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REVIEW ARTICLE

Valorisation of the Residues of Coffee Agro-industry: Perspectives and Limitations

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Abstract: Over ten million tonnes of solid residues are generated yearly from coffee agro-industry worldwide, along with larger amounts of wastewaters and cultivation residues. Both wastewaters and solid residues, such as defective coffee beans and spent coffee grounds, along with coffee husks (pulp and mucilage) that constitute around 60% of the wet weight of the fresh fruit, represent a relevant source of pollution and environmental threat, particularly from the widely adopted wet processing of coffee berries. Several attempts have been done to re-use the coffee processing solid residues, which include direct use as fuel in farms, animal feed, fermentation studies, adsorption studies, biodiesel production, briquetting, pelletizing, tannin extraction and production of specialty commodities. For the re-use of wastewaters, biogas production and direct delivery on plantations have been proposed or adopted, along with the treatment through infiltration, irrigation or (anaerobic) lagooning, reed bed and aerobic lagooning. In this study, the possible alternatives for the re-use and valorisation of the coffee processing and plantation are critically reviewed, taking into account the experiences with other agro-industrial residues and wastewaters, in the frame of a sustainable agro-industrial development.

Keywords: Coffee processing, Solid residues, Wastewaters, Residue valorisation, Sustainable development.

INTRODUCTION

The gross amount of coffee (*Coffea arabica, Grevillea robusta* and the Ethiopia's natural *C. arabica* Harrar variety) produced in the world (2015/2016) was 8.598 million metric tonnes according to ICO [1], or 9.162 $\times 10^9$ kg according to the United States Department of Agriculture [2]. Therefore, just considering the top ten producing Countries (Guatemala 224.871 tonnes, Mexico 257.940, Uganda 314.489, Honduras 380.296, India 385.786, Ethiopia 423.287, Indonesia 814.629, Colombia 892.871, Vietnam 1.818.811, Brazil 2.859.502) yearly over ten million tonnes of (liquid and solid) residues are produced, to be disposed of. In the coffee-producing countries, the residues and the by-products of coffee berries processing such as defective coffee beans and spent coffee grounds, along with coffee husks (pulp and mucilage) that constitute around 60% of the wet weight of the fresh fruit, represent a relevant source of pollution and environmental threat [3 - 5]. A review of green coffee processing has been published by Ghosh and Venkatachalapathy [6]. Coffee silverskin and spent coffee grounds (SCG) are the main coffee industry residues [7]. Numerically, 1 tonne of green coffee generates about 650 kg of SCG, and about 2 tonnes of wet SCG are obtained as residue for each tonne of soluble coffee produced [8]. Over 6 million tonnes of solid residues were generated only as SCG in 2004 [9]. This amount excludes the residues from cultivation (pruning, leaves) whose amount is difficult to estimate due to the differences in agronomic management practices. The above figures of coffee residues are comparable to the amount of residues and by-products of another problematic agro-industrial commodity, namely the olive oil extraction residues, totalling in southern European Union 6.01 million m^3 (wastewaters) and 8.06 million tonnes (olive husks), respectively

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[10]. Between the two problematic residues, there are many more similarities in terms of environmental impacts, decontamination needs, possible re-uses as it will be discussed later in this paper.

For the solid residues from coffee processing, the applications proposed include the direct use as fuel in farms, animal feed, liquid and solid-state fermentation, adsorption, biodiesel production and the production of other minor industrial commodities. For the wastewaters, applications proposed include their direct application in cropped fields, biogas production, extraction of fine chemicals and production of valuable metabolites *via* chemical or biotechnological processes, decontamination *via* infiltration (*e.g.* in Colombia), aerobic lagooning or waste treatment plant, reed bed, anaerobic lagooning (*e.g.* in Costa Rica). For solid residues from coffee cultivation, leaves are used for making herbal teas, for the extraction of functional products, or left *in situ*. Coffee tree pruning's usually are left *in situ* to act as mulch or amendment, or are used as fuelwood, less frequently as bulking agent in appropriate composting processes.

The objective of this study is to critically review the possible alternatives for the re-use and valorisation of the coffee plantation and processing, in the frame of a sustainable agro-industrial development.

