Mercury presence in cassava farms*, Manihot esculenta* Crantz, near artisanal gold mining areas in Southern Amazonia

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ABSTRACT

Cassava, **Manihot esculenta** Crantz (Euphorbiaceae), a plant native to Brazil, is one of the main sources of carbohydrate in the Brazilian diet. In gold-producing regions such as the southern Amazon, the close proximity of crops to artisanal and small-scale gold mining (ASGM) is inevitable, resulting in the risk of mercury (Hg) contamination. Due to the importance of cassava in the diet of the world's population, this study aimed to evaluate the effect of proximity of ASGM on Hg concentration in soil and cassava samples, and to assess the risk of human exposure to Hg through consumption of this food. Samples were collected from two areas along the BR-163 highway in Mato Grosso, Brazil. 42 samples of cassava (roots, stems and leaves) and soil were collected. Effects of ASGM on soil Hg concentration was not observed. The highest concentrations of Hg in leaves were observed in the area close to ASGM, indicating greater atmospheric deposition. The higher bioconcentration factor near the mining area also indicates the effect of atmospheric Hg on root concentration. Estimates of daily intake and health risk quotient were made for cassava and cassava flour, with the highest values observed in the vicinity of ASGM. However, all were below the established limits, indicating that currently, the consumption of these foods by the population is safe. The cassava crop can be used as a bioindicator of Hg emissions caused by ASGM.

KEYWORDS: Mining. Risk quotient. Bioindicator.

1 INTRODUCTION

Cassava farming is the fourth most important food production process for the world's population. A native plant of Brazil, cassava, Manihot esculenta Crantz (Euphorbiaceae) is one of the main sources of carbohydrate in the Brazilian diet (BRASIL, 2008). Due to its high nutritional potential, it has been widely distributed over different parts of the world, and is considered one of the main sources of carbohydrate in the diet of low-income earners, being consumed by more than 800 million people (FILGUEIRAS; HOMMA, 2016).

In northern Brazil, cassava is of great economic, social and cultural importance. Cassava flour is an essential food product in the Amazon. The people of this region consume the most cassava flour, with an average consumption rate of 38 g day^{-1} person^{-1}, compared to the national average of 8.0 g day^{-1} person^{-1} (IBGE, 2019). The northern region is the largest producer of cassava in Brazil, with an average annual production of 7 million tons. Cassava leaves are also consumed and used in the manufacture of animal feed and as an industrial raw material. The ground leaf is called maniva and is the main ingredient in a regional dish known as maniçoba, a dish in which maniva replaces beans (EMBRAPA, 2021).

Small producers are responsible for about 80% of cassava production in Brazil (IBGE, 2019), which is commonly cultivated throughout the country, including in areas close to gold mining. Artisanal Small-Scale Gold Mining (ASGM) is one of the main sources of anthropogenic Hg emissions (AZEVEDO et. al., 2003; UNEP, 2019). In this gold mining process, Hg is used to extract smaller gold particles through amalgamation. The formed amalgam is then burned, and the metallic mercury, Hg^0, is vaporized and emitted into the atmosphere, leaving only gold (TORKAMAN et. al., 2021). Artisanal gold mining occurs primarily in developing countries in South America, Asia and Africa, where Hg is used illegally and without the necessary protections for worker's health and the environment (BANK, 2020; UNEP, 2019).

Due to the contamination of soil, water and air that can be caused by ASGM, it is essential to verify if foods that are grown close to these mining areas, such as cassava, have Hg levels that cause human health problems from exposure to the metal, as studies have linked Hg concentration in foods to proximity of ASGM areas (e.g. EGLER et. al., 2006; CHENG et. al., 2013;

BOSE-O'REILLY et. al., 2016; GHASEMIDEHKORDI et. al., 2018).

Considering the importance of cassava in the regional and world diet, the large number of artisanal gold mines in the southern Amazon, and aiming to better understand the risk to the environment and human health from exposure to Hg, this study determined total Hg (THg) concentration in cassava cultivation areas, analyzing the relationship between Hg concentration with proximity of gold mining areas. The ability of cassava to absorb Hg present within the environment was evaluated using the translocation, bioaccumulation and bioconcentration factors, and, consequently, the plant's ability to bioindicate environmental contamination from the metal from ASGM in this region was shown. At the same time, an assessment of the risk to human health from exposure to Hg was carried out through the consumption of cassava and cassava flour, estimating the daily intake of the metal and the health risk quotient for the consumption of these foods by the population.

