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New sustainable perspectives for “Coffee Wastewater” and other by-products: A critical review

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ABSTRACT

Coffee sector has a tendency to increase consumption and fall in international coffee prices, as a commodity. There is a need for a strategy to minimize the impact of high costs for producing families and maintaining the competitiveness of the product. In this context, the proper disposal of “Coffee Wastewater” (CWW) can be an alternative, both to mitigate the environmental impact, if it is discarded without treatment, and to generate a source of extra income for coffee growers, when used in the food, pharmaceutical industry, or cosmetic. Proper management of CWW, as well as knowledge of its composition and toxicity, could help to identify solutions at the beginning of the processing chain, however, to date, there are no reports that have discussed CWW. In order to identify effective solutions for this, data covering economic, social and sustainable aspects were verified, focusing on trends in the use of coffee residues, which stimulate the investigation of a new sustainable by-product, which will enable the generation of extra income for coffee growers who have difficulty in bear production costs. The impact can vary between coffee producers and their waste, creating mitigation opportunities.

1. Introduction

With the prospect that coffee will reach a totally sustainable environment, it should be noted there are still by-products that have not received such popularity to be reused. Perhaps due to an underestimation of its potential, or due to the ascendancy that other by-products have received today, the water used in washing coffee, which has economic and sustainable potential, remains scientifically unexplored as a by-product. It is known one of the main concerns in relation to the sustainability of the coffee production chain involves the recovery of a large amount of its generated by-products (Kasuya et al., 2015; Oliveira and Franca, 2015), including more than 10 million tonnes of solid waste, along with large amounts of wastewater and crop residues (Echeverria and Nuti, 2017).

Lopes et al. (2014) affirm the waste generated in the coffee processing process has become a major problem for producers who have installed processing machines on their properties in order to produce finer or better-quality coffee beans. This has led to a significant increase in environmental problems, caused by large volumes of wastewater, bark, and wet pulps. The consumption for washing and separation varies from 0.1 to 0.3 L of water per liter of fruit, while in peeling and/or pulping, the consumption is 3 to 5 L of water per liter of fruit. In this way, the activity of processing coffee fruits generates large volumes of wastewater, which have a high concentration of nutrients, which consist of organic material in suspension and organic and inorganic constituents in solution, of great polluting power or having a negative environmental impact if they are discarded in watercourses (Matos et al., 1998).

According to Galanakis (2017), coffee washing water, when released into receptive water bodies, quickly forms anoxic zones as a result of its anaerobic stabilization, generating, as by-products of organic material´s degradation, methane, phenols, and hydrogen sulfide, which emit unpleasant odors. In addition, nutritional enrichment of these waters can lead to the development of vegetables (cattail, water hyacinth, saltwater, algae in general, etc.) which can harm the aquatic ecosystem. It is estimated accelerated growth of residues is due, among many factors, to the fact that coffee is one of the most popular drinks in the world, being consumed for having a comforting effect in specific contexts, having stimulating properties and health benefits (Dankowska et al., 2017). Therefore, coffee industries must strive to value the by-products resulting from the processing of coffee through innovative and useful applications (from the field to the table), in order to increase process sustainability (Galanakis, 2017). This includes extra care in wet or semi-wet processing, as coffee fruits generate huge amounts of effluents with a

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large amount of organic material, requiring systematic treatment before disposal (Rattan et al., 2015).

This type of sustainable awareness requires a fundamental change in the goal of exploring waste in all its possible aspects of coffee reuse. Untapped by-product identification added value can reorient perceptions around the wastewater versatility has hitherto been offering. Although there is extensive literature on physical, chemical, biological methods, economically viable or not, involving advanced technology or not, exploring the potential of wastewater as a by-product, there is no specific evidence from any study that considered coffee washing water as a value-added by-product.

Based on these premises, this present work aims to provide a review of the challenges in the reuse of coffee residues, encompassing economic, social, and sustainable aspects with a focus on trends for the use of these subproducts, which stimulate the investigation of a new sustainable by-product, which will enable the generation of extra income for coffee growers who have difficulty covering production costs. This review will be supplemented through data obtained from physical-chemical and microbiological analyzes performed in washing water of Brazilian coffee variety, which will be referred to in this study as "Coffee washing wastewater" (CWW).

Section 1 sets out the particularities of the dry, humid, and semi-humid processes and their consequences for the generation of wastewater, in addition to potential impacts of waste production. In section 2, sustainable application trends for coffee residues, in physical-chemical or biotechnological scope that are ascending to wastewater. Finally, section 3 presents an analysis of the coffee sector, including limitations and future perspectives on the use of coffee washing water and other waste as a by-product, pointing out problems and solutions in the use as an ingredient for industrial use.

2. Coffee processing, waste production and potential impacts

2.1. Processing of coffee and waste generated

For impacts discussion arising from the effluents from coffee processing, it is considered coffee fruit is basically composed of bark, pulp, parchment, silver film, and seeds. The nutritional composition of these constituents is influenced by the species and varieties of the plant, planting practices, altitude, maturation levels, storage conditions, among others (Saath et al., 2019).

Coffee from crops can consist of unripe fruits, ripe or "cherry", super-ripe or "raisin" fruits, dried fruits, leaves, branches, sticks, soil, and stones (Borem, 2015). The ways of processing can be classified as "Dry way" when product is dried directly after washing and removing impurities (Fig. 1); and as "Semi-humid way" and "Wet way" when the peeled and/or pulped fruits are dried, respectively, and both in peel removal and pulp removal stages, water is used (Fig. 2). In these processes, as shown in Figs. 1 and 2, various residues are generated, such as wastewater, bark, pulp, and parchment.

As shown in Figs. 1 and 2, forms of coffee processing are significant waste generators. Fruit washing and hydraulic separation for segregation of "coffee float" from green and cherry fruits (CWW); removing the peel and/or pulp (CPW); the washing of residual mucilage (CMW) and fermentation (CFW) are examples of steps that favor the production of large volumes of waste and liquids, such as the different washing waters mentioned, and solids, both rich in organic and inorganic constituents. These once disposed of the environment without treatment, are likely to cause major environmental problems, compromising flora and fauna development.

During coffee processing, there are two constituents that deserve to be differentiated: pulp and mucilage. The pulp contains 6 to 8% mucilage. In C. arabica it represents between 39 and 49% of fruit fresh weight in the cherry ripening stage, and in C. canephora, Robusta variety, it represents 38% of that weight. It should be considered, however, some differences in the relationships may occur due to genetic, environmental, and processing effects (Roltz et al., 1971; Zaluaga, 1999).

