 mg/kg, 19.0 mg/kg to 29.6 mg/kg, 1.69 mg/kg to 5.80 mg/kg, 1.16 mg/kg to 5.87 mg/kg, 1.03 mg/kg to 12.6 mg/kg, and 1.43 mg/kg to 3.56 mg/kg, respectively (Ihesinachi & Eresiya, 2014). Similarly in Colombia, a study of vegetables in Sibaté found Pb concentrations of up to 7.07 mg/kg (Lizarazo et al., 2020). Moreover, a study conducted in the Pacific region in Colombia found Pb concentrations exceeding regulatory limits in some fruits, with levels reaching 7.07 ± 1.3 mg/kg in lulo (Caicedo-Rivas et al., 2022).These finding highlight the importance of periodic monitoring of Pb in these matrices. In contrast with Hg in fruits, Pb is included in the National Regulation (4506/2013), therefore, national control is expected. Hg and Pb are highly toxic heavy metals that, when accumulated in the body, can have serious health effects. Pb damages the brain and nervous system, causing developmental problems in children, learning difficulties and behavioral disorders. In adults, it can increase blood pressure and the risk of heart disease, as well as causing chronic kidney damage, anemia and a weakened immune system (Tepanosyan et al., 2017). On the other hand, Hg affects the central and peripheral nervous system, causing neurological problems such as tremors, loss of coordination, personality changes and memory difficulties (Zeng et al., 2015). It also damages the kidneys, and, in pregnant women, it can affect the development of the nervous system of the fetus, causing cognitive and motor delays (Caicedo-Rivas et al., 2023). Both metals, being bioaccumulative, pose a significant long-term risk, even at low levels of exposure, highlighting the importance of their regulation and elimination in the environment of the Antioquia region and country.

As was detected in samples from sampling 4. All samples were below the maximum level of 0.500 mg/kg. The highest concentration was 0.174 mg/kg ± 0.0358 in cape gooseberry (Fig. 1). These results will be compared with other studies where concentrations also were below regulatory limits have been found. For instance, in India concentrations ranged between 0.00700 mg/kg and 0.0200 mg/kg for As (Mawari et al., 2022c). Similary, in Sibaté, Colombia, As concentrations in vegetables were measured up to 2.36 mg/kg (Lizarazo et al., 2020). A study conducted in various municipalities of the Pacific region in Colombia found As concentrations exceeding regulatory limits in certain fruits. The highest levels were recorded in lemon at 50.06 ± 9.3 mg/kg, followed by corn at 26.43 ± 5.3 mg/kg, plantain at 18.11 ± 4.0 mg/kg, and lulo at 16.66 ± 7.9 mg/kg (Caicedo-Rivas et al., 2022).

Finally, Cd and Cr levels in all samples were below the MQL, with thresholds of 0.136 mg/kg for Cr and 0.0151 mg/kg for Cd. Our findings for these two metals are lower than those reported in other studies. For instance, in Colombia, Cd levels were found at 50.92 ± 10.3 mg/kg in achin, 0.00822 ± 0.0023 mg/kg in lulo, and 35.79 ± 12.3 mg/kg in yuca (Caicedo-Rivas et al., 2022). This absence in fruits could be due to the mobility of these metals, which may limit their accumulation in edible parts (Devi & Bhattacharyya, 2018). Furthermore, Cd can be absorbed by plants in acid soils. When pH is low, Cd is found in more soluble forms, increasing its bioavailability and, therefore, its uptake by plant roots. However, this absorption depends on several factors, such as soil pH, organic matter, cation exchange capacity, and the presence of other competing ions (Vavrincová et al., 2024). Regarding Cr, its bioavailability is more complex, since it depends on its oxidation state. Cr (III) is much less bioavailable than Cr (VI). Cr (VI) is very soluble and can be absorbed more easily by plants, but it is less common in natural soils and tends to be reduced to Cr(III), especially in soils with a high organic matter content (Lin et al., 2024). Therefore, the environmental conditions of La Union, Antioquia did not favor the transfer from soil of these metals to plants. Moreover, plants have specific transport mechanisms for essential nutrients, which sometimes also allow the entry of heavy metals due to their ionic similarities. In the case of Cd, there are transporter proteins that facilitate its entry into the roots through divalent cation channels (zinc and calcium channels). Cr, especially in its Cr (VI) form, can be absorbed through sulfate transporters due to its structural similarity to the sulfate ion (SO_4^{2-})(Palsania et al., 2022). Furthermore, some plants, called hyperaccumulators, have the ability to uptake and accumulate large amounts of heavy metals without suffering serious toxic effects. These plants are selective for certain metals and are used in phytoremediation (cleaning of contaminated soils)(Rascio & Navari-Izzo, 2011). Other plants do not accumulate heavy metals as easily and uptake can be restricted by exclusion mechanisms that prevent the metals from entering the roots or store them in less sensitive tissues (Muszynska & Hanus-Fajerska, 2015). In summary, the selectivity of plants to uptake heavy metals depends largely on their essential nutrient transport mechanisms, soil conditions, and the plant species in question. The results of this study suggest that the evaluated plants are not hyperaccumulator plants and have mechanisms to exclude the uptake of Cd and Cr; furthermore, the environmental conditions could have an important role in the bioavailability of these metals. This is discussed in more detail in the metal transfer section below.