2 METHODOLOGY

2.1 Study area

The study was conducted within an area of the southern Amazon in the northern region of Mato Grosso. Samples of cassava crops and soil were obtained from existing plantations on properties that practice family farming along the BR-163 highway, covering the cities of Matupá, Peixoto de Azevedo and Terra Nova do Norte (Figure 1).

In 2019 Mato Grosso produced more than 14 tons of gold (BRASIL, 2020). The study area is part of the Mineral Province of Northern Mato Grosso, which is responsible for approximately 60% of the state's total gold production, and is divided into four districts in terms of gold mining: Peixoto do Azevedo, Teles Pires, Cabeça and Aripuanã, totaling an area of 873,125 hectares (BRASIL, 2002).

Area I comprises the cities of Matupá and Peixoto de Azevedo in the extreme north of Mato Grosso, close to the border shared with the State of Pará, with an estimated population of 17,017 and 35,695 inhabitants, respectively. Mining has long been established in the region, occurring since 1979, and it has one of the largest mining cooperatives in the country, Cooperativa de Garimpeiros do Vale do Rio Peixoto (COOGAVEPE), with over 5,000 members (IBGE, 2021). All collection points were located close to ASGM.

Area II is located in the greater Terra Nova Norte city area, with an estimated 9,284 inhabitants (IBGE, 2021). Area II has no mining activity in the vicinity, although Terra Nova do Norte has a history of gold mining at the beginning of the region's colonization around the 1980s (LOVATO, 2017). Currently there are no new mining sites in the area.

