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Residual Assessment of Metal Transfer from Selected Agricultural Machinery to Processed Commodities

Mark Romy E. Nanali[1], Arthur L. Fajardo[2], Omar F. Zubia[3], Ralph Kristoffer B. Gallegos[4], and Rina A. Bawar[5]

[1]Instructor I, College of Technology, Don Mariano Marcos Memorial State University, City of San Fernando, 2500 La Union, Philippines

[2]Professor 5, Agribiosystems Machinery and Power Engineering Division (AMPED), Institute of Agricultural and Biosystems Engineering, College of Engineering and Agro-Industrial Technology, University of the Philippines Los Baños, 4031 Laguna, Philippines

[3]Associate Professor 4, Agribiosystems Machinery and Power Engineering Division (AMPED), Institute of Agricultural and Biosystems Engineering, College of Engineering and Agro-Industrial Technology, University of the Philippines Los Baños, 4031 Laguna, Philippines

[4]Associate Professor 2, Agribiosystems Machinery and Power Engineering Division (AMPED), Institute of Agricultural and Biosystems Engineering, College of Engineering and Agro-Industrial Technology, University of the Philippines Los Baños, 4031 Laguna, Philippines

[5]Assistant Professor 7, Agricultural Food and Bioprocess Engineering Division (AFBED), Institute of Agricultural and Biosystems Engineering, College of Engineering and Agro-Industrial Technology, University of the Philippines Los Baños, 4031 Laguna, Philippines

Email: [1]markromy.nanali@dmmmsu.edu.ph (corresponding author), [2]alfajardo@up.edu.ph, [3]ofzubia@up.edu.ph, [4]rbgallegos@up.edu.ph, and [5]rabawar@up.edu.ph

ABSTRACT

Stainless steel, particularly grades such as AISI 304SS and 316SS, is extensively used in food processing due to its excellent corrosion resistance, durability, and ease of cleaning, which are essential for maintaining food safety and hygiene standards. However, the verification of food-grade materials has rarely been evaluated. This study investigated the potential transfer of metal residues from food-grade machines specifically a calamansi juice extractor, and coffee grinder to processed agricultural products such as calamansi juice, and coffee. An X-ray Fluorescence (XRF) analyzer was used to determine the metal composition of the processing equipment. Levels of iron (Atomic Absorption Spectrophotometry, AAS) and lead (Inductively Coupled Plasma-Optical Emission Spectroscopy, ICP-OES) in the processed products were determined. The results showed minimal presence of impurities. Levels of iron and lead in the final products remained below international safety standards, suggesting minimal contribution of processing equipment to metal residue content. By providing empirical data on the material composition of commonly used food-processing equipment, this research contributes to improving regulatory frameworks and guiding manufacturers in selecting appropriate materials. These findings support the development of safer, high-quality food-processing equipment, thereby enhancing food safety practices in the Philippine agricultural sector.

Keywords: *Agricultural machinery, food safety, metal residue, x-ray fluorescence (XRF) spectroscopy*

INTRODUCTION

The emission of metals from agricultural machinery significantly contributes to contamination in food and humans (Oniya, 2018). As food safety remains a crucial public concern, global food production must increase by 50% to meet the nutritional needs of a projected 10 billion people by 2050 (Katsigiannis et al., 2021). Despite these demands, approximately 820 million individuals lack access to safe food, and contamination frequently occurs during processing and storage (FAO, IFAD, UNICEF, WFP and WHO, 2019.) In the Philippines, food safety remains a challenge, with the Food and Drug Administration (FDA) identifying concerns such as microbiological contamination, metal traces, and the improper use of food additives (Pabuayon, 2017; PAG, 2017).

Stainless Steel 304 (AISI 304) typically contains 18% chromium and 8% nickel, which provide excellent corrosion resistance and durability. Stainless Steel 316 (AISI 316) includes approximately 16% chromium, 10% nickel, and 2% molybdenum. The presence of molybdenum enhances resistance to chloride-induced corrosion, making 316 especially suited for acidic and saline environments often found in food processing. These properties explain the widespread adoption of both grades in hygienic food applications.

The surface characteristics of stainless steel (SS) play a critical role in food preservation and safety, making its application in the food industry essential (Schmidt et al., 2012). However, pitting corrosion in SS can lead to localized contamination, influenced by chloride concentration and the commodities being processed (Li et al, 2023). Food processing equipment, particularly those involved in size reduction, undergoes significant wear due to rotation and friction, leading to contamination from metal components, lubricants, and deteriorating machine parts (Katsigiannis et al., 2021; Moerman, 2017; Holah, 2014). Development in food processing technology has further exacerbated risk for contamination through heavy metals and environmental pollutants (Rai et al., 2019).