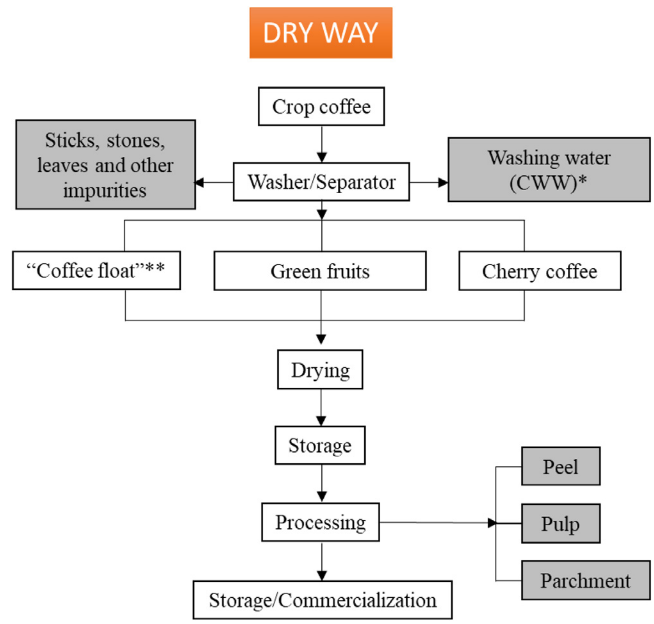

Fig. 1. "Dry process" processing steps. *CWW - Coffee washing wastewater; **"Coffee Float" - consisting of dry coffee, super-ripe and almost dry fruits, called "raisin", badly-grated fruits, green and ripe fruits with only one developed seed. These conditions reduce the specific mass, causing them to pass to washers' surface.
Source: Adapted from Borem, (2015).

Listing the possible residues produced during the aforementioned processing steps, Fig. 3 was constructed, which presents them separately. As can be seen, wet processing is one that generates a greater amount of effluent in relation to other methods, i.e., it is a method with the greatest environmental impact in relation to wastewater production.

Among the waste generated, summarized in Fig. 3, the ones with the greatest potential for use are CWW, CPW, CFW and CMW, and barks. What has been verified in the literature is the wastewater coffee use, in general, for fertigation (Matos, 2003) and barks for composting and energy production (Matos, 2015). These residues, in general, present a significant nutritional load that can be reused for nutritional enrichment of foods and/or development of other products such as tea from coffee peels (Dierberger et al., 2016). Currently, adding value to waste is little explored; however, it is a secondary source of income for coffee farmers.

2.2. Main waste generated characterization

2.2.1. Solid waste

Among the solid residues, the peel is the first to be generated. It represents 39% of fresh weight or 29% of fruit's dry matter, while the parchment represents around 12% of the fruit (Matos, 2015). It is worth mentioning the amount of peel present in the cherry type fruit depends on the state of ripeness, climatic conditions, irrigation degree, location, coffee variety, among others (Ferrão, 2009; Matos, 2015; Siqueira and Abreu, 2006). Table 1 shows the mineral composition of the coffee fruit peel, in relation to dry matter.

As shown in Table 1 coffee peel is rich in numerous nutrients like potassium and nitrogen, which shows its wide use in the agricultural area, either as organic fertilizer "in nature" or after composting. The coffee fruit peel's use is a good option to correct potassium-deficient soils (Matos, 2015).

In the coffee peeling process, the peel is removed along with part of the mesocarp and vascular bundles, resulting in the pulp, which is composed mainly of carbohydrate, crude protein (N x 6.25),

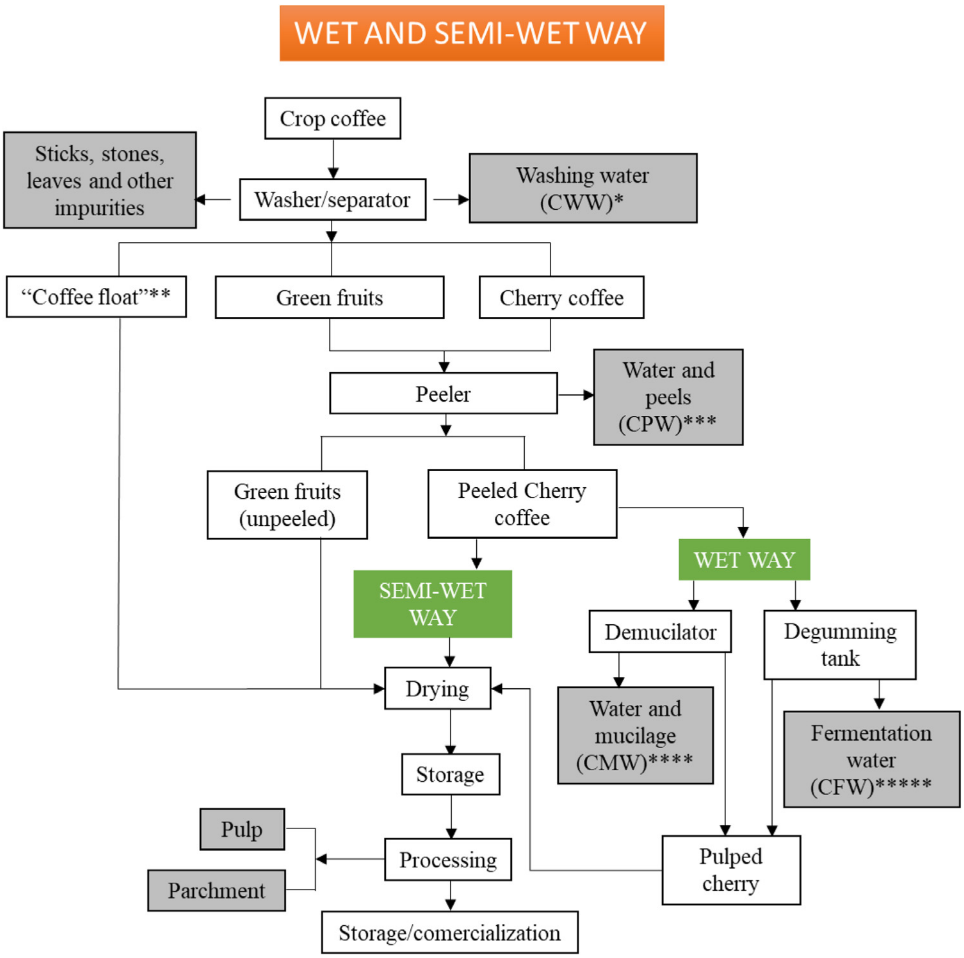

Fig. 2. Processing stages "Wet way" and "Semi-wet way". *CWW - Coffee washing wastewater; **"Coffee Float" - consisting of dry coffee, super-ripe and almost dry fruits, called "raisin", badly-grated fruits, green and ripe fruits with only one developed seed. These conditions reduce the specific mass, causing them to pass to washers surface; ***CPW – Coffee peeling wastewater; ****CMW – Coffee mucilage wastewater; *****CFW – Coffee fermentation wastewater.
Source: Adapted from Borem (2015).