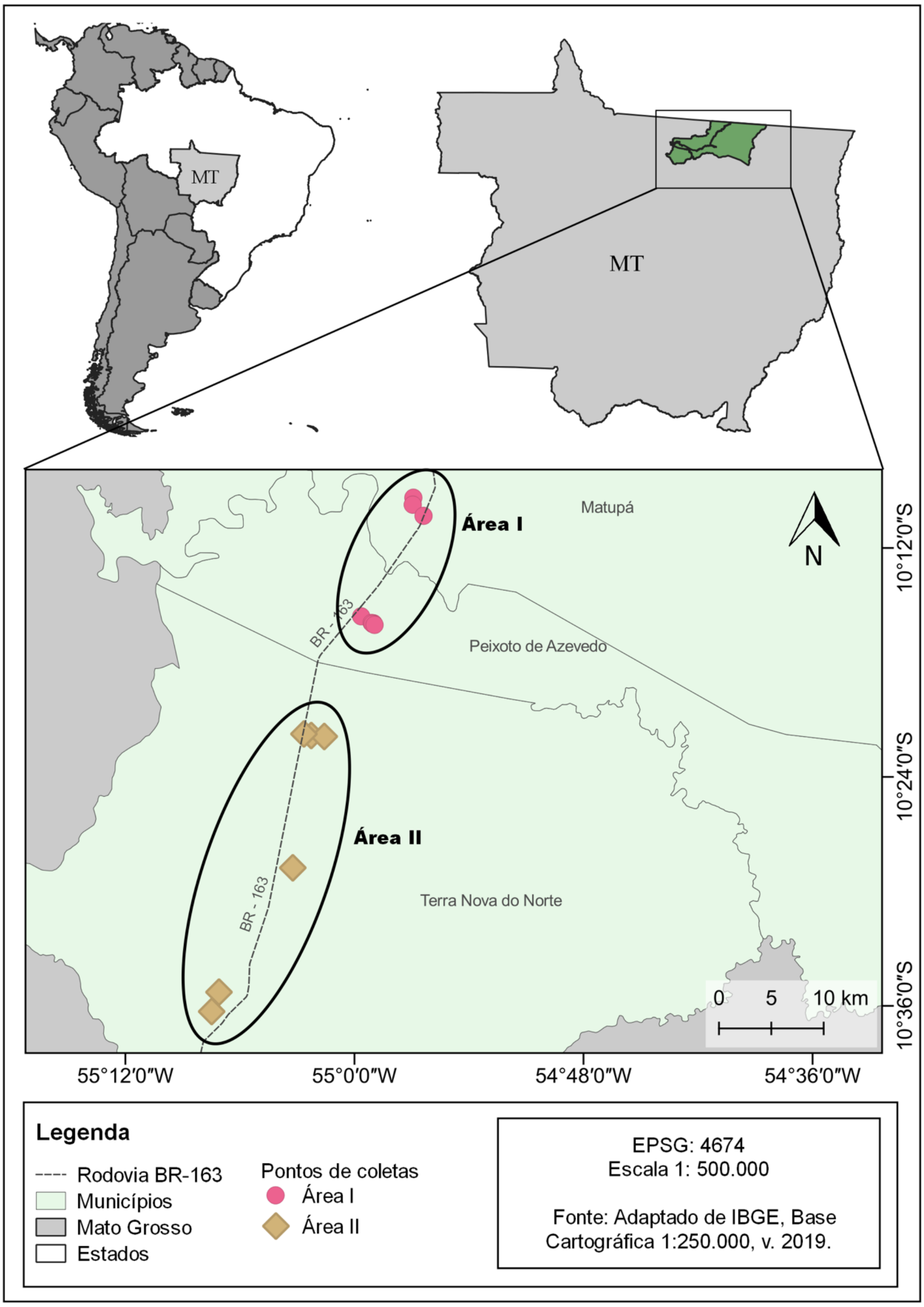

Figure 1 - Geographic location of cassava sample areas in the north of the state of Mato Grosso, south of the Amazon
Drawing: Own authorship.

2.2 Sample collection

Whole cassava plants were collected in September and October 2020. Altogether, 14 small properties were visited, comprising family farming kitchen gardens with areas smaller than 50 m x 50 m of cassava cultivation, intended mainly for subsistence and the sale of surplus. Three plants from each property were sampled, with eight properties in Area I and six properties in Area II, totaling 42 whole plants collected. All plants were in the mature phase and ready for harvest, consumption or commercialization, with an average cultivation time of eleven months. Samples were stored individually in plastic ziploc bags. In addition to the plants, 42 soil samples were collected around the roots at a depth of 0-20 cm.

The samples were sent to the Laboratório Integrado de Pesquisas Químicas (*Integrated Laboratory of Chemical Research*) (LIPEQ) at Universidade Federal de Mato Grosso, Sinop campus, for separation and preparation for chemical analysis. The plants were washed in the laboratory under running water to remove solid residues. Each plant was separated into roots, stems and leaves, obtaining a total of 42 samples for each part, which were then weighed to record the fresh weight. The material was placed in a drying oven with air circulation at 50 °C until constant weight was obtained. After drying, the plant samples were ground, sieved to homogenize the parts, individually packaged and stored at -20 °C until time of chemical analysis. The percentage of water present in the different parts of the fresh plant was then determined.

Soil samples were sieved through a 1 mm mesh sieve, dried in a drying oven with forced air circulation at a temperature of 50 ºC until constant weight was obtained, and stored at -20 ºC for further chemical analysis.

2.3 Chemical analysis

Soil and plant material samples (roots, leaves and stems) were analyzed following the same procedure. Approximately 0.3 g of each sample were weighed on a digital balance with an accuracy of ± 0.1 mg and subsequently transferred to digestion tubes. A 2 mL mixture of nitric acid (HNO_3) and perchloric acid ($HClO_4$) was added in a 1:1 ratio, in addition to 5 mL of sulfuric acid (H_2SO_4). The tubes were then heated in a digester block at 230 °C for 60 minutes (AKAGI; NISHIMURA, 1991), cooled and transferred to 25 mL volumetric flasks, followed by dilution with distilled water.

The sample solutions were then analyzed using atomic absorption spectrometry with atomization by cold vapor generation using tin(II) chloride as a reductant, in a Varian AA140 Atomic Absorption Spectrometer equipped with a cold vapor generation accessory (VGA77). A standard solution (Specsol brand) was used for the calibration curve and compared against the NIST (National Institute of Standards and Technology),. The linear method was used from 0.2 to 40 $\mu g\ L^{-1}$.

The relative precision of ±5.8% of the analytical method was determined for THg in leaves and soil with samples fortified before digestion with three different concentrations of Hg (17, 165 and 415 $\mu g\ kg^{-1}$) and seven replications for each concentration. The recovery of Hg in the fortified samples varied between 97% and 110%. For every 10 samples analyzed, a replica was added to control the precision of the non-fortified samples, obtaining an average coefficient of variation between the replicates of 7%. The detection limit, defined as the average plus three times the standard deviation of ten analyzes of blanks, was 6.7 $\mu g\ kg^{-1}$ and the quantification limit, defined as the average plus ten times the standard deviation of ten analyzes of blanks, was 13.3 μg kg^{-1} (NASCIMENTO NETO et. al., 2012).