The highest detection frequency of Hg was in the Hass avocado; furthermore, the higher values were even one magnitude order higher with respect to the other two fruits of the study. This indicated that Hass avocado has the capacity to accumulate this metal more than As and Pb. This could be explained because Hg tends to accumulate more in fatty tissues than As and Pb, mainly due to the way mercury is converted to methylmercury (CH_3Hg^+) in the environment (Dey et al., 2024). This compound is highly lipophilic, meaning it has an affinity for fatty tissues and can cross cell membranes, accumulating in lipid-rich tissues such as Hass avocado (Haedrich et al., 2020). However, the levels of As and Pb suggest that the source of contamination between crops could be the same because the percentage of samples detected, and the levels found were similar and in the same magnitude order. Furthermore, no significant differences were found between farms, fruits, and levels of these metals ($p > 0.05$). Indeed, the higher levels of As were in sampling 4 and Pb in sampling 4 and 6, which were in the dry season in the Antioquia Region. Colombia is a tropical country; therefore, during a year there are two wet seasons and two dry seasons, each of three months (Cerón et al., 2022). Higher levels of Pb and As in the dry season could be explained because rainfall can increase leaching of metals from soils and mining areas and dissolve them in water. These occur because acidic rainwater can react with certain minerals and release metal ions into the aquatic environment. Furthermore, in the dry season, the reduction in water volume can also have a concentration effect on water reservoirs, increasing the total concentration of metals per unit volume. In summary, the wet season is a released season, and the dry season is a concentration season, therefore higher levels of Pb and As were found in the dry season.

It is worth noting that a fruit that exceeds the maximum level cannot be distributed, commercialized, and consumed because it represents a risk to the population considering national and international regulations. Therefore, it is important to identify possible sources of contamination to mitigate and reduce the risk to the population. Furthermore, exportation of tropical fruits from Colombia to other parts of the world plays an essential role in the economy of the country (Cubillos et al., 2021). It is well known that the residuality of pollutants is a key factor in the quality and competitiveness of these products on international markets. Therefore, guaranteed innocuity must be a priority for producers and stakeholders included in the value chain of these products.

In that sense, it is relevant to point out that the analyzed portion of the fruits was the edible part. The peel, bone and husk of the fruits were analyzed separately to evaluate whether the contamination of the fruits could be by migration through contact with air, dust, rain and irrigation or transfer from soil and water to plants by uptake of roots. Furthermore, a general recommendation to reduce metal exposures by consumption in fruits is to wash the fruits (Afonne & Ifediba, 2020; Mostafidi et al., 2020) to remove residues from the peel. However, the metals were not detected in these non-edible parts of the fruits, suggesting that the contamination of the fruits could be occurring by uptake by root from soils or water.

Finally, a significant test using the Kruskal-Wallis indicated not significant differences between the various types of fruits studied regarding the quantity of metals present ($p < 0.05$). Cd and Cr were not considered in the test as their concentration was below the detection limit in all samplings. Furthermore, a significant correlation was found between the concentrations of Pb and As (0.548 ***) using the Spearman test. This correlation is particularly notable in the purple passion fruit and cape gooseberry, with correlation coefficients of (0.697 **) and (0.628 **), respectively. This suggests that the distribution of these two metals in these fruits could have a common origin as was explained above (Li et al., 2023; Zhang et al., 2021).