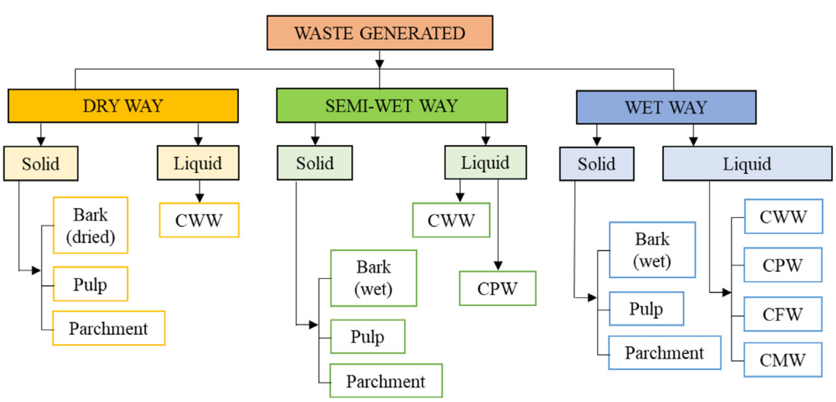

Fig. 3. Main residues generated summary in the coffee processing steps.
Source: Authors' computation.

crude fiber, and ash. Parchment can also be considered as waste, but much of it ends up being incinerated during the roasting of the coffee.

In Robusta coffees, the pulp contains more cellulose and tannins than in arabica coffees. Measures of acidity and solid material of ripe Arabica coffee fruits, variety Colombia, revealed the total titratable acidity of the pulp is equal to 11.4 mL NaOH 1N 100 g-1, 4.5 pH, and soluble solids content is 17% (Martín-López et al., 2003). The typical composition of Arabica and robust coffee pulps are shown in Table 2.

From the composition of the pulp, it is possible to infer CWW of wet and semi-wet processes have significant nutritional potential, especially in relation to dry processes.

2.2.2. *Liquid waste*

Liquid residues are those generated during processing, which is carried out with water; in the case of coffee, the use is quite significant. As already mentioned, liquid waste (coffee wastewater) can be classified as CWW, CPW, CFW, and CMW, been the dry way producing the only CWW; semi-dry way, CWW, and CPW; and the wet way can produce the four types of wastewater.

The first stage of post-harvest coffee is washing, which removes dirt's initial load and also promotes hydraulic separation of the highest quality fruits. These, in turn, go to the bottom and separate from those of lesser quality (also called "float" fruits) which emerge to the surface. CWW can be classified as water with the highest amount of dirt, as it is the

Table 1
Mineral constitution of coffee husk.

Compound (g kg^{-1})	Content (g kg^{-1})		
	(1)	(2)	(3)
C – total	529.5	–	–
N – total	14.7	13.2	18.8
P – total	1.7	0.5	2.1
K	36.6	31.7	47.0
Ca	8.1	3.2	3.0
Mg	1.2	–	2.9
S	1.4	–	–
Mn	125.0	–	–
Zn	30.0	–	4.4
Cu	25.0	–	18.7

Source: Adapated from Matos et al. (1998) (1), Vasco (2000) (2) and Brandão (1999) (3).

water that will first come into contact with freshly harvested fruit. That way, it can carry sand, earth, stone, leaf, pieces of soil, pieces of wood, insects, microorganisms, pesticides, among others. On the other hand, a reasonable amount of nutrients from coffee can be found in this water. This amount can be increased if the coffee remains at rest in the wash tanks.

It is worth noting that during hydraulic separation stages, water consumption can be reduced, due to the implementation of recirculation and/or reuse of water in washers, especially mechanical ones, which is a practice commonly performed on coffee properties. This recirculation tends to increase the concentration in the washing water of the biotic and abiotic constituents present in the harvested coffee. Table 3 presents the physical, chemical, and biochemical characteristics of CWW for Coffea arabica and Coffea canephora.

As it turns out, the high BOD (Biological Oxygen Demand) and COD (Chemical Oxygen Demand) values indicate that CWW has a high organic load and, consequently, causes problems for receiving water bodies, if they are launched without prior treatment. Results by Beyene et al. (2012) revealed the ecological commitment of the downstream locations due to the direct discharge of high organic waste from the coffee processing industries in the nearby rivers. BOD measurements show that concentrations of oxidizable organic materials from coffee residues can cause almost complete deoxygenation of rivers and eliminate organisms sensitive to pollution for a long period of time. This fact reinforces the need to reuse this water in other sectors, given its high concentration of nutrients and its high polluting potential. Therefore, good agricultural practices, as well as manual harvesting, tend to reduce this incidence, since the fruits harvested in this way tend to have a lower load of impurities such as stones, soil, sticks, leaves, which are components that can carry these organisms, thus reducing the amount of contamination in these waters. Impurities reduction made possible by manual harvesting allows the use of wastewater as a food ingredient or even as a drink, after heat treatment.

Regarding CPW, there is a higher concentration of particulates and compounds from coffee when compared to CWW. Since the coffee has been cleaned before being peeled, it is expected that this water will have less of the aforementioned dirt, and a greater quantity of components from fruit. This is because, in addition to peel, part of the pulp ends up being removed and diluted in the CPW, enriching it and making it more nutritious. This fact can be reinforced by Table 2, which presents the constituents of the coffee pulp, which, in most cases, can be diluted in water.

CMW may correspond to one of the waters with the highest concentration of nutrients, especially sugars, as it is related to the removal of mucilage attached to the grains. This occurs because the demucilator, which works with water, has strict control of the output of this component, being possible to control how much will be demucilated, which allows the generation of water with a higher concentration of nutrients as shown in Table 4. In other words, for the food industry, this by-product would be very interesting from a nutritional point of view, due to the high concentration of nutrients (mainly sugars), and from an economic point of view, as different from other wastewater, as it has less dirt; therefore, the industry would spend less to prepare CMW for use.