There are numerous analytical techniques available for this discipline, but since its inception, X-ray fluorescence (XRF) spectroscopy continues to be widely accepted and used for characterization of materials. XRF is a nondestructive technique that can accurately identify the elemental composition of metal materials to verify they are acceptable for food grade material standards.

XRF-based material analysis can also be facilitated by local institutions such as the Philippine Nuclear Research Institute (PNRI) which they provide material testing for multiple industries (DOST-PNRI, 2015). Furthermore, the Nanotech Analytical Services and Training Corporation (NASAT Labs) use XRF techniques to characterize the metal composition of materials, reaffirming the importance and relevance of assessment in all industrial standards (NASAT Labs, 2021).

The presence of heavy metals in food products is a serious issue of health and safety because they can cause acute toxicity and chronic health problems from prolonged exposure (Kumar et al., 2020). Heavy metals such as arsenic (As), mercury (Hg), nickel (Ni), copper (Cu), chromium (Cr), lead (Pb), and cadmium (Cd) can enter food through cross contamination with the environment, the equipment used, and the packaging (Rusin, 2021).

The presence of lead (Pb) can have suggested effects on reproductive health and cognitive impairments, with studies that report negative effects on cognitive impairment even with low chronic exposure to lead (Pb) (Saraiva et a., 2023; Kumar et al., 2020; Nkwunonwo et al., 2020; Rehman et al., 2018). As an acknowledgement of these serious health issues, the World Health Organization (WHO) staying ahead of the risks, had been gradually decreasing the allowable limit for lead in a food product, from 50 ppb in 1995 to 10 ppb in 2010 (WHO, 2022).

This study is focused on assessing the level of metal contamination in food products processed using selected agricultural machinery to provide empirical evidence that may support future strategies in reducing contamination risk.

MATERIALS AND METHODOLOGY

Sampling involved collecting 100 grams of coffee, and 500 ml of manually squeezed and 350 ml of machine-extracted calamansi juice. These quantities were based on laboratory testing requirements. Each sample was gathered before and after the processing operation to compare any metal residue differences. Since no samples exceeded safety thresholds, replicates were not required.

The researchers obtained 100g of each product for conducting physicochemical tests in addition to metal residue analysis. All samples were placed into small double ziplock plastic bags before submitting them to laboratories within a 24-hour time frame. For the coffee grinder, pre-processed roasted Arabica coffee beans were used and stored in clean, dry containers prior to grinding. Calamansi fruits were manually washed with potable water to remove surface contaminants and kept in insulated containers to preserve freshness before extraction. These handling procedures reflect the typical practices followed by farmers and operators of the machines evaluated in this study.

The X-ray Fluorescence (XRF) Bruker S1 Titan model 500/800 analyzed the metal compositions of the samples in terms of food-grade metal analysis. For more detailed metal residue analysis, standard tests like Atomic Absorption Spectrophotometry (AAS) and Inductively Coupled Plasma – Optical Emission Spectroscopy (ICP-OES) were conducted by SentroTek laboratory.

Agricultural Machineries for Food Processing

a. Calamansi Juicer

The juice extractor (**Figure 3a**) is a 3-year-old machine with a minimum capacity of 50 kg per hour. The process flow (**Figure 1**) is shown based on the processor's routine. The machine is used commercially during the calamansi harvest. Food grade parts were identified and characterized (**Table 1**).

b. Coffee Grinder

The grinder machine (**Figure 3b**) is 1-year-old with a processing capacity of 75 to 250 kg per hour. The process flow (**Figure 2**) is shown based on the processor's routine. The machine is used continuously for business purposes. Food grade parts were identified and characterized (**Table 1**).

Processing capacity was approximately 50 kg/load for calamansi juice (extractor), and 75–250 kg/hr for coffee (grinder). The collection was conducted per batch, reflecting standard processor operations.