2.14. *Metals in soils*

Concentrations of all the metals of the study were found in the soil samples. Table 2 displays the maximum and minimum values found, as well as the median and mean concentrations of metals found in the analyzed soil. Individual results of all analyzed samples with their associate uncertainty are shown in Table S3.

Fig. 2 shows the concentrations of each metal in the soil, along with the maximum limits. The graph visualizes the concentrations of different metals and compares these values to the established regulatory limits. The concentrations of metals detected in the analyzed soils revealed that Hg and Cd were the only metals exceeding the maximum limits. For Hg, concentrations ranged from 0.614 ± 0.114 mg/kg to 11.30 ± 2.11 mg/kg, both of which surpass the established limit of 0.45 mg/kg. Cd concentrations varied from 2.21 ± 0.443 mg/kg to 145 ± 29.0 mg/kg, exceeding the maximum limit of 1.0 mg/kg. Although, at lower concentrations, heavy metals play an important role in plant growth and

Table 2
Concentrations of metals in soils (mg/kg).

	Soil of the Hass Avocado farm		Soil of the Purple Passion Fruit farm		Soil of the Cape gooseberry farm	
Metal	**Mean (Median)**	**min - max (Percentile 95th)**	**Mean (Median)**	**min - max (Percentile 95th)**	**Mean (Median)**	**min - max (Percentile 95th)**
Hg	4.44 (3.46)	1.15–11.3 (8.82)	5.30 (6.15)	0.91–9.4 (9.12)	2.46 (2.60)	0.61–4.25 (4.09)
Cd	22.1 (4.91)	<0.015–98.1 (84.4)	25.27 (7.16)	<0.015–145 (103.6)	1.07 (0.100)	<0.015–3.17 (3.03)
Pb	24.8 (25.5)	<0.150–48.9 (47.5)	33.9 (35.4)	<0.15–97.2 (67.5)	12.9 (10.5)	<0.15–35.0 (31.5)
As	0.520 (0.270)	0.13–2.45 (1.55)	0.42 (0.280)	0.12–0.89 (0.890)	0.170 (0.140)	0.0800–0.360 (0.308)
Cr	17.51 (17.00)	1.34–34.8 (33.0)	15.6 (16.7)	1.26–33.6 (31.1)	16.41 (16.2)	0.450– 31.0 (30.3)