It is also important to emphasize the CFW, whose main characteristic is the lower pH, which characterizes greater acidity when compared to the others, a behavior expected due to the degumming processes (removal of mucilage by means of fermentation). According to Choussy (1940), Stern (1944) and Avallone et al., (2002), pH at the end of degumming varied from 4 to 4.5. For Lima et al., (2009), pH of the medium of the degumming process at the end of the process ranged from 3.8 to 4.5. Conforming to Stern (1944), coffee can reach the endpoint of degumming if the pH of the tank remains below 4.5 for a period of three h. As for Jackels and Jackels (2005), regardless of the time that fermentation may require or at which pH values it starts, a pH value less than 5.0 would indicate that the fermentation would be complete after 2 h. Similarly, a pH of around 4.0 would indicate that the fermentation

Table 2
Composition of Arabica coffee pulp and robust coffee.

Arabica coffee var. "Típica"[1]		Robusta coffee[2]	
Componente	Teor (dry basis) (%)	Componente	Teor (dry basis) (%)
Dry matter	93.07	Non-nitrogen extract	57.9
Carbohydrates *	74.10	Crude fiber	27.7
Non-nitrogen extract	59.10	Reducing sugars	12.4
Crude fiber	15.10	Crude protein	9.2
Crude protein	8.25	Pectic substances	6.5
Ashes	8.12	Tannins	4.5
Water content	6.93	Ashes	3.3
Tannins	3.70	Non-reducing sugars	2.0
Potassium	3.17	Lipids	2.0
Ethereal extract	2.50	Chlorogenic acids **	1.61
Nitrogen	1.32	Caffeine**	0.54
Caffeine	0.75		
Calcium	0.32		
Phosphor	0.05		
Chlorogenic acids **	1.1		

* Carbohydrates correspond to the sum of non-nitrogenous extract and crude fiber
** Clifford & Ramirez-Martinez (1991)
[1] Zuluaga (1999)
[2] Wibaux (1961).

Table 3
Results of physical and chemical analyzes of CWW samples.

Fruit	Recirculation	Water/fruit ratio	pH	EC dS m^{-1}	SDS mL L^{-1}	TS	SS	DS	TFS	TVS	COD	BOD	N_T	P_T	K_T	Na_T
						mg L^{-1}										
Canephora	No	-		0.259	17	1.069	380	689	390	679	1.520	411	77	5	41	26
Arabica	No	-	4.9	-	130	18.134	6.200	11930	3.546	14.588	-	-	-	-	-	-
Arabica	Yes/with dilution*	0.15:1	5.5	0.344	50	3.255	867	2.388	984	2.271	5.604	514	55	12	49	16
Arabica	Yes/with dilution*	0.15:1	5.5	0.599	80	5.038	2.430	2.608	898	4.140	6.583	1.887	75	15	77	23

pH - Potential Hydrogen; EC - Electrical Conductivity; SDS - Sedimentable Solids; TS - Total Solids; SS - Solids in Suspension; DS - Dissolved Solids; TFS - Total Fixed Solids; TVS - Total Volatile Solids; COD - Chemical Oxygen Demand; BOD - Biochemical Oxygen Demand; Nt - Total nitrogen; P_t - Total phosphorus; Na_t - Total sodium; Kt - Total potassium;

* dilution made by adding "clean" water whenever the water conditions became inadequate for the continuity of the hydraulic separation of the fruits. Source: Matos (2003) and Rigueira (2005)

would have ended two or three h earlier. According to the same authors, a fermentation for a very long period could result in a pH value equal to or below 4.0, which would cause greater difficulty in the industrial use of the washing water generated in this process.

Since CFW has a more complex constitution and a lower pH, both characteristics resulting from fermentative processes are believed that this water needs further investigation in relation to its constitution, in order to better direct its reuse and/or treatment for return it to the environment.

2.3. Perspectives of the coffee scene in Brazil

Brazil is the world's largest producer, presenting, in 2020, a harvest of 63.08 million bags, 27.9% higher than in 2019, a record within the national historical series of coffee production and an increase in cultivated area of 1.4%, totaling 2.16 million hectares. In this scenario, Minas Gerais remains the state with the highest production (34.65 million bags), followed by Espírito Santo, Brazil, with a production of 13.96 million bags and São Paulo with 6.18 million bags (Conab, 2020). This increase was influenced by the positive bienality effect, seen in most coffee producing regions in this cycle. The bienality effect consists of one-year alternation with large flowering followed by another with less intense flowering. The eradication of low productive areas, investment in technologies, and even favorable climate issues, are also important factors to explain such an improvement in overall performance (Conab, 2020).

When considering waste generation, Brazilian production in 2019 generated between 1,740,350 and 5,221,060 tons of water, considering only the washing process. Based the harvest increase of 2020, Brazil generated at least between 2,226,353 and 6,679,059 tons of water. These values were generated from the knowledge that 1L of coffee generates 170 grams of processed coffee, consuming between 0.1 and 0.3 L of water in the washing process. At world levels, global production in 2020/21 is estimated to rise by 1.9% to 171.9 million bags (ICO, 2021).

Although Brazil has the largest area dedicated to coffee production, Uganda is the country with the largest number of coffee growers (1.7 million) (Fig. 4), which shows the variability in the average size of coffee farms between countries. The reduction in the cultivated area in recent years, was accompanied by an increase in productivity, which results from the application of new technologies by producers. In Brazil, this reduction is a trend, followed by almost all producing states, with the exception of the State of Minas Gerais, which showed an increase in cultivated area between 2001 and 2020 (Conab, 2020).

Coffee prices have experienced a continuous downward trend since 2016, reaching values 30% lower than the average of the last 10 years, making small coffee producers have to struggle to cover operating costs, which continue to increase (ICO, 2019b; ICO, 2019a). As a result, there is a reduction in farm income and an increase in the risk of the livelihoods of coffee producing families, which generates severe economic and social consequences for countries producers (ICO, 2019b).