Coffee Processing and Composition

Coffee berries (Fig. **1**) are processed either by dry or wet processes (Fig. **2**), the former being adopted mostly (ca. 95%) for *C. arabica* in Brazil, Ethiopia, Haiti, Paraguay, partially in India and Ecuador, almost totally for *G. robusta* everywhere. Irrespective of the species or cultivar, wet processing is used commonly in Costa Rica, Colombia, Guatemala, Peru, Bolivia and Ecuador. In the dry process the coffee cherries are dried to about 10-11% moisture content. Drying can be accomplished by either natural or artificial methods. Then the coffee beans are separated from the covering layers (skin, pulp and parchment) in a de-hulling machine. The solid residues generated by de-hulling are called coffee husk. In the wet process, drying is not required. The skin and pulp are mechanically removed, generating a solid residue called coffee pulp. Then beans are fermented to remove the layer of remaining pulp material or dried directly to 12% moisture content. Finally the beans are de-hulled to remove the parchment.

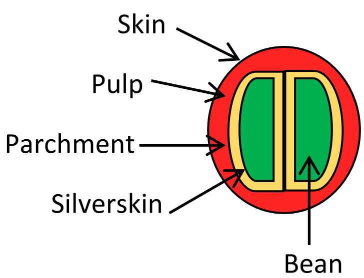

Fig. (1). Scheme of a coffee cherry.

Table 1. Yields of green coffee after dry and wet processing (modified from [4]).

Dry Processing						Wet Processing			
Coffee		*C. arabica*		*G. robusta*		Coffee		*C. arabica*	
Product	Moisture (%)	Weight (Kg)	Bulk density (Kg/m^2)	Weight (Kg)	Bulk density	Product	Moisture (%)	Weight (Kg)	Bulk density
Fresh Berry	65	100	616	100	645	Fresh Berry	65	100	616
Dry Coffee Berry	12	37.2	422	42.2	440	Dry Parchment Coffee	12	23	352
Green Coffee	12	19	650	22	750	Green Coffee	12	19	250

During the primary stage of dry processing, the solid wastes generated are the coffee husks and pulps, and the low-quality or defective coffee beans. Secondary processing leads to the production of roasted coffee and soluble coffee. The major solid residue generated during this stage is represented by the spent coffee grounds from soluble coffee production. Due to the high amounts generated during the two stages, these solid residues (*i.e.* coffee husks, defective coffee beans and SCG), having different water content and bulk density, are problematic in terms of disposal, and pose environmental concerns and specific problems associated with the type of residue. Coffee husks, formed by dry outer skin, pulp and parchment, are probably the major residue from coffee berries processing [11]: for every tonne of coffee beans produced, ca. one tonne of husks are generated during dry processing, ca. two tonnes during the wet processing, depending on the amount of water added. Defective beans represent over 50% of the coffee beans consumed, while SCG are produced at a proportion of 1.5 tonne (25% moisture) for each tonne of soluble coffee. This solid residue presents an additional disposal problem, since it can be used to adulterate roasted and ground coffee, being practically impossible to detect. The technical data of post-harvest processing are summarized in Table **1**.