Experimental Method

Although stainless steel is typically low in lead, Pb analysis was included as a precaution due to potential legacy components or external contamination sources. Chromium, a primary

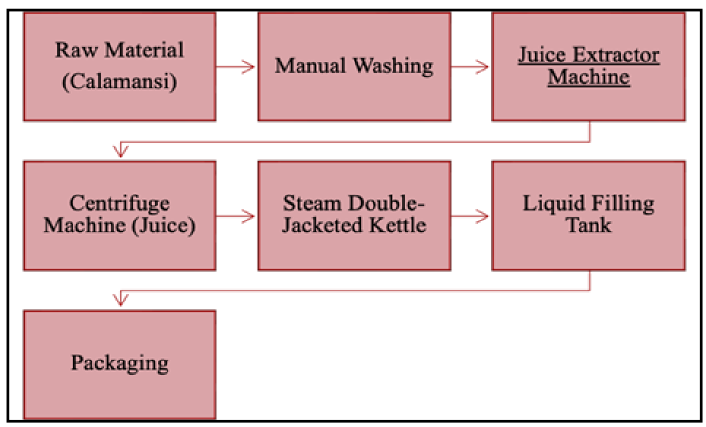

Figure 1. Calamansi juice process flow.

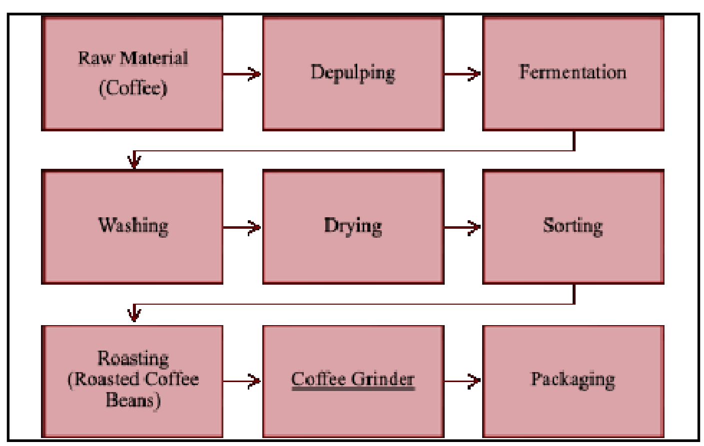

Figure 2. Coffee grinder process flow.

stainless steel component, is less likely to leach under the processing conditions used and was not prioritized in this study.

The study employed a multi-technique approach to analyze the presence of heavy metal residues in food-grade materials used in agricultural processing machines. Primary screening was conducted using a handheld X-ray Fluorescence (XRF) analyzer, specifically the Bruker S1 TITAN 500/800 model, recognized for its non-destructive, rapid material analysis. Metal surfaces in contact with food were meticulously cleaned to eliminate any contaminants that could affect measurement accuracy.

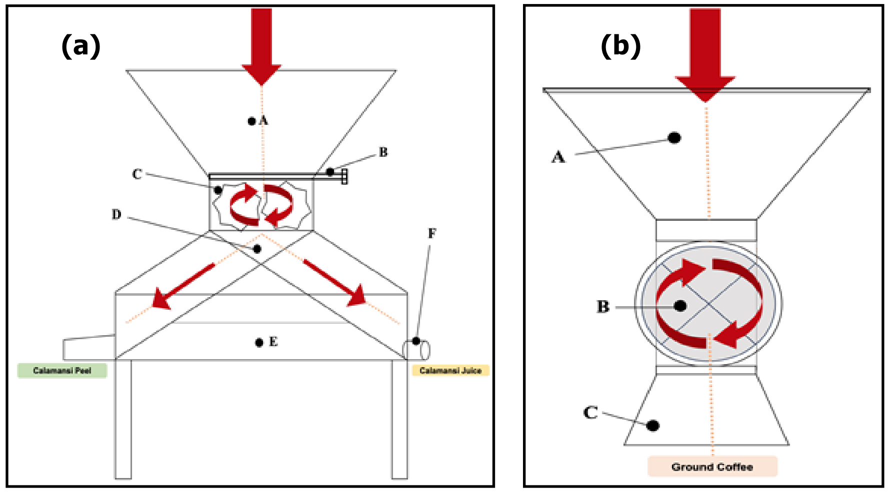

Figure 3. Material flow of agricultural machinery (a, calamansi juicer; and b, coffee grinder) that are directly in contact with commodity.

Table 1. Results of XRF material analysis.

FOOD GRADE MATERIAL	TYPE	MATCH QUALITY
1. Calamansi Juice Extractor		
A. Hopper (Surface)	AISI 304 Stainless Steel	9.74
B. Hopper (Stoper)	AISI 304 Stainless Steel	9.95
C. Roller Squeezer	Silicone Food-grade	N/A
D. Perforated Screen	AISI 304 Stainless Steel	9.96
E. Flat Conveyor	AISI 316 Stainless Steel	9.95
F. Base (Juice outlet)	AISI 316 Stainless Steel	9.96
2. Coffee Grinder		
A. Hopper	Nitronic 32 Steel	5.09
B. Unidentified	N/A	N/A
C. Output Chute	AISI 204 Stainless Steel	9.39

For validation and detailed quantification, advanced methods, including Atomic Absorption Spectrophotometry (AAS) and Inductively Coupled Plasma–Optical Emission Spectroscopy (ICP-OES), were employed following the Official Methods of Analysis of A.O.A.C. International (21st edition). These instruments, calibrated against certified standards, provided precise data on the type and concentration of metallic residues, enabling a comprehensive assessment of potential contaminants and ensuring the safety of food contact materials.