min: minimum concentration, **max:** maximum concentration

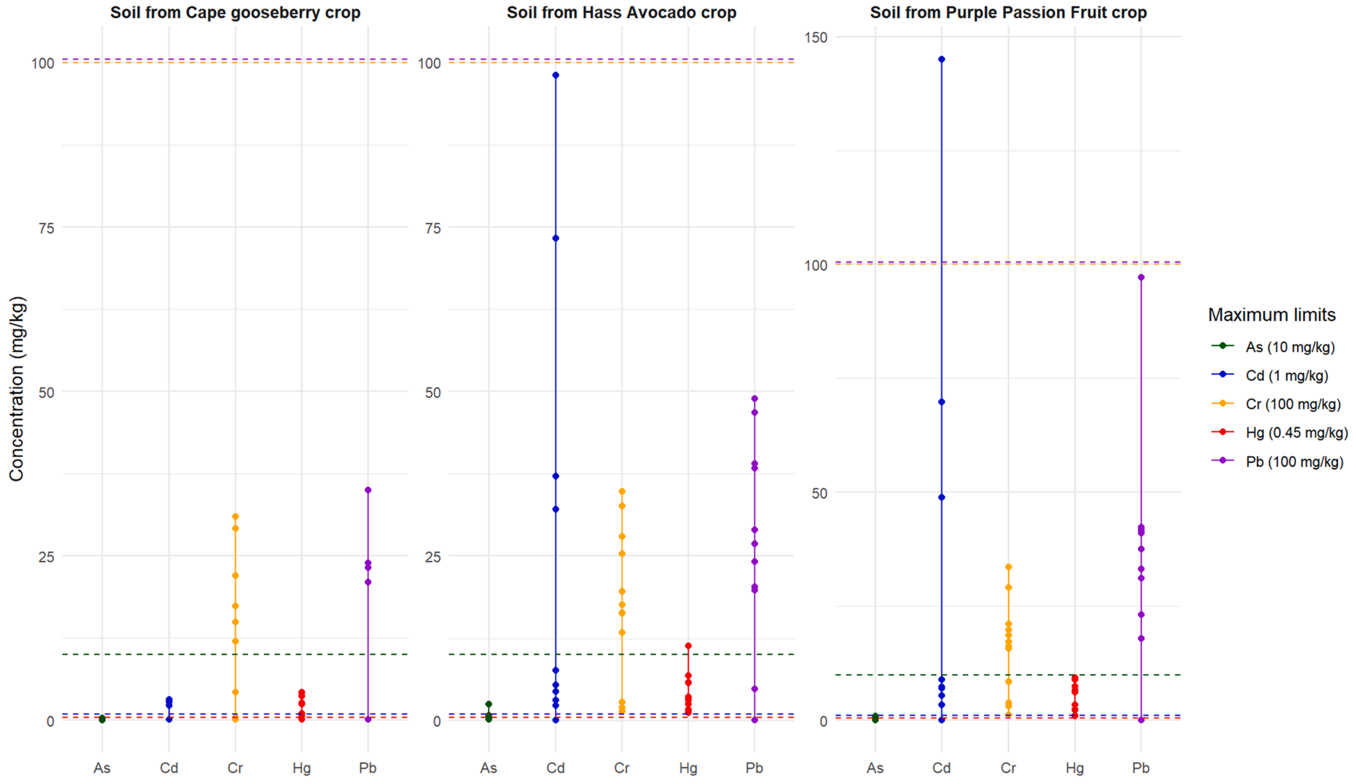

Fig. 2. Metal concentrations in soil.

development as essential nutrients, at higher concentrations they cause various adverse effects (Alengebawy et al., 2021). One of the possible causes associated with the presence of these metals is chemical fertilizers, which are a major source of heavy metal contamination in agroecosystems (Andrea et al., 2019). In agriculture, the excessive use of chemical fertilizers increases the residues of these metal ions in the soil. Once these metal ions accumulate in the soil, microbes and other agents cannot easily degrade them, unlike organic products. This contributes to the persistence and accumulation of heavy metals in the environment, increasing the risk of toxicity to plants and consequently to human health through the food chain (Rashid et al., 2023).

In contrast, As, Cr, Pb were within the maximum limits. As concentrations ranged from 0.077 ± 0.015 mg/kg to 0.893 ± 0.178 mg/kg, all below the maximum limit of 10 mg/kg. Pb concentrations reached a maximum of 48.9 ± 9.79 mg/kg, well below the limit of 100 mg/kg. Cr concentrations ranged from 1.34 ± 0.241 mg/kg to 34.8 ± 6.61 mg/kg, all within the maximum limit of 100 mg/kg.

The results obtained in our study provide a comprehensive perspective of heavy metal concentrations in agricultural soils from La unión Antioquia, contrasting with previous research that has analyzed only some of these metals. Our findings are consistent with and, in some cases, exceed the levels reported in studies in other contexts. For instance, in Beijing, concentrations of Pb were found to be 18.48 mg/kg, Cd 0.18 mg/kg, and Cr 75.74 mg/kg (Liu et al., 2005). In India, Cr levels were 2.19 mg/kg and Pb 0.95 mg/kg (Raju et al., 2013). In Yangzhou, Cr concentrations reached 77.20 mg/kg, Pb 35.70 mg/kg, Cd 0.30 mg/kg, Hg 0.20 mg/kg, and As 10.20 mg/kg (Huang et al., 2007). Chengdu reported Cr at 59.50 mg/kg, Pb 77.27 at mg/kg, Hg at 0.36 mg/kg, and As at 11.27 mg/kg (Su, 2014). Lastly, in Spain, concentrations of Cr were observed at 63.48 mg/kg, Pb at 213.93 mg/kg, and Cd at 1.42 mg/kg (Zimakowska-Gnoińska et al., 2000).