2.3 Translocation (TF), bioaccumulation (BAF) and bioconcentration (BCF) factors

The translocation (TF), bioaccumulation (BAF) and bioconcentration (BCT) factors were calculated using the Hg concentrations determined in the soil, roots and leaves of the plant. The translocation factor (TF) (Eq. 1) was calculated as the ratio of metal concentration in plant leaves ($[Hg]_{leaves}$) and the metal concentration in roots ($[Hg]_{roots}$) (MARRUGO-NEGRETE et. al., 2020).

$$(1) \qquad TF = \frac{[Hg]_{leaves}}{[Hg]_{roots}}$$

The bioconcentration factor (BCF) (Eq. 2) was determined by the ratio of metal concentration in roots, $[Hg]_{root}$, and the metal concentration in soil, $[Hg]_{soil}$ (MARRUGO-NEGRETE et. al., 2020).

$$(2) \qquad BCF = \frac{[Hg]_{root}}{[Hg]_{soil}}$$

Finally, the bioaccumulation factor (BAF) (Eq. 3) was calculated by the ratio of the metal concentration in the leaves, ($[Hg]_{leaves}$) and the metal concentration in the soil, $[Hg]_{soil}$ (MARRUGO-NEGRETE et. al., 2020).

$$(3) \qquad BAF = \frac{[Hg]_{leaves}}{[Hg]_{soil}}$$

2.3 Health risk assessment

2.3.1 Estimated daily intake

Estimated daily intakes (EDI) of Hg were calculated based on THg concentrations in cassava roots and average per capita consumption of cassava and cassava flour (Eq. 4) (LEÓN-CAÑEDO et. al., 2019).

$$(4) \qquad EDI = \frac{C_{[Hg]}.f.IR}{b_w}$$

where "$C_{[Hg]}$" is mercury concentration in the roots in μg kg^{-1}, "f" is the fresh mass conversion factor (dry mass (g)/fresh mass (g)) with an average value of approximately 0.3153 in this study), "IR" is average daily per capita consumption of cassava (kg/day), and "b_w" is an individual's average body weight (assumed to be 70 kg for adults in this study).

To calculate the estimated daily intake for cassava flour, a conversion factor equal to 1 was used, considering that the procedure for preparing and drying the roots is similar to the production process for cassava flour. The average daily consumption per capita for the Brazilian population was 9.0 g for cassava and 8.0 g for cassava flour (IBGE, 2019). The estimated daily intakes were compared with the provisional tolerable daily intake (PTDI) of 0.57 µg kg^{-1} $person^{-1}$ day^{-1}, a limit established by the Joint FAO/WHO Expert Committee on Food Additives (JEFCA, 2011; MARRUGO-NEGRETE et. al., 2020) indicating the compound maximum dose, below which there is no known risk of health effects.

2.3.2 Target risk quotient

The health risk related to Hg exposure through the consumption of cassava and cassava flour was estimated according to the total risk quotient (THQ), which was calculated by Equation (5) for cassava and flour:

$$(5) \qquad THQ = \frac{E_f \, . E_d . C_{[Hg]} . f \, . D_{IR}}{R_{fD} \, . b_w \, . T_{an}} \times 10^{-3}$$

The methodology for estimating the non-cancerous THQ health risk is described in detail by USEPA where "E_f" is the exposure frequency (365 day/year); "E_d" is the exposure duration (70 years) (LIANG et. al., 2019), equivalent to the average lifetime; "D_{IR}" is the rate of food intake (g/person/day); "$C_{[Hg]}$" is the Hg concentration (mg/g) in cassava; "R_{fD}" is the oral reference dose (Hg = 3×10^{-4} mg/g/d) (LEÓN-CAÑEDO et. al., 2019; BARONE et. al., 2018; EREGNO et. al., 2017); "b_w" is the average body weight (70 kg) of an adult population and "T_{an}" is the average exposure time for non-carcinogens (365 day/year × ED). The THQ for cassava was calculated relative to the fresh mass, using the conversion factor "f" of approximately 0.3153, and for cassava flour the factor used was equal to 1.