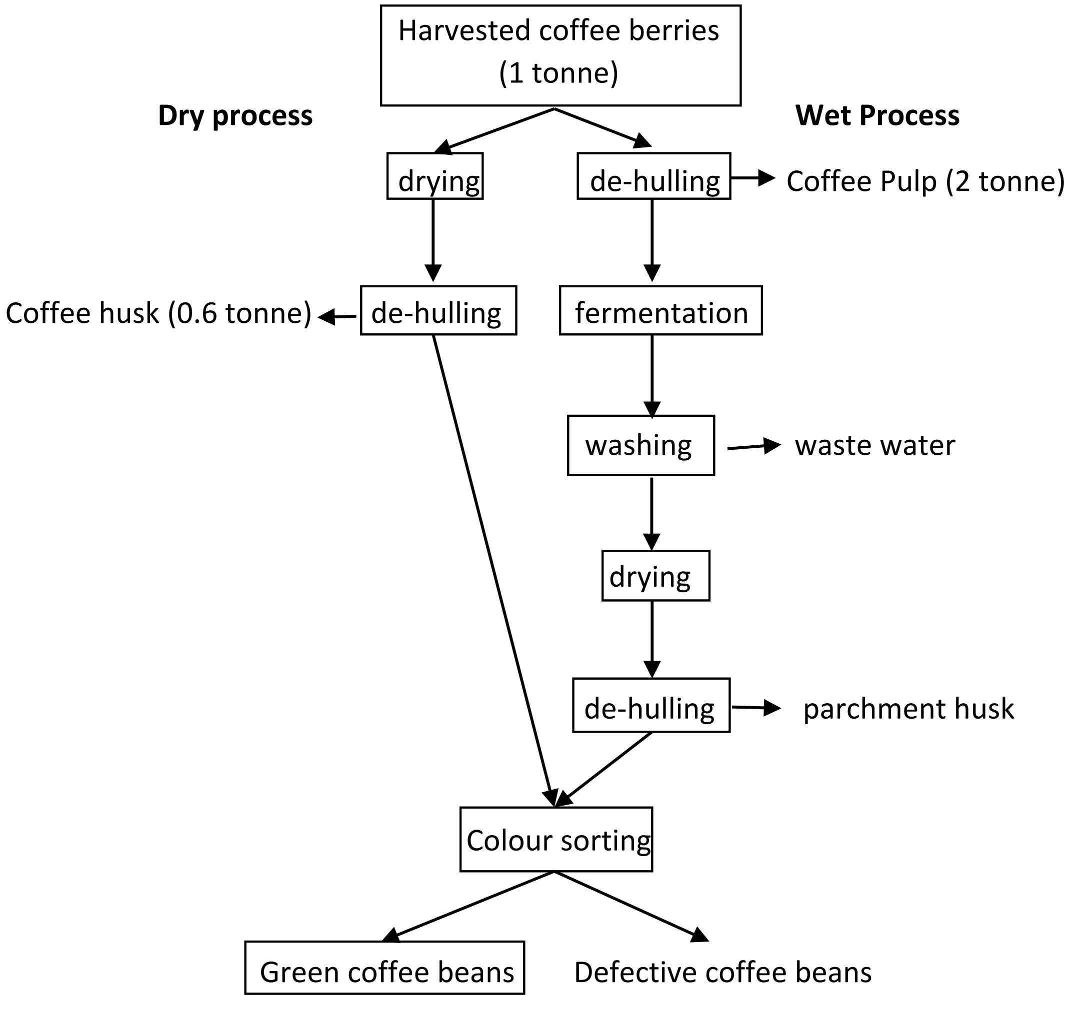

Fig. (2). Coffee processing and residues produced (adapted from Ghosh and Venkatachalapathy [6]).

According to Franca and Olivera [2] and Ghosh [4] green coffee beans are composed by carbohydrates (ca.60% w/w), namely insoluble polysaccharides like cellulose and hemicellulose, and soluble carbohydrates such as the monosaccharides fructose, glucose, galactose and arabinose, the oligosaccharides sucrose, raffinose and stachyose, and polymers of galactose, mannose, arabinose and glucose. In addition, there are non-volatile aliphatic acids (citric, malic and quinic acids) and volatile acids such as acetic, propanoic, butanoic, isovaleric and hexanoic acids. Oils and waxes account for 10-16% of the dry mass, along with proteins and free amino acids (10-11% w/w) and minerals (ca 4% w/w). The average composition of the coffee beans for the *Grevillea arabica* cv. Arabica and Robusta are shown in Table **2**.

Table 2. Average chemical composition of coffee beans (g/100 g dry weight) (modified from [7]) .

Component	*C. arabica*	*G. robusta*
Polysaccharides	49.8	54.4
Glucides	9.1	7.4
Proteins and aminoacids	10.3	11.3

(Table 2) contd.....

Component	*C. arabica*	*G. robusta*
Aliphatic acids	1.1	1.2
Chlorogenic acids	6.5	10.0
Lipids	16.2	10.0
Minerals (as ashes)	4.2	4.4

Residues Composition and Uses

The chemical composition of coffee husks and pulp does not differ dramatically, from a quantitative point of view, from that of coffee beans (Table **3**, [12]), except that there is lower content of lipids, different ratios among the glucidic fractions, and a higher content of minerals. However, both husks and pulp still contain caffeine, lignins and tannins. The first component is a bioactive compound, the latter two being recalcitrant to bio-degradation. The possible uses of the solid residues and wastewaters are briefly summarized in Tables **3** and **4** [13 - 21].