RESULTS AND DISCUSSION

Metal Identification and Chemical Composition Analysis of Food-Grade Metals

Most of the metals (**Table 1**) required by PNS/PAES for agricultural machinery related to food commodities to be food-grade, especially those in direct contact with commodities were identified. XRF analysis confirmed that the majority of components were made from AISI 304 Stainless Steel due to its corrosion resistance and mechanical properties, making it suitable for direct food contact. Other parts utilized AISI 316 Stainless Steel and low alloy steels, with the latter being used in non-food-contact areas.
According to a study by Taha et al. (2017) 304SS has been a material of choice in food and cooking ware for its high corrosion resistance, along with good mechanical properties.

Table 2 presents the quantification of metal residues in agricultural products, specifically describing the iron and lead contents of coco sugar, turmeric, calamansi juice, and coffee before and after processing.

Atomic Absorption Spectrophotometry (AAS) was the measurement technique of iron (Fe), whereas Inductively Coupled Plasma - Optical Emission Spectroscopy (ICP-OES) was the one for lead (Pb). Based on the analyzed data, it was derived that the content of iron in coco sugar powder is 0.19 mg for every 100 grams, while in regular coco sugar is 0.14 mg per 100 grams.

The inference of the investigation is the only slight increase in iron content during the processing period. The iron concentration of turmeric is observed to be even less than 0.05 mg per 100 grams in both dried and powdered forms, showing the very little existence of iron. The pure manually extracted calamansi juice has an iron content of 0.08 mg/100g, which is a low level, particularly when considering dietary iron requirements.

The machine extracted juice shows an increased iron content of 0.13 mg/100g, suggesting that the formulation process might dilute or increase the concentration of iron. Lead content in both juice forms was below 0.05 mg/kg, which implies negligible lead content, ensuring safety concerning this contaminant.

Roasted coffee shows an iron content of 3.6 mg/100g, decreasing to 2.9 mg/100g in ground coffee sample, possibly reflecting natural variation or differences in processing methods. As with the other products, the lead content in coffee is non-detectable (ND), indicating that consumers are not at risk from lead exposure through coffee consumption.

Lead was included in the analysis due to its toxicological significance and the possibility of contamination from components beyond core stainless steel parts. Chromium, although abundant in stainless steel, was excluded due to its stable behavior in the observed food-processing conditions.

The results suggests that the processing of these agricultural products does not significantly increase the content of iron or lead, with all samples showing low levels of these metals. This is important as both metals, especially lead, can be toxic in high amounts. Metal residues may occur during pre-processing and post-processing stages.

This could happen, for example, during harvest if workers use metal tools or equipment that can leach contaminants into the food. Paints, rust, and corrosion on processing equipment can also contribute to metal contamination. Considering that heavy metals can accumulate in the body and cause health problems, it follows that the agricultural products sampled may not increase heavy metal

Table 2. Metal residue quantification in agricultural products before and after processing (mg/100g) using AAS and ICP-OES method.

PARAMETER	SAMPLE IDENTIFICATION			
	Calamansi		Coffee	
	Before[1]	After[2]	Before[2]	After[2]
Iron (Fe), mg/100g	0.08	0.13	3.6	2.9
Lead (Pb), mg/kg	<0.05	<0.05	ND	ND

Note:
**AAS¹: Atomic Absorption Spectrophotometry*
**ICP-OES²: Inductively Coupled Plasma - Optical Emission Spectroscopy*
**ND: None-detected at the method detection level of 0.10 mg/kg for Lead*

Table 3. Analysis of metal residue levels in agricultural products (mg/100g) using AAS and ICP-OES methods.

PARAMETER	ALLOWABLE LIMITS (INTERNATIONAL FOOD STANDARDS)	SAMPLE IDENTIFICATION	
		Calamansi	Coffee
Iron (Fe), mg/100g	300 mg/100g (Ji et al., 2021)	0.3 [a]	2.9 [a]
Lead (Pb), mg/kg	0.1 mg/kg to 0.2 mg/kg	0.2 [a]	ND [c]

Note:
Within safe consumption limits [a]
Below the method detection levels, posing no health risk [b]
Non-detectable (ND), indicating no risk of contamination [c]

poisoning through dietary means given the low iron levels as well as undetectable lead levels (Balali-Mood et al., 2021).