2.3.3 Statistical analysis

The sample data from Area I (with ASGM presence) and Area II (without ASGM presence) were examined, with the number of observations from Area I being equal to 24 (n = 24) and from Area II being equal to 18 (n = 18). For analysis of the collected data, after presenting normal distribution, the t-Student test was used for independent samples, with the purpose of comparing the averages between the two groups. The parameters evaluated were the concentrations of mercury in the leaves, stems and roots of the plants, and in the soil, as well as the BAF, BCF and TF indices. Results were considered statistically significant when p values < 0.05.

3 RESULTS

3.1 Hg accumulation and artisanal mining

The average concentration of Hg present in the cassava parts varied between the evaluated areas (Table 1). Area I had the highest average concentration of Hg in leaves and roots. The average concentration of Hg found in the soil and in the stem did not differ significantly. Area I, close to an ASGM, showed an average concentration of Hg in leaves up to 83% higher than that observed in Area II. In Area I, an average concentration of Hg around 150% higher than the average concentration in Area II was observed in the roots. In Figure 2 it is possible to observe the distribution of the THg concentration data in the different parts of the plant and areas studied.

Table 1 Comparisons of the mean concentration of mercury (μg kg-1 ± SD)* in different parts of the cassava plant and in the soil between the areas studied in Southern Amazonia

AREA	**PARTS**			
	Roots	Stems	Leaves	Soil
I	92.35 ± 102.65	35.41 ± 15,46	52.74 ± 23.38	102.99 ± 101.40
II	36.85 ± 21.98	33.12 ± 10.59	28.81 ± 10.73	64.75 ± 44.99
P-value	0.01621	0.57253	0.00013	0.10937

* p-value < 0.05 indicates significant difference between groups. Source: Own authorship.

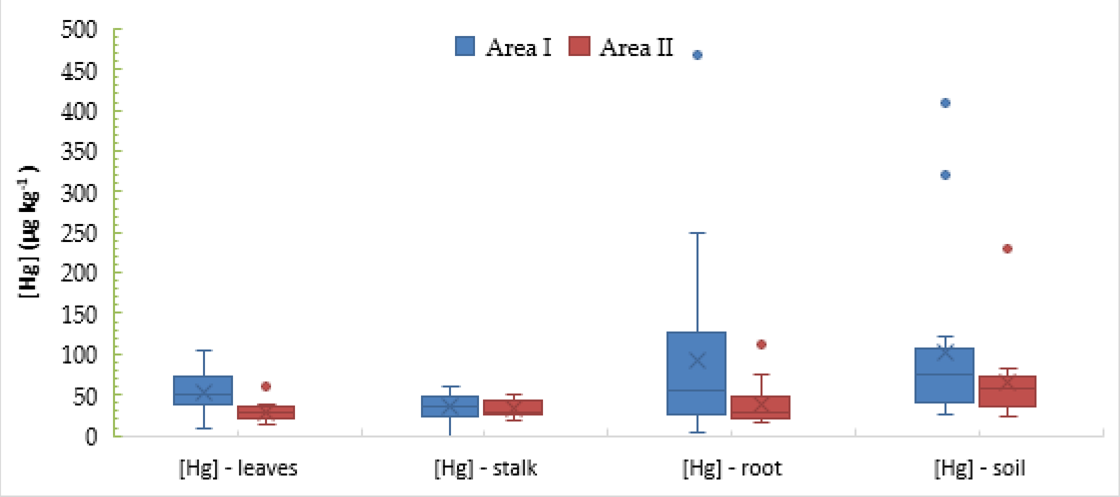

Figure 2 Distribution of THg concentration data (μg kg^{-1}) obtained in the different parts of the cassava plant and in the soil among the studied areas in Southern Amazonia

Source: Own authorship.

The translocation, bioaccumulation and bioconcentration factors are shown in Table 2. The highest bioconcentration factor (BCF) was 1.08 observed in Area I. The translocation (TF) and bioaccumulation factors (BAF) showed no statistical difference between the areas evaluated and TF values greater than 1 were observed for the two evaluated areas.

Table 1 Comparison of mercury translocation (TF), bioaccumulation (BAF) and bioconcentration (BCF) factors in cassava plants collected in two areas in southern Amazonia.

Collection areas	**TF**	**BAF**	**BCF**
I	1.47 ± 2.35	0.81 ± 0.77	1.08 ± 0.83
II	0.96 ± 0.48	0.58 ± 0.37	0.64 ± 0.25
P-value*	0.32185	0.2164	0.02408

* p-value < 0.05 indicates difference between groups. Source: Own authorship.