Table 3. Chemical composition of coffee husks and pulp (g/100 g dry weight).

Component	Coffee husk (Dry processed)	Coffee pulp (Wet processed)
Glucides	58-85	45-89
Protein	8-11	4-12
Lipids	0.5-3	1-2
Minerals	3-7	6-10
Caffeine	Ca. 1	Ca. 1
Tannins	Ca. 5	1-9

The coffee pulp can replace up to 20% of commercial concentrates in feeds for milking cows [22, 23]. For pigs, the replacement of cereals with dehydrated coffee pulp can reach up to 16% in the cereal feed. This, in turn, could spare for human consumption, or other uses, up to 50 kg of cereals at the end of one pig feeding cycle. In field trials in Brazil, the pigs fed with up to 15% ensiled coffee pulp and 5% of bagasse showed the same weight as those fed with commercial concentrates [21]. Similar results were obtained when feeding fishes, chicken, lambs and rabbits. The pulp has also been proposed for silage to reduce the meat production costs. However, due to the presence of caffeine, pre-treatments are needed which include repeated washings and the use of commercial inoculants to speed-up the fermentation process, making this alternative poorly feasible economically. Thus, to reduce the costs, animal feeding without pre-treatment is the more frequently applied technology, and could represent a possible re-use.

Table 4. Use of liquid and solid residues from coffee processing.

Residue	Production of energy	Other end-of-uses (agro-industrial commodities, decontamination processes)
Wastewater	Biogas	*Fertirrigation*, infiltration, lagooning (aerobic/anaerobic), reed bed
Pulp	Biogas, pyrolysis/gasification, combustion	Cultivation substrate (mushrooms), *compost, amendment, animal feed*, caffeine, tannins, alcohol, paper
Parchment	Combustion, gasification, briquetting, pelletizing	*Compost*, paper, polymers
Mucilage	Biogas	*Aerobic/anaerobic lagooning*, reed bed, infiltration, fertirrigation

Italics: Common uses.

The mucilages, and particularly the pulp, are also important for their content of polyphenols, antocyanins and bioflavonoids. The chemical extraction of these bioactive compounds has been proposed, to be commercialized as food “natural” supplement. Mucilages and pulp could be used as a source of pectin to be used as a substitute for fat in the preparation of emulsions such as those for salad dressing and mayonnaise, or to be used as soluble dietary fiber for humans. Raw unrefined pectins form thermo-soluble irreversible gels with distinct flavour [3]. The pulp is also used as a source of substrate for fermentation to produce alcoholic beverages [24]. The presence of caffeine is not considered an obstacle since this compound is often added to the beverages, and there are on the market liqueurs based on coffee, such as “Caffè Borghetti” in Italy or “Kahlua” in Mexico [3]. The natural sugars of the coffee berry, after the de-pulping phase, have a distinct fruity flavour, which might be of interest for food industry, once the single chemical compounds will be analytically identified. However, the large annual production of coffee berries and the fact that 80% of the fruit becomes waste during processing [25] poses clearly problems of decontamination or requires the re-use of large, yearly amounts of residues. The re-use of coffee by-products for cosmetic purposes [26] has been recently evaluated extensively by different research groups [27 - 32]. The results clearly suggest that coffee silverskin aqueous extract may be used for other applications, such as antiaging cosmetics and dermaceutics, due to the presence of anti-oxydant compounds, phenols and other bioactive components. However these potential uses, for cosmetics or industrial niche commodities cannot, though brilliant, cope with the accumulation of million tonnes of solid residues and wastewaters every year. In addition, there are components in the residues which are poorly degradable such as the tannin and lignin fractions, and decontamination tools must be put in place to alleviate the overburden of environmental impacts. The advantages and disadvantages of the uses of coffee residues are summarized in Table **5**.

Table 5. Advantages and disadvantages of the coffee husk and pulp utilization, and further developments.