Lower coffee prices have a negative impact on the economy. In an online survey conducted by the International Coffee Council to measure the impact of low coffee prices in exporting countries, a 46% reduction in the time dedicated by farmers to coffee production and processing across Brazil, Colombia, Peru, Costa Rica, Cameroon, Papua New Guinea, Honduras, among others. Jobs in the field have also declined, with a 51% drop in Cameroon and 25% in Honduras. The social impact goes further, leading to an increase in food insecurity, with families reducing food consumption due to lower gains and reduced purchasing power. Added to this is the lower investment in health and education and the increase in poverty, reported by several producing countries, with variations depending on the importance of coffee as an income generating activity. Should the fall in prices continue, more and more producers will find it increasingly difficult to cover operating costs, aggravating the negative economic and social impact on poverty and the supply of quality coffee. In this moment of falling prices and income, the costs of inputs, such as labor, fertilizers and pesticides, have had

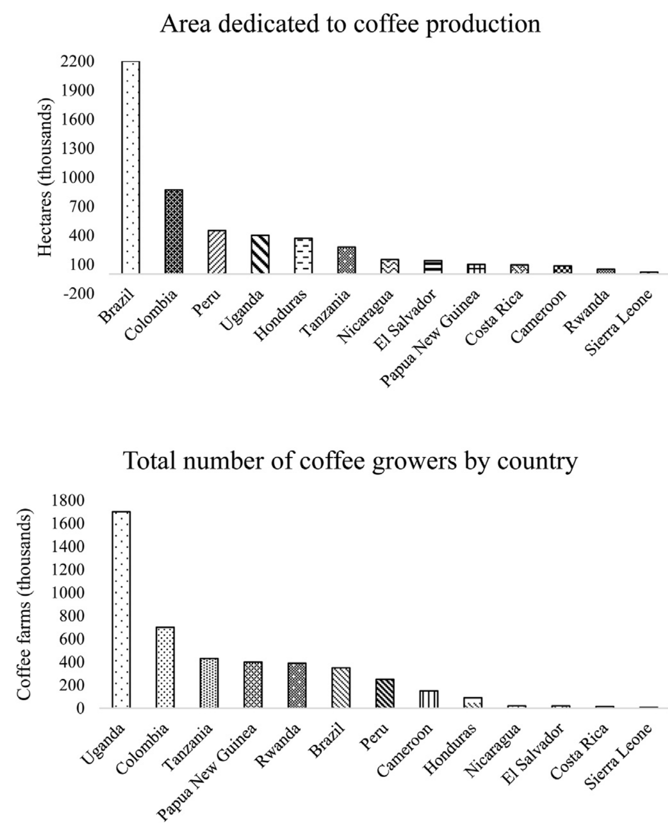

Fig. 4. Area dedicated to coffee production and number of coffee growers by country. The data corresponds to estimate for different years, depending on each country.
Source: ICO, 2019b.

Table 4
Results of physical and chemical analyzes of wastewater from peeling and demucilating coffee fruits

Fruit	Recirculation	Water/fruit ratio	pH	EC dS m^{-1}	SDS mL L^{-1}	TS (mg L^{-1})	SS	DS	TFS	TVS	COD	BOD	N_T	P_T	K_T	Na_T
Canephora	No	3:1	4.75	0.585	0	4.889	850	4.039	126	4.763	5.148	2.525	106	9	115	45
Canephora	1	3:1	4.1	0.718	180	5.504	1.888	3.616	706	4.798	10.667	3.184	125	11	154	58
Canephora	2	1.8:1	4.1	0.992	330	6.403	2.336	4.067	848	5.555	11.000	3.374	160	14	205	77
Arabica	No	-	3.5–5.2	0.55–0.95	0–45	2.100–3.700	-	-	370–530	1.800–3.200	3.430–8.000	1.840–5.000	120–250	4–10	315–460	2–6
Arabica	1	-	-	-	-	14.000–18.200	-	-	-	-	18.600–29.500	10.500–14.340	400	16	1.140	17
Arabica	Yes/with dilution*	3:1	5.4	1.090	850	16.507	2.647	-	1.406	15.101	18.680	6.384	168	23	157	46
Arabica	Yes/with dilution*	1.8:1	5.3	0.800	900	14.827	2.780	-	1.210	13.617	18.066	5.006	163	22	157	58

pH - Potential Hydrogen; EC - Electrical Conductivity; SDS - Sedimentable Solids; TS - Total Solids; SS - Solids in Suspension; DS - Dissolved Solids; TFS - Total Fixed Solids; TVS - Total Volatile Solids; COD - Chemical Oxygen Demand; BOD - Biochemical Oxygen Demand; Nt - Total nitrogen; P_t - Total phosphorus; Na_t - Total sodium; Kt - Total potassium; *dilution made by adding "clean" water whenever the water conditions became inadequate for the continuity of the hydraulic separation of the fruits. Source: Matos (2003) and Rigueira (2005).

a negative impact on the profit margin of coffee producers, with the importance of each input it depends on the productive system and the context in which the country is located (ICO, 2019a).

3. Sustainable trends for coffee waste

The generation of waste proved to be one of the intrinsic characteristics of forestry and agricultural production of greatest concern (De Oliveira et al., 2013). Between the years 2008 and 2013, the production of coffee residues in Brazil was estimated at 48% each year (Galanakis, 2017). These residues and by-products, rich in carbohydrates, proteins, pectins, bioactive compounds such as polyphenols, are a source of serious contamination and present serious environmental problems (Murthy and Naidu, 2012). In addition to the quantity, the chemical composition of residues and by-products of coffee activity makes them a source of contamination and a serious environmental problem (Torga and Spers, 2020).

According to Kourmentza et al. (2018), in the context of the circular economy, waste is perceived as a source for the recovery of high added value compounds and researchers from around the world are actively studying the reuse of coffee waste via physical-chemical or biotechnological routes (e.g., phytotechnology). Sources of bioactive compounds are among the most valued and used for different industries and fields, such as food, pharmaceuticals, or cosmetics.

Bonilla-Hermosa et al. (2014) used coffee pulp and wastewater as substrates for specific yeast strains to produce fruity/flowery aromas from fermentation. The authors perceived the potential for using coffee substrates in the flavor industry (pharmaceutical and food), mainly due to the potential to generate the odor of a rose, caused by the presence of 2-phenyl ethanol. Coffee washing water also stands out as a supporting manufacturing ingredient, especially with regard to its nutraceutical properties, which have been shown to facilitate the insertion of new functional foods based on coffee residues. According to Herpin et al. (2017), in addition to the possibility of recovery and use as a fertilizer, wastewater is rich in antioxidants in the coffee pulp, which can be used to produce molasses and cosmetic products. However, previous studies demonstrate that there are many controversies surrounding the bioactivity of coffee residues, their potential for synergy with plant species (e.g., microalgae), and the way they are managed.