The average concentration of Hg present in cassava roots and leaves varied between the areas evaluated, showing an association between gold mining and environmental contamination. The highest average concentration of Hg in the leaves belongs to Area I, close to the ASGM, that is, a region of anthropogenic Hg emissions. ASGM releases Hg^0 into the atmosphere, which can be oxidized (Hg^+ or Hg^{+2}) and bind to heavier particles, facilitating their deposition. When deposited in soil, water or on the surface of plants, it can be modified into an organic form and biomagnify in the food chain, causing damage to living beings (e.g. BANK, 2020; AZEVEDO et. al., 2003; SOMMAR et. al., 2020). Hg stands out among the pollutants, as it does not degrade in nature and has a tendency to bioaccumulate in organisms (TURKYILMAZ et. al. 2018). The deposition of elemental Hg gas in ecosystems can take months, making it difficult to discover the emission source (ARIYA et. al. 2015; SAIZ-LOPEZ et. al., 2018).

Ma et. al. (2019) stated that, in general, the Hg found in plants results from the process of atmospheric deposition or by absorption from the soil. Therefore, Hg present in leaves can be absorbed from the soil and translocated to the upper parts via the roots (CHANDRA, et. al., 2017), or it can be accumulated directly from the atmosphere (CASAGRANDE et. al., 2020). In conditions where Hg soil concentrations do not differ, as found in this study, the higher average Hg concentration in leaves from Area I suggests greater deposition of Hg on the leaf surface in areas close to gold mining, as also observed in other studies (e. g. CASAGRANDE et. al., 2020; ESBRÍ et. al., 2018).

The samples obtained in Area I have a higher concentration of Hg in the leaves and roots compared to Area II, despite the two areas having the same concentrations of Hg in the soil. It is noteworthy that leaf stomatal uptake of Hg and subsequent transfer to the roots is a possible route for the uptake of Hg by certain plants (ASSAD et. al., 2016; MA et. al., 2019). The results indicate that for cassava, the leaves, in addition to the soil, can contribute to the uptake of Hg by the roots. Therefore, cassava is able to store the captured Hg from the atmosphere in leaves and roots, showing a high potential for bioindication of the emission of this metal by ASGM.

The average concentrations observed in the soils indicate that there is no Hg contamination in the areas, as they remained below the established limit of 300 $\mu g\ kg^{-1}$ (UNEP, 2002). These results coincide with the values observed by Casagrande et al. (2020), in the same region of this study, in which Hg soil levels were not affected by the proximity of ASGM and also did not have values above the established limits. The amount of Hg found in soils can be attributed to several factors, such as plant material deposition, atmospheric deposition or fertilizer use (MA et. al. 2019; ASADUZZAMAN et. al. 2019; WANG et. al., 2016).

The accumulation and retention of Hg in the soil depends on its physical and chemical properties, amount of organic matter present and chemical bonds with functional groups that facilitate the retention of Hg (OBRIST et. al., 2011; OBRIST et. al., 2018). Adjorlolo-Gasokpoh et. al. (2012) analyzed the levels of total Hg concentration in the soil surface and cassava harvested from farms located near gold mines in Ghana. The results, unlike those found in the present study, indicated that the topsoil layer and cassava crops were heavily contaminated by Hg, showing that cassava cultivation in soils with high concentrations of Hg should be avoided.

The bioaccumulation factor (BAF) indicates the plant's ability to absorb Hg from the soil into the leaf tissues. Values greater than 1 indicate that the plant is considered an accumulator (NAPOLI et. al., 2018). The BAF values of the evaluated areas were lower than 1, showing a low transfer of metal from the soil to the cassava leaves (e.g. EGLER et. al., 2006;), reinforcing that the higher concentration of Hg present in the leaves from Area I is from the atmosphere.

The translocation factors (TF) obtained for the evaluated areas were greater than 1, confirming that translocation of Hg from the roots to the aerial parts of the plant occurs. However, the higher concentration of Hg found in the leaves of Area I cannot be explained only by translocation, since the concentrations of Hg in the soil are statistically equal in the two areas, demonstrating the contribution of stomatal uptake by the leaves to the storage of Hg in the roots. This fact reinforces the effect of greater atmospheric deposition on leaves in the area close to ASGM.