Utilization	Advantages	Disadvantages	Research
Animal feeding	Coffee husk and pulp are rich in organic components, mainly carbohydrates, proteins and minerals that are present in the mesocarp of ripe fruits. It has been used as partial substitutes of animal feed amendments such as cereal grains.	The presence of tannins and caffeine diminish the acceptability and palatability of husk by animals. Caffeine has stimulatory and diuretic effects and tannins decrease the protein availability and inhibit digestive enzymes.	Some research studies have been done to remove these anti-nutritional substances, it include biological decaffeination with microorganism and silage. Silage presents and ideal method to preserve the material and partially reduce the contents of anti-physiological compounds. Coffee husk added up to 30% improve fermentative standard for silage of good quality increasing the protein content. Several studies have been done to evaluate their use as dietary supplement for cattle, swine, sheep, chicken, horses and fish. Good results have been observed with concentrations between 5 and 40%. Il all cases a saving of 30% is estimated. Animal feeding could represent a possible-re-use.
Growth substrate for mushrooms	Coffee husk and pulp could be used for edible and medicinal fungi production without any pre-treatment. Residues after fungi cultivation could be used to feed ruminants because caffeine and tannic acids decrease while protein increase (9%).	There are not large scale application probably because the cost of sterilization.	Development of detoxification pre-treatment of the substrate would help to obtain an entirely safe mushrooms production.
Silverskin for cosmetics and dermaceutics	Aqueous extracts may be used for the production of added value products, *i.e.* cosmetics and dermaceutics, beacause of the presence of anti-oxydants and bioactive substances.	This re-use can help in alleviating the environmental overburden of silverskin for limited global quantities of this residue.	The acquisition of preclinical data on the nutraceutical. benefits should be accompanied by safety assessment data in order to facilitate the authorization of these products for use in humans.
Spent coffee grounds for biodiesel production	Oil extraction with isopropanol and a mixture of hexane/isopropanol (50:50, vol/vol) allowed high oil recovery (21 %) at a relatively lower cost.	The quality of the obtained biodiesel, evaluated according the NP EN 14214:2009 standard, shows that biodiesel obtained is out of the standard limits for all the evaluated parameters.	Many improvements of the process need be developed to make it both technically and economically viable.
Ethanol production	Given the high concentration of carbohydrates in the coffee husk, this residue is viewed as potential raw material for bioethanol production.	Has not been adopted on a practical scale.	Many improvements of the process need be developed to make it both technically and economically viable.
Organic Fertilizers/ green amendments	Coffee husk and coffee pulp are rich in potassium and other mineral nutrients, which results in an organic/green fertilizer or amendment.	Disposal of coffee husk and pulp residues without treatment result in severe environmental problems including the proliferation of flies, foul odours, soil infiltration and others. Correct composting technology is seldom applied.	Appropriate composting and worm-composting provide a product that can be easily handled, stored, and applied to the land without adverse effects. However the voluminous supply of husks and pulp and the composting process currently used do not guarantee the destruction of the coffee borer that may be infecting some of the coffee pulp.

A relatively few studies have focused on the use of coffee husk and coffee pulp as a substrate for mushrooms production, among them *Pleurotus ostreatus*, *Lentinus edodes* and *Flammulina velutipes*. In all studies, the biological efficiency of fungi increased 40 to 97% in 60 days and fructification was observed after 20-25 days of inoculation [33 - 36]. With *Pleurotus florida*, 220 g of mushrooms were obtained after four flushes per 100 g of substrate in optimal conditions [17]. Caffeine and tannins concentrations of coffee husk decreased 60% and 70%, respectively. However, in some cases caffeine was found in the fruiting body indicating that it was not completely degraded. Nonetheless, the results obtained so far suggest the feasibility of using coffee residues as a substrate without pre-treatment for the cultivation of edible and medicinal fungi [30]. Residues remaining after the fungal cultivation have been proposed to feed ruminants as several toxic compounds decrease while the protein concentration increases (~9%) [34, 35]. There are no large-scale applications to date, probably because the elevated cost of sterilisation and inoculation in aseptic conditions [34].