3.1. Prospects for using coffee wastewater

The effluents from wet and semi-wet methods involved in coffee processing are loaded with organic matter and have high toxicity if they are discarded in water bodies, with serious consequences such as degradation of the level of oxygen in the water, which can kill practically all life water, clog waterways and further contribute to anaerobic conditions. This hostile environment favors the growth of health-threatening bacteria, generating a bad smell and dark appearance, caused by toxic chemicals such as tannins, phenolics, and alkaloids (Ijanu et al., 2020; Rattan et al., 2015). In this sense, the study of coffee wastewater clearance has been the subject of numerous studies, some of which are summarized below.

In a study by Pires et al. (2019), they evaluated the efficiency in assisted purification of coffee processing wastewater from the selected mixed wild microbial inoculum. They assessed efficiency from bacterial bio-increase in biological treatment of Coffee Processing Wastewater (CPW) at pilot wastewater treatment plant, based on Biochemical Oxygen Demand (BOD) and chemical demand for oxygen (COD) as indicators of treatment efficiency. As a result, the greatest reduction in BOD (∼ 33%) and COD (∼ 25%) was observed between 72 h and 8 days of biological treatment, and the greatest efficiency was related to spontaneous biological treatment of CPW by bio-increase of native microorganisms at the wastewater treatment plant on a pilot scale. This advance, according to the authors, ensures that the discharge of effluents into the environment would not have toxic effects on plants. Pin et al. (2020), aiming also to find new alternatives of disposal suitable for coffee wastewater, without contaminating the waterways or the soil, analyzed the production of biogas from the anaerobic digestion of coffee wastewater in Brazil. The authors observed the greater efficiency of biogas production when digestion with coffee wastewater and inoculum was carried out and concluded that improvements in preparation of the substrate could optimize the biomethane production, in order to define the "optimal standard" (quantity of water per quantity of beans) for processing wet coffee. Improvements in the structure of the microbial community and in the activity of nitrogen removal enzymes by bioaugmentation have also been proposed (Jia et al., 2019).

The microbial response mechanisms' identification and operational conditions optimization for the high-efficiency performance of toxic degrading compounds in anaerobic conditions are being studied and the potential of Acinetobacter in the caffeine degradation (harmful to the ecological system due to its recalcitrant property) in anaerobic condition was highlighted (Lei et al., 2019). In a study by Montoya et al. (2019), *Clostridium sp*. was the most important microorganism for co-digestion of coffee residues, and other indigenous microorganisms from the pulp, peel, and wastewater (e.g. *Lactobacillus, Saccharomyces*) also had a high metabolic potential for a wide variety of processing routes for waste coffee in acids, alcohols, and H_2O_2.

Ijanu et al. (2020) presented a review about current methods of treating coffee effluents, proposing the most appropriate technology and the type of spring that takes into account all parameters of concern (effectiveness, availability, accessibility, and being environmentally friendly) for each treatment. According to the authors, methods of physical-chemical treatment of industrial wastewater have been preferred when compared to biological treatment, due to their ability to break down complex compounds in wastewater to degrade organic materials in a relatively short period of time in a controlled environment, in addition to a better efficacy in the treatment, removal of color or other acidic components of coffee wastewater. Ferraz and Yuan (2020), using used coffee grounds activated carbon, observed excellent performances in the actual treatment of leachate in landfills, with more than 90% of color and COD removed, proving their efficiency in synthetic wastewater and real leachate.

Among the current physicochemical methods (valiant zero iron, photo-Fenton, ultraviolet radiation with ozone and electro-oxidation) and biological methods (expanded bioreactor for granular sludge bed, coagulation and chemical flocculation, electrochemistry, and adsorption) used in the management of wastewater from coffee, the authors suggested the ion exchange technique as a better alternative in the coffee wastewater management, considering its ability to act as an ion exchanger and absorber, in addition to the fact that the use of the ion exchange technique, which is a cheap, effective and environmentally friendly treatment process.

According to El Achaby et al. (2019), coffee pulps (CP), rich in cellulosic compounds, could be used to remove dyes from wastewater, but their use is still not valued. The authors reported there are some efforts to valorize CP residues as compost, for composting, vermicomposting, biogas generation, and also the production of pellets for heating, but only a small fraction of the CP waste generated during processing of coffee is used. In this sense, these authors aimed at the future growth of the use of cellulose in advanced applications extracted highly hydrated cellulose microfibrils (MFCs) from coffee pulps due to their attractiveness for the development of a sustainable and economically viable material. The coffee pulp residues were transformed into MFCs with exclusive morphology to be used as an adsorbent material in the methylene blue cationic removal dyes from concentrated aqueous solutions. The MFCs' special morphology and high-water capture capacity have proved to be promising adsorbents for the removal of dyes from industrial wastewater.

Galanakis (2017) emphasize the challenges faced by modern coffee industries include recovery of high added value ingredients, as well as recycling, through the new product generation which finds applications in several biotechnological fields, such as the pharmaceutical, food, or cosmetics industries. This is because the current cutting-edge handling of coffee processing residues includes poor practices that degrade substrate or lead to a reduction in its polluting load without advancing with high added-value ingredients and their applications.

3.2. Perspectives on the use of post-harvest coffee residues

3.2.1. Coffee peel

The coffee peels, the main solid by-product of dry processing, are usually used in animal feed, but the concentration of tannins, considered anti-nutritional factors, is limiting. Other approaches suggest the use of husks in fertilizers for composting or vermicomposting, as biosorbents for bioethanol production or caffeine extraction.

Among the global trends in the reuse of cherry coffee peels, Blinová et al. (2017) highlight their main applications as a substrate for biogas, alcohol production, cyanide biosorbents, for the removal of heavy metals and dyes from aqueous solutions, for dewatering of water, for lead and for ion exchange materials preparation, converted into fuel pellets or extracted to recover bioactive substances. For specific foods, these authors also point to the use of coffee husk as a substrate for the production of edible mushrooms or a functional composting ingredient in smoothies, granolas, and juices, as a source of caffeine and tannins in energy drinks, as a source of dietary fiber, development of food bars or ingredients in fermented foods due to their high amount of fermentable sugars. Its "naturally gluten-free" appeal is an important trend for celiac individuals. De Oliveira et al. (2013) highlighted coffee husks also provide low-cost, renewable, and underutilized residues, ecologically correct and potentially capable of generating heat, steam, and electrical energy. Its studied biomass showed chemical characteristics suitable for use as a renewable solid fuel for energy generation through thermochemical conversion. Cerda et al. (2017) also proposed the use of coffee husk as a wood-cellulosic substrate for fermentation as a promising technology that can potentially reduce the cost of cellulases, using residues as substrates in the production of bioethanol on a commercial scale.