Figure S2 shows the boxplot and the Kruskal-Walli's test results, which reveals significant differences in the concentrations of Hg and Cr between the different sampling, with p-values below 0.05 (0.0077 and 2.3×10^{-5} respectively). These findings indicate that the concentrations of these metals in the soil varied significantly between sampling periods, suggesting that climatic conditions such as pH or humidity could influence the presence of these two metals, depending on the time of year (Kicińska et al., 2022). Furthermore, these results suggest common sources of these metals as well as the results explained in fruits. Indeed, the behavior of Hg and Cr during the sampling time was very similar. The significant differences were with the same sampling time (3) and the distribution and trends of the levels were similar (Fig. S2A and S2E). Although the Cd and As levels did not have significant differences in levels during the sampling time, the same pattern is evident between the sampling. In sampling 1 and 3 there was less dispersion of the results in comparison with the samplings 5 and 7. These findings suggest that the origin of these couple of metals is common. The source could be associated with natural minerals in the region or anthropogenic activities such as mining, landfills, and industrial processes in the region. This issue should be evaluated in future research to identify the source to reduce released to the environment, reducing the adverse effects of these pollutants on the biota.

The Spearman correlation analysis revealed relationships between metals. Strong correlations were identified between Hg and Cr (0.667 ***) and between As and Hg (0.509 **). It is important to note that these correlations are observed globally across the four sampling periods, as no significant correlations were detected for these metals individually. In contrast, specific correlations were found in certain samples, such as between Pb and As in sampling periods five and seven (0.837) and between Cd and As (0.736). These correlations may be attributed to environmental conditions that facilitate the accumulation of these metals or the application of certain fertilizers during specific periods that may contain one of these metals (Zhang et al., 2021).

These results support the hypothesis that the common origin of these metals in the study soil is common and highlight the importance of identifying sources to reduce exposure to these pollutants. Moreover, knowledge of sources could be useful in minimizing negative effects in the environment and reducing the amount of releases when possible. Furthermore, soil remediation strategies could be implemented considering that Hg and Cd levels represent a risk, and these soils should not be used in agricultural uses in the region. However, this situation was unknown in the region until the date of this study. Therefore, these results could be a scientific tool to start solving this problem in the region.

2.15. *Metal transfer factor from soil to plant*

In Table S4, the average transfer factor was determined by calculating the ratio between the average concentration of each metal in the fruits and the average concentration of the same metal in the soils. The metal transfer factor (MTF) from soil to vegetables in the study area is considered a crucial parameter for assessing human exposure to heavy metals through food ingestion. The MTF represents the bioavailability of metals in a particular soil substrate for a specific plant species (Rehman et al., 2018).

In this study, it was observed that the concentration ratio of all metals is less than one (Rehman et al., 2018). Plants with MTF values greater than one is considered hyperaccumulators. Therefore, it cannot be inferred that the analyzed plants are hyperaccumulators. Additionally, heavy metals accumulate in plant species with varying intensities, suggesting that the accumulation capacity can differ significantly among species and under different environmental conditions. These findings highlight the need to consider multiple factors when evaluating the capacity for heavy metal accumulation in plants, including plant species, the type of metal, and specific environmental conditions (Mirecki et al., 2015). These findings suggest that the source of contamination of the fruits is not the soil.