Owing that some of the coffee residues have a high content of volatile solids and sugars, they can be considered potentially good feedstock for bio-digesters. However, methanogenesis can be hampered by the presence of toxic or non-biodegradable compounds such as saponins and lignins, thus requiring pre-treatments [37]. The use of actinobacteria such as *Streptomyces* has been suggested as a pre-treatment to minimize the content in polyphenols, which are known to act as antimicrobial compounds [38]. Some studies carried out in Tanzania suggest high methane (CH_4) yields from coffee residues: 650 m^3 CH_4/tonne of volatile solids for *Grevillea robusta* solid waste and 730 m^3 CH_4/tonne of *Coffea arabica* solid waste. Case studies on the coffee processing factories indicate that exploitation of the residues for the production of electricity on site is feasible [39]. Although several attempts were carried out as early as in the 90's, the technology of bio-gasification is far from being adopted on a large scale. Feasibility studies indicate that slurries containing 20% (w/v) coffee waste solids can be treated anaerobically in one and two-phase thermophilic methane fermentation systems at 53°C without discharging anything but the coffee waste residues [40]. Biogas could be produced by the co-digestion of coffee-pulp and cow-dung mixture under solar radiation [41]. From the first month of co-digestion at mesophylic conditions, methane content in the biogas attains 50% of the yield. This content increased up to 60% and remained almost constant for at least eight months of further digestion. Unfortunately combustion emission of the biogas contain several components like CH_4, C_3H_8, CO, SO_2, HI, and probably Br_2 which are strongly harmful to human and animal health (for the presence of isocyanic acid and bromomethane in the biogas). These results indicate that if the biogas is to be considered as a fuel, the conventional combustion technology has to be upgraded to prevent these hazardous emissions to the atmosphere.

Coffee tree is widely used as a firewood for domestic use, particularly in small coffee farms, or it is sold for firewood as whole trees and logs, providing a range of flexible uses and therefore yielding the highest returns per household. In Kenya there is a heavy reliance on *Grevillea robusta* to respond to market demands for firewood and timber [42]. Diversification of fast-growing species would enhance farmers' product options and the sustainability of the landscape. However, in several Countries the farmers' tree planting activities are limited by the lack of coordination of germplasm supply, leading to a limited diversity and quantity available at farm level. Though varying among countries, the yields of firewood per ha from annual prunings of coffee bushes can be significant: as an example, in Costa Rica [43] the yield ranged from 121 kg to 1.6 tonnes/ha for plantations with less than 3.800 coffee bushes (low density) per hectare; for plantation with more than 3.800 coffee bushes/ha (high density) the range was wider and covered 288 kg to 2.9 tonnes/ha. The amount of firewood produced had no strong correlation with the plant density. lndications exist that coffee fuelwood yield is more strongly correlated with pruning intensity, which on its turn depends on the management practice adopted by the farmer.

Recently [3] a multi-stage bio-refinery concept has been hypothesized, with the potential to convert waste produced at crop processing operations, such as coffee pulping stations, to valuable biofuels and bio-products using biochemical and thermochemical conversion technologies. The bioconversion stages use the yeast *Kluyveromyces marxianus* to produce bioethanol from sugars, *Yarrowia lipolytica* to produce bio-based ammonia for fertilizer, and peptides and free amino acids for animal feed. The lignocellulosic fraction would be treated to release sugars for fermentation in a third stage, while the residual protein and lignin solids can be jet cooked and passed to a fourth-stage fermenter where another yeast, *Rhodotorula glutinis,* would convert methane into isoprenoid intermediates. The mixed residues would be transferred into pyrocracking and hydroformylation reactions to convert ammonia, protein, isoprenes, lignins, and oils into renewable gas. The remaining waste could be thermo-converted to biochar as a humus soil enhancer. This interesting integrative vision of multiple technologies for the treatment of coffee waste has the potential to contribute to economic and environmental sustainability of the process, though its accomplishment would necessarily depend on the size of the coffee pulping installations, their localization in a country, their economic robustness and the variety of expertise involved. Moreover, most of the technologies proposed need to be fully developed yet at industry-level, assessed for safety-related aspects, and evaluated by using Life Cycle Management tools to uncover the end-of-use impacts and the overall real sustainability in coffee-producing countries. The requirement for a sustainable coffee industry, and the subsequent need for the development of methods for the utilization of coffee by-products has been stressed also by Cholakov [44]. Among these tools, the preparation of renewable fuel additives (*e.g.* biodiesel) and carbon adsorbents is a promising alternative to the eventual dumping of biogenic substances, harmful to the environment. The actual commonly adopted use of coffee husks is the treatment in coarse ovens to dry out the coffee and obtain the parchment, in addition or in alternative to sun drying, or burning the partially dried husks in a gas generator coupled to a power converter. The residual heat may be used to dry out more coffee. The use of coffee pulp for the production of briquettes and pellets for heat generation has recently been proposed [14]. The study included pulp drying (using air, solar and hot air methods); the production of briquettes and pellets; the evaluation of their energy, physical and mechanical properties; and the evaluation of pellet quality using X-ray densitometry. The results clearly show that hot air drying coffee pulps is the best option for coffee residues because of its low drying time. The physical properties of the pellets and briquettes comply with most of the standards established for these products. A negative aspect of the pellets is that their durability failed to comply with some requirements specified in the literature, because of the presence of cracks which may affect the pellet quality. In another recent study, briquettes made from fat dregs mixed with coffee residue were shown to be easy to ignite, left no stains on hands, burned for a long time, and had good heat output. These briquettes did not give off sparks and had less smoke and ash content than those of charcoal they normally used [45].