3.2.2. Coffee Pulp

Biotechnological advances offer potential opportunities for the economical use of coffee pulp. This residue contains a certain amount of caffeine and tannins and is characterized by its high nutritional value (Londoño-Hernandez et al., 2020). Coffee pulp is rich in sugars, proteins, minerals, amino acids and also contains functional molecules of high industrial interest (phenolic compounds with antioxidant, anti-inflammatory, anti-mutagenic, antibacterial, and anticancer properties) (da Silveira et al., 2019).

The fermented coffee pulp has nutritional characteristics and can be used in animal feed (Londoño-Hernandez et al., 2020). Shenoy et al. (2011) also highlight that dry and wet coffee pulp can be potential sources of ethanol production; however, they emphasize this area deserves the attention of new studies and research.

3.2.3. Coffee grounds

Coffee grounds, the main residue generated in the extraction process for beverage preparation have been the focus of many studies. The use of sludge has shown good results in pest control, such as ants, and because of this, it has been considered a good alternative in organic production. In addition, due to its sandy nature, this material has been used in utensil development such as mugs, plates, and decorative objects.

In a review by Atabani et al. (2019), the authors state of the more than a thousand organic compounds presents in coffee grounds (proteins, carbohydrates, tannins, fibers, caffeine, cellulose, non-protein nitrogen, fatty acids, amino acids, polyphenols, minerals lignin and polysaccharides, galactomannans and arabinogalactans), 700 volatile compounds remain insoluble or and must be valued in different ways. The authors also pointed out that these components are of high quality, with organic and energetic content, and with proven superior physical properties. In addition, they were previously recycled in different ways to produce various types of biofuels, such as bio-hydrogen, biobutanol, biodiesel, fuel pellets, petroleum bio-fuels, bioethanol, biogas, and hydrocarbons or value-added products, such as bioactive compounds for the food industry, pharmaceutical, cosmetic and chemical and adsorbents for antitumor activities, composting, co-composting, vermicomposting, nano-composites, biopolymers, creams and scrubs, soaps and detergents, odor control, textile, easy preparation of pyrolytic carbon as the anode in the sodium-ion battery, inks and screen printing, yarn and paper and cellulose production, water retention capacity, oil retention capacity, emulsifying activity and emulsion stability.

Among the components found in the sludge, oil deserves to be highlighted. Oil extraction or other bioactive compounds is an alternative for immature or defective grains. Currently, unrefined oil extracted from coffee grounds is a raw material used in addition to the manufacture of soap, which partially resolves restrictions on the production of biodiesel (e.g., costs) (Jin et al., 2018; Lappeman et al., 2019). Although coffee beans are still underutilized as an alternative raw material for the production of biofuels and bio-chemicals, anaerobic digestion, compost, and biogas production, mushroom cultivation and recovery of bioactive compounds have been investigated as a way to stimulate their commercial viability (Kourmentza et al., 2018).

It is known microencapsulation attenuates the limitations of coffee antioxidants for food applications (Aguiar et al., 2016b). Polyphenols were efficiently extracted from coffee grounds, which could also be reused and converted into higher value-added products (Ramón-Gonçalves et al., 2019). In addition, some studies have been successful in using sludge as new raw materials with potential application in the food industry, such as: development of new powders from the mixture of ground coffee with concentrated whey (SCG), industrial waste coffee and cheese, with attractive technology to be used as a raw material in the stabilization of products with high fat content, emulsions, foods that require foaming, some products such as yogurt, ice cream and bakery products; protective effect on SCG particles, which allows the preservation of high-value compounds and supports the development of functional foods (Osorio-Arias et al., 2020); beneficial extraction of antioxidants from used coffee beans, wet, which allows its use as a future raw material for bio-based industries (Tongcumpou et al., 2019); nutraceutical sugars (eg manooligosaccharides) extracted from the SCG to be used as a food additive to improve health benefits (McNutt and He, 2019); use of parchment as a natural source of antioxidant dietary fiber, and bark and silver as a source of two food ingredients: aqueous extracts enriched in phytochemicals and antioxidant dietary fiber (Iriondo-DeHond et al., 2019); coffee flower use as a new resource for the production of bioactive compounds, melanoidins and bio-sugars in the production of healthy functional foods and drinks (Nguyen et al., 2019); spent espresso reuse as a sustainable source of fiber and antioxidants to enrich food (Severini et al., 2019); extract of coffee parchment residues in a gel gum film for food preservation due to its antifungal activity (Mirón-Mérida et al., 2019).

4. Challenges on the use of coffee wastewater and other residues

The effluent amount generated during coffee processing is quite significant, causing an environmental impact if it is not properly refurbished before being released into the environment. On the other hand, this effluent also has an expressive nutritive load, which allows its reuse for other purposes. Among the different physical-chemical processes that have a rare application in the management of coffee wastewater (anaerobic, swamp, advanced oxidation, coagulation-flocculation, fertigation, and adsorption), Collivignarelli et al. (2019) highlighted fertigation as the first choice of coffee effluent management for producing countries due to its low cost, additional nutrient value and ease of technological application. Even when using fertigation, pH correction is necessary for better crop results, since this effluent tends to have low pH values.

In addition, the high nutrient load of this effluent favors its employability in industries such as food and pharmaceuticals. However, other factors limit this use, such as the presence of dirt (e.g., soil and sand), carried mainly during the harvest and drying stage, in addition to the presence of microorganisms, pesticides, and toxins, mainly mycotoxins, which would not represent a barrier to its application in the textile and ceramic industries.

It is worth noting that adding value to CWW as a future perspective should not only prioritize the production of specialty coffees, as currently, the coffee buyer has one of the analyzed quality parameters, the question of sustainability practiced by the producer. Because coffee is very social, the producer knows the importance of sustainable practices, the adequate disposal of waste, the need to conserve water sources, manage and rehabilitate animals (e.g., the care of the Brazilian producer with the environment generates a consumption by those who export) (SIC, 2019). All of this reflects in the way in which the washing water will be seen as suitable for human consumption. In this sense, limitations and actions to mitigate barriers to the nutritional potential of washing water will be explained below, in order to expand its reuse.