The results also indicate that processing does not significantly increase the metal content, which is important for ensuring the safety of processed foods. Regular monitoring of these metals is important to maintain safe levels and to ensure consumer safety (Nkwunonwo et al., 2020).

Table 3 illustrates the results of analysis of metal residue levels in agricultural products, comparing them to international food standards for allowable limits. For pulverized coco sugar, iron content is measured at 0.19 mg/100g, which is below the international allowable limit of 0.3 mg/L. Turmeric powder shows even lower iron levels, at less than 0.05 mg/100g, which is significantly below the allowable limit, indicating a very minimal risk of iron overdose from its consumption. The calamansi juice shows an iron concentration of 0.13 mg/100g, which is still lower than the specific risk amount, proving that its consumption does not lead to iron toxicity.

The fact that lead is at undetectable levels (<0.05 mg/kg) shows that there is no contamination health hazard, since it is well within the acceptable limits. Furthermore, the coffee sample has an iron content of 2.9 mg/100g, which is safe for human consumption in considered to the acceptable limit of 0.3 mg/L. The lead levels being at non-detectable levels fits with international safety standards and implies no significant risk of lead poisoning.

These findings are positive. Iron levels in the food products tested are significantly below the safety limit, indicating that the products are safe to eat with regard to iron content. Moreover, the lack of detected lead in the samples is especially significant because of the serious health ramifications from lead contamination. Because lead can build in the body and lead to serious health issues, it is encouraging and suggests that the food products investigated have met the safety limits for lead (Kumar et al., 2020).

A visual inspection of all food-contact components of the machines revealed no signs of rust, corrosion, or degradation. Though the surfaces were not mirror polished due to use, all parts were clean and consistent with food-grade standards. No coatings were observed on the metal surfaces. Machines were cleaned using cloth and water before and after processing to minimize bacterial growth and ensure sample integrity.

To aid manufacturers and regulators, this study proposes a simple five-point framework to guide and assess the selection of safe food-grade materials for agricutural processing equipment:

1. Visual Inspection – Evaluate and Identify for rust, cracks, pitting, or surface damage;
2. Material Verification – Use XRF to identify food-grade alloys (e.g., AISI 304/316);
3. Metal Residue Testing – Conduct AAS/ICP-OES analysis pre- and post-processing. Analyzing product contamination through AAS and ICP-OES;
4. Raw Material Compatibility – Ensure no corrosive interaction with produc, and do not react adversely with food; and
5. Sanitation and Fabrication Review – Assess cleanability and current hygiene practices and Evaluate presence of dead spaces, and construction quality.

In addition to verifying metal composition and residue levels, the proposed assessment framework incorporates hygienic design considerations such as mterial compatibility with raw products, ease of cleaning, surface finish quality, and structural features like the absence of dead spaces or sharp corners to ensure both functional performance and long-term, food safety in agricultural processing machinery. It is recommended that future research expand metal residue assessment to include chromium and other potential leachables. Equipment manufacturers should ensure routine inspection and documentation of machine wear, corrosion, and sanitation practices to minimize contamination risk.

CONCLUSION

The research conclusively identified and characterized the chemical composition of food-contact components in selected agricultural machinery, specifically juice extractors and coffee grinders. The analysis confirmed that AISI 304 Stainless Steel, known for its corrosion resistance and mechanical durability, was predominantly used in direct food-contact areas. This material selection underscores the importance of using appropriate and durable metals in food processing to support hygienic practices. Furthermore, the assessment of metal residue levels in processed products including calamansi juice, and coffee revealed that concentrations of iron and lead remained below internationally accepted safety limits.

These findings indicate that the equipment in use is reasonably installed and maintained, as supported by its observed condition—specifically, the absence of visible corrosion, the use of certified food-grade components, and adherence to basic cleaning protocols. Overall, the results provide empirical evidence that current processing practices do not significantly contribute to metal contamination, thereby supporting consumer safety and guiding future efforts to reduce contamination risks.

CONTRIBUTIONS OF THE AUTHORS

The authors are responsible for all conceptualization, methodology, collecting and gathering data and analysis and interpretation of the results. The authors wrote the manuscript and have provided relevant literature and checked for academic integrity and ethics.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest in the conduct of this study. No financial, professional, or personal relationships have influenced the findings, analysis, or conclusions presented in this research.

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