In Figure S3 a correlation between Hg concentrations in soils and fruits was observed. Although the correlation is weak, with a value of −0.419 * , it is statistically significant. When the concentration of Hg in soil increases, the concentration in fruits decreases. However, the relationship is not very strong, which suggests that other factors might also be influencing the Hg concentration in the fruit as was explained before. This could prove that the metal is not coming directly from the soil to the plant, but that there is another source that could be influencing it (Rehman et al., 2018). In this study, additional factors were investigated to identify a possible source. In that sense, the irrigation water (groundwater) of the crops were analyzed. Concentrations of Hg and Pb were found in the irrigation water, with the following average values: for Hg, 1.15 ± 0.13 μg/L in Hass avocado farms; 1.01 ± 0.11 μg/L in purple passion fruit farms, and 1.04 ± 0.11 μg/L in cape gooseberry farms. For Pb, concentrations of 13.0 ± 1.1 μg/L were detected in Hass avocado farms, 6.10 ± 0.54 μg/L in purple passion fruit farms, and 3.10 ± 0.27 μg/L in cape gooseberry farms. The samples were analyzed using a previously validated method at the GDCON laboratory. These data suggest that soil and fruit contamination might be related to the presence of trace metals in the irrigation water, which accumulate in these matrices. These findings could also explain why Cd and Cr were detected in the soil but were not present in the fruits. Indeed, metals are more bioavailable in water because they are present in ionic forms, which are more soluble and can be up taken by plants. Furthermore, metals in soil could not be bioavailable due to adsorption phenomena, precipitation, or chelate forms. In addition, they need to compete with the active site in root plants, which includes other essential cations such as Ca^{2+} and Mg^{2+}. In that sense, Pb and Hg can be uptake mainly from water reservoir instead of Cd and Cr, which cannot be uptake from soil. This highlights the importance of continuous monitoring, as it can help identify additional sources of contamination, facilitating better regulation of these metals in the region.

2.16. *Estimated daily intake of heavy metals and assessment of carcinogenic and non-carcinogenic risks*

In Table 3, the results of carcinogenic and non-carcinogenic risks associated with the metals studied in each of the evaluated fruits are shown. The Cr and Cd indices are not presented, since in all the fruits they were below the MQL. A non-carcinogenic risk associated with the consumption of Hass avocado was identified to Pb and Hg, as the HQ values for both exceed the threshold of 1.0 (IRIS, 1987). The mean HQ were 1.20 and 1.07 at the 95th percentile to Pb and Hg, respectively. Likewise, a HQ mean of 1.28 to Pb in purple passion fruit was estimated. These results indicated the importance of considering the quantities of these fruits consumed and potentially setting limits to reduce health risks. For cape gooseberry, the indices were calculated only with Hg since the other metals were below the MQL, and the HQ value for this metal was below the threshold (0.17). Secondly, it is important to mention that no associated ILCR was identified in any of the fruits evaluated. This is because the permissible limits for risk to be considered acceptable are in the range of 10^{-6} and $< 10^{-4}$ (IRIS, 1987), for single-element carcinogens and multi-element carcinogens. In the specific case of Hg, as this is not considered a carcinogenic element, the OSF value, or oral slope factor $(mg/kg \times day)^{-1}$, was not calculated (Kortei et al., 2020). Other research has concluded that these metals, when consumed in excess, can pose serious health risks, including an increased risk of cancer. Similarly, a study that investigated the presence of Pb in vegetables found a carcinogenic risk associated with its consumption (Kumar et al., 2013; Kumar & Denre, 2017).

2.17. *Monte Carlo Simulation (MCS)*

Figures S4 show the application of the Monte Carlo simulation for Hg, carried out with the parameters specified in the methodology section. Additionally, when observing Figure S4A, it is evident that Hg presents a non-carcinogenic risk from the 85 % quartile, since from this point onwards the total danger index exceeds one, which indicates that in 15 % of cases a non-carcinogenic risk may be presented from the consumption of avocado, based on the samples analyzed and with the parameters used in the simulation (Woldetsadik et al., 2017). Regarding Figures S4B and S4C, both represent a non-carcinogenic risk from the 97.5 % quartile, which is in accordance with the HQ calculated specifically, indicating that a non-carcinogenic risk only occurs in the case of avocado.

In Figures S5, the Monte Carlo simulation for Pb is shown. In both figures, it is observed that the Pb HQ exceeds the threshold in 20 % of the population. This finding suggests that approximately 20 % of the population could be affected when consuming the evaluated fruits under

Table 3
Estimated daily intake of heavy metals and assessment of carcinogenic and non-carcinogenic risks in the 95th percentile. The values correspond to the mean of the HQ estimated.