The presence of fungi in fruits and coffee beans can alter product quality, considering that fungi have a very broad enzymatic potential. In addition, some species of fungi can produce toxins, such as so-called mycotoxins (Prado et al., 2000; Rocha et al., 2014). However, some species can still act as protectors against the invasion of other fungi and many rare species that do not produce toxins. Therefore, it is essential to identify fungi species that are associated with coffee and evaluate the interaction role of these fungal communities with each other and with the substrate to which they are associated, under specific environmental conditions. Thus, based on this information, one can anticipate the likely effects of these interactions on the quality of the final product with an emphasis on the safety aspect. In recent years, interest in studying fungal microbiota, potentially toxigenic, in coffee beans has increased in order to assess the concrete threats to compromise product safety (Matiello et al., 2015; Scussel, 2002).

Parallel to coffee wastewater safety, when considering the “extract” (concentrated water with nutrients from the fruit as indicated in Tables 3 and 4) and coffee husks, which today have potential use in various products such as food, the need for more research regarding the presence of these compounds, which are potentially harmful to health. And, if concentrations of compounds like mycotoxins are found above the safety level, it is necessary to develop and/or apply methodologies that manage to minimize the concentration of these toxins without changing the nutritional potential of these residues, in order to make them safe for consumers.

Unfortunately, the final product potential is not supported by solid information about the physical-chemical and microbiological reliability of the substrate. Köck-Schulmeyer et al. (2013) reinforce that reports on pesticides elimination during wastewater treatment are rare since these substances are normally considered to be of agricultural and non-urban origin, i.e., traces of pesticides may be present in coffee wastewater, at levels of toxicity sufficient to harm aquatic life, or even reach the consumer’s table. Phytotoxicity and cytogenotoxicity in coffee wastewater have been found in previous studies (Aguiar et al., 2016a).

In an investigation by Truzzi et al. (2020) aiming to find alternative breeding substrates of low cost and environmentally favorable for the growth of Hermetia illucens (HI) (Diptera, Stratiomydae) - which is used in human food - realized the inclusion of microalgae improved the residual peel’s nutritional value of the coffee and HI, due to the greater amount of lipids and proteins observed, demonstrating a way to enhance its use as an ingredient for the functional food market. Supramolecular solvents have also proved to be a viable alternative for the recovery of bioactive compounds from coffee wastewater and for use as an authorized food ingredient. In this case, its potential as an industrial ingredient stands out when its high caffeine recovery potential, good antioxidant capacity, stability at a temperature range of 4 to 24°C for the preservation of bioactive substances, and aid in the purification of wastewater (e.g., by improving its quality parameters, such as BOD, total suspended solids and conductivity) (Torres-Valenzuela et al., 2020).

Previous reports state the removal of the pesticide in wastewater treatment plants has already been shown to be unsatisfactory (Köck-Schulmeyer et al., 2013) and that coffee wastewater is released directly into the clay soil or into settling tanks for a later destination in soil, through fertigation, infiltration in the subsoil or surface drainage, without monitoring this effluent toxicity potential (Aguiar et al., 2016a). Alemayehu et al. (2019) reinforce that, due to the lack of economic and technological viability, the processing industries apply inefficient technologies to manage wastewater. What has been observed so far is the evidence of physicochemical methods, which are often able to eliminate complex compounds and do not leave chemical residues in the treated water. Dyes, for example, particularly nitrogenous ones, have complex aromatic structures and their degradation does not occur effectively with conventional biological treatment methods (Collivignarelli et al., 2019).

Barros et al. (2020) obtained a considerable removal of organic matter, reduced toxicity, and improved effluent biodegradability by treatment by Fenton oxidation and coagulation/flocculation, enabling its successful recirculation to the anaerobic reactor. Although the use of ozone in coffee effluents is recent, processes using ozone (O_3) and combined ozone and ultraviolet (O_3/UV) for removing color and degrading coffee wastewater have been shown to be effective in degrading caffeine and color wastewater, with differences in effectiveness in neutral and basic pH (Takashina et al., 2017).

According to Collivignarelli et al. (2019) there is a carcinogenic risk for humans if the water used for industrial purposes is wastewater treated by ozone since toxic by-products (e.g., BrO_3 and nitrosamines) can be formed from the reaction of ozone with biodegradable substances contained in WW. However, the authors reinforce the adequate dosage of O_3, as well as the addition of H_2O_2 to the O_3/UV process, allows to accelerate the ozone decomposition with the consequent increase in the production rate of the OH^* radical, optimizing the benefits provided by ozone treatment (for example, color removal from wastewater).

Further research on wastewater and its compounds at each stage of processing (for example, soluble dietary fiber, natural coffee sugars, antioxidants and flavonoids, colored chemicals) will be needed to mitigate negative ecological and economic consequences in the sustainability and bio-economy scenario.

5. Conclusions

Due to the current context presented by the coffee sector, with a tendency to increase in coffee consumption and a drop in international product prices, as a commodity, there is no doubt that a strategy should be devised in order to minimize the impact of high costs on producing families and maintaining the competitiveness of coffee. This can be done by placing the product in new market niches or using sustainability, with the residues from coffee processing being used to add value to the product. Both actions require innovative practices that place coffee at a different level. In this context, the proper destination of the coffee washing wastewater can be an alternative, both to mitigate the environmental impact, if it is disposed of without proper treatment, and to generate a source of extra income for coffee growers, when it is used as raw material for the food, pharmaceutical or cosmetic industries. In this case, more research will be needed to reduce bottlenecks in the use of this waste or coffee processing by-product and to guarantee the sustainability of the chain. The challenge to manage the water used in washing coffee residues is great and, according to Galanakis (2017), it is the bottleneck of facing the problem of environmental pollution and wastewater for sustainability. For this reason, the systematic treatment of this abundant by-product before disposal, in addition to the high degree of knowledge in processing in the management of large amounts of effluents with the potential to damage the environment, added to scientific knowledge in microbial biotechnology, pharmaceutical, and/or food technology, could overcome barriers to the use of wastewater as a versatile by-product. In addition, the proper management of coffee resting water, as well as knowledge of its composition and toxicity could help to identify solutions at the beginning of the processing chain, however, to date, there are no reports that have discussed “coffee resting water”.

Conflict of Interest

None

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