It is understood that cassava leaves can be used to bioindicate the emission of Hg by ASGM, since the concentration of Hg in the atmosphere of these regions tends to be higher, affecting the concentration of Hg in the leaves of the vegetable (CASAGRANDE et. al., 2020; LIU et. al., 2020; ESBRÍ et. al., 2018; ZHENG et. al., 2018; EGLER et. al., 2006). Marrugo-Negrete et. al. (2016) noted that the translocation factor should not be used to characterize the ability of plants to absorb Hg in areas with high rates of anthropogenic Hg emissions, as within ASGM areas atmospheric emissions should be considered as a significant factor in the increase of Hg levels in the leaves.

The bioconcentration factor (BCF), when greater than 1, indicates that the plant is accumulating soil Hg in its roots. The BCF calculated for Area I was higher in relation to Area II, and only in Area I was it greater than 1. Considering that Hg concentration in the soils of the two areas was the same, the fact that the BCF of Area I was greaterthan 1 confirms that the Hg concentrations in the roots come from the higher atmospheric deposition of Hg due to mining activity, demonstrating the role of the leaves in the absorption of Hg and subsequent bioconcentration in the roots.

It is noteworthy that the concentration of Hg in the roots in Area I was 150% higher than that of Area II, and the concentration of Hg in leaves in the first area was 83% higher than in the second area, despite the concentrations of Hg in the soil from Areas I and II not differing from each other. This reinforces that cassava roots can absorb Hg both from the soil and the atmosphere, through stomatal absorption and transport to the roots (ASSAD et. al., 2016; MA et. al., 2019). This result shows that for cassava, BCF can verify atmospheric deposition in regions with anthropogenic Hg emissions, as the leave's absorption of Hg can also affect the concentration in the roots, interfering with the BCF.

Roots grown in Area I, where the deposition of atmospheric Hg can be higher, and the bioconcentration factor is greater than 1, show the ability to accumulate this metal in the root region from the soil and atmosphere, and that, under certain conditions, cassava may pose a risk of Hg contamination to human health that needs to be considered. It is understood that when the soil or the atmosphere reach Hg levels above certain limits, the levels in cassava may also increase and reach values that affect the quality of the product for consumption.

The results also reinforce that certain plants, including commercial ones, can be used as potential bioindicators for the presence of metals in the environment (CASAGRANDE et. al., 2020; CASAGRANDE et. al., 2018; SALAZAR; PIGNATA, 2014; ESBRÍ et. al., 2018). Thus, the use of Hg by ASGM can be detected in leaves and roots of cassava when comparing the concentration in the roots and leaves between plants grown in proximity to ASGM with plants collected in areas with no history of this activity. Therefore, collection and analysis protocols can be developed in order to use cassava as an aid in monitoring the irregular use of Hg by ASGM.

3.2 Health Risk Assessment

For the health risk assessment, the Hg EDI in cassava and cassava flour were calculated using the average concentration of Hg in the roots of each area (Table 3). The highest EDI values belonged to Area I, both for cassava and cassava flour. The THQ by exposure to Hg was calculated using the average concentration of the roots of each area. Both for cassava and cassava flour the values obtained were below 1 (Table 3), however, Area I presented the highest values.

Table 2 Estimates of daily intake (EDI) of Hg and health risk quotient (THQ) for the consumption of cassava and cassava flour by the population of southern Amazonia

Areas	**EDI**		**THQ**	
	Cassava	**Flour**	**Cassava**	**Flour**
I	0.004	0.011	0.012	0.040
II	0.001	0.004	0.005	0.016

Source: Own authorship.

The calculated values of EDI and THQ (Table 3), both for cassava and cassava flour, do not pose a risk to the health of the population in the studied region as they were below theestablished limits. Although below the established limits, the highest values obtained for EDI and THQ belong to Area I. Therefore, it is necessary to periodically investigate these factors in crops close to ASGM due to the possibility of increased contamination by Hg in conjunction with increased prospecting or intensity of this activity.

The average per capita consumption rate of cassava and cassava flour in Brazil is 9.0 and 8.0 g day^{-1}, respectively. For the 1st quartile of the population, represented by low-income earners, the average per capita consumption rate of cassava flour rises to 13.2 g day^{-1}. For the northern region, the average per capita consumption rate of cassava flour is 38.0 g day^{-1}. In 2017 and 2018, the frequency of consumption of cassava flour was almost three times higher in rural areas than in urban areas (IBGE, 2019).