	Hass avocado			Purple Passion Fruit			Cape gooseberry	
Metal	EDI	HQ	LCRs	EDI	HQ	LCRs	EDI	HQ
Hg	1.07×10^{-4}	1.07		2.10×10^{-5}	0.21		1.74×10^{-5}	0.174
Pb	5.99×10^{-4}	1.20	5.09×10^{-6}	6.40×10^{-4}	1.28	5.44E−06		
As	4.29×10^{-5}	0.14	6.43×10^{-5}	5.97×10^{-5}	0.20	8.95×10^{-5}		

EDI: Estimated daily intake, **HQ:** non-carcinogenic risk considering the hazard quotient, I**LCRs:** expressed as the increased lifetime cancer risks

the simulation conditions described. In southern Poland non-carcinogenic risk in fruits was assessed, with HQ values found below the 1.0 in all analyzed fruit varieties (Gruszecka-Kosowska, 2019). In contrast, there are no recorded studies assessing metal risk in fruits in Colombia. Comparing our findings with those from Poland, there appears to be a higher concentration of metals in the analyzed fruits in the region where this study was conducted. Figure S6 shows the carcinogenic risk associated with Pb using the Monte Carlos simulation. The graph was created using the base ten logarithm function to better scale it. The red line represents the threshold value. The results align with the specific analysis, which indicated no carcinogenic significance associated with Pb in any of the analyzed fruits, as their values are below the threshold (10^{-6} and $<10^{-4}$)(IRIS, 1987).

Data from studies conducted on apples indicated that there is no carcinogenic risk of Pb in adults. However, it is important to note that these studies also assessed exposure in children (Gruszecka-Kosowska, 2019). Since children tend to consume a greater quantity of fruits, particularly apples, the potential risk could increase for this demographic group. Pb is a neurotoxin that can affect almost every organ or system in the human body, including bones, teeth, kidneys, and the reproductive system. It can also cause neurological and gastro-intestinal distress and oncogenic effects (Tajik et al., 2021). It is crucial to consider this factor when interpreting the findings and formulating public health policies to ensure food safety for all age groups.

The results of the risk assessment indicated that consumption of Hass avocado and purple passion fruit could represent a risk to the region population considering the levels of Hg and Pb in these fruits. These findings are congruent with those exposed in the section of metals in fruits, in which there was evidence of high levels of Hg and Pb in these matrices. In fact, around 20–30 % of the fruits analyzed exceeded the maximum limits of the national and international regulations. However, it should be noted that the risk was calculated considering the worse scenario for the population, such as high-rate intakes for a long term of exposure and high frequency of intake. In that sense, the findings of this study are a warning that exposes the risk associated with these pollutants in the region and encourages further research on this issue in the region and country. Furthermore, the results could help establish and improve national policies on metals in fruits and soils. Finally, it is highly recommended for the population to have a varied diet to reduce exposure to these pollutants.

3. Conclusions

For the first time in Antioquia, Colombia, heavy metals were monitored and quantified in cape gooseberry (*Physalis peruviana*), purple passion fruit (*Passiflora pinnatistipula*), and Hass avocado (*Persea americana L. Hass*), as well as in the soils used for their cultivation. Fruits had concentrations of Hg and Pb above maximum levels, and soils had higher levels of Hg and Cd. Strong relationships have been found between As and Pb in fruits and between Hg, Cd, and As in soils, indicating common sources of contamination. However, the results suggest that the plants are not hyperaccumulators. Furthermore, a non-carcinogenic risk (HQ>1) of Pb and Hg by consumption of Hass avocado was estimated. Likewise, the was non-carcinogenic risk by consumption of Pb in purple passion fruit. The above highlight potential health concerns that warrant attention. This study serves as a basis for the analysis of these metals in these matrices, seeking greater regulation of them and considering the risks to health. In that sense, the country should adopt strategies to monitor and reduce Hg and Pb exposure in fruits and vegetables, identifying sources to ensure food safety and protect public health. Finally, the study found Hass avocado accumulates Hg more than other metals due to lipophilic nature, emphasizing the need for soil remediation to mitigate risks and prevent agricultural use of contaminated lands.

CRediT authorship contribution statement

Gustavo A. Peñuela: Supervision, Resources, Conceptualization. **Sara E. Gallego Ríos:** Writing – review & editing, Supervision, Formal analysis, Conceptualization. **Boris Santiago Avila:** Resources, Investigation, Conceptualization. **Jovan Mateus Castañeda Vargas:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foohum.2025.100503.

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