Considering that cassava roots bioaccumulated the Hg present in the atmosphere and in the soil in which they were grown, and considering a daily cassava consumption rate of 9.0 g day^{-1} person^{-1}, it can be estimated that the EDI would be above the established limit of 0.57 µg kg^{-1} person^{-1} day^{-1} only for roots with an average Hg concentration of 14.06 mg kg^{-1} or higher.. Under these conditions, the THQ will be 1.9, demonstrating the health risk of consuming cassava in conditions where soil and atmosphere are contaminated by Hg. It should be noted, therefore, that for the current average per capita consumption, cassava roots will only be toxic when they have Hg concentrations above 14.06 mg kg^{-1}.

For cassava flour, the toxic levels of Hg are lower compared to cassava. For flour with concentrations upwards of 4.99 mg kg^{-1} the EDI and THQ indices would be above the critical limits, considering a daily cassava flour consumption rate of 8.0 g day^{-1} person^{-1}. It is understood that with the loss of water in the flour manufacturing process, the concentration of Hg increases, and to consume the same levels of Hg it would be necessary to consume more cassava than cassava flour. The threshold Hg concentrations in roots that the EDI and THQ did not indicate as being a health risk from exposure to Hg varies according to the consumption rates of the population of interest. Thus, the higher the consumption, the lower the concentration of Hg must be for safe consumption.

It should be noted that for roots with an average concentration equal to the roots of Area I (92.35 µg kg^{-1} or 0.092 mg kg^{-1}), it is safe to ingest up to 1,370 g of cassava and 432 g of cassava flour daily, where these consumption rates would not exceed the limit established for EDI. However, for the health risk quotient (THQ) for exposure to Hg to remain < 1, it is safe to consume less than 722 g of cassava and less than 227 g of flour, a limit that would be exceeded by a population with high average consumption. Therefore, it is forwarned that for cassava cultivated in regions close to ASGM, where the concentration of Hg in the atmosphere and soil tend to increase due to prospecting activity, and the local population has a high consumption rate of cassava or cassava flour, monitoring must be undertaken to prevent health risks from exposure to Hg.

Something else that should be highlighted is the consumption of cassava leaves produced close to ASGM areas. Although within this study region the daily consumption of leaves is low, the leaf is an essential ingredient in a typical dish in the northern region of Brazil, and in the diet of 60% of the population of Sub-Saharan African countries. With the results of the present study, it is understood that cassava leaves grown close to gold mining areas may contain higher Hg concentrations due to atmospheric deposition, and under certain conditions, the edible parts may present mercury above critical values, harming the health of the population. It is important to highlight that the average daily consumption of leaves by the population can be safe, however, in regions where cassava crops are close to ASGM, the high consumption of cassava leaves can pose a health risk even at concentrations below the established limits.

4 CONCLUSION

Hg concentrations in cassava plants were higher in the area close to ASGM. The difference between Hg concentrations in cassava leaves grown in the vicinity of an emission source and cassava leaves grown in an area with no recent history of Hg emission by ASGM allowed us to estimate the effect of ASGM on atmospheric Hg deposition within a chosen area. Thus, it is assumed that cassava has potential use as a bioindicator of atmospheric deposition of Hg emitted by ASGM. The BCT greater than 1 in the area close to ASGM demonstrated the effect of ASGM proximity, and also on Hg concentrations in cassava roots. The use of Hg by ASGM can be detected in the leaves and roots of the cassava plant, and collection and analysis protocols can be developed to facilitate the of monitoring irregular Hg use using cassava as a bioindicator.

The consumption of cassava and cassava flour by residents of the studied region does not represent a health risk due to the low average per capita consumption rate. It is stipulated that for the region's population, cassava consumption is safe up to about 722 g day^{-1} $person^{-1}$ and cassava flour about 227 g day^{-1} $person^{-1}$. For the current consumption of the population, the roots are toxic with levels starting at 14.06 mg kg^{-1} and for cassava flour around 4.99 mg kg^{-1}. The need for periodic monitoring of Hg concentrations in commercially grown plants is reinforced, in order to avoid the production of food contaminated by the metal. It is also forwarned regarding the consumption of cassava leaves grown in mining areas, as atmospheric deposition considerably increases the concentrations of Hg present in the leaves and can become a direct route for contamination of the population that consumes them.

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