Finally, the solid residues of coffee processing are very often disposed into arable land and surface water leading to environmental pollution, although their physical-chemical traits represent an ideal substrate for making excellent fertilizers. Moreover, when the bio-transformation process, namely composting, is carried out particularly at small-scale coffee farms, mostly is made in uncontrolled conditions (or just adding animal manure) giving rise to immature, non-humified and non-sanitized amendments. Bioconversion processes in controlled conditions, with the addition of plant material and/or microbial starters and/or chemical fertilizers, have been published [46 - 48] sorting beneficial effects [49]. The polyphenolic compounds can be removed prior to composting in solid-state fermentations, if considered desirable or economically profitable [50]. Very similar experiences have been described for another agro-industrial commodity, *i.e.* the olive oil. To extract olive oil from olives (15-20% w/w) the Countries of Mediterranean basin, totalling 94% of the world production, which includes the three major producers, *i.e.* Spain, Italy, Greece (totalling 86% of the world production), face every year problems surprisingly similar to those of the coffee production and extraction: vast amount of residues, both solid (olive husks) and wastewaters strongly impacting the environment, recalcitrant to biodegradation. Also the possible, alternative uses of wastewaters and solid residues of olive oil extraction are very similar to those described for coffee, including [10] thermo-chemical processes, *i.e.* combustion, pyrolysis or gasification; anaerobic digestion; alcoholic fermentation; blending and chemical extraction; agronomic: direct application by land-spreading, usage as animal feed, composting and subsequent field usage as soil amendment, the re-use for the production of industrial niche commodities and green amendments. These similarities should allow to comparatively evaluate the impacts and the possible exit strategies for the disposal coffee residues, particularly taking into account and comparatively assess the impacts of the various transformation processes. In fact, the main uses of olive virgin husks and waste waters in the Mediterranean basin are power generation, domestic heating and composting, the latter process leading to a high-quality, deeply humified “green” fertilizer without the addition of animal manure, at both industrial [51] and farm level [52]. The use of this amendment has an environmental impact 2-4 times lower than the use of the husks for the production of electricity and house-hold heating, generates beneficial effects on the quality of horticultural products, can substitute for turf in the preparation of cultivation substrates. The latter findings have been calculated using the tools of Life Cycle Impact Assessment [10]. If the correct composting strategy of the coffee residues could be implemented at a larger scale also in small farms, it could help minimize the eutrophication effects of nutrient leaching in soil, avoid lagooning of large volumes of wastewaters, and provide the ecosystem with more stable, humified organic carbon. The latter aspect is particularly relevant in those fields where biodiversity is a conservation goal and where soils need to restore their fertility through the maintenance or increase of organic matter above the threshold of 3.5%, which is the minimum to maintain the soil functional biodiversity.

CONCLUSION

The coffee production and processing generates waste amounts of liquid and solid residues, second by quantity only to traded petroleum industry, and similar to the amounts of another agro-industry, namely the residues of the olive oil extraction production and processing. For coffee, the vaste amount of residues encompasses the yearly generation of environmental and agricultural problems. These should be faced and properly assessed, also in terms of Life Cycle Management options. For a minor part of the global amount of residues, there are different possible re-uses, often technically feasible. These include the animal feeding through silage to increase the protein content of the dietary supplement, the use of coffee husk and pulp for edible and medicinal fungi production particularly where detoxification pre-treatments of the substrate are available, and the possible use of silverskin for cosmetics and dermaceutics.

For the majority of the global amounts of residues, the environmental and agricultural problems could be circumvented by the application of recently developed technologies spanning from bio-gasification and biodiesel production to composting. For the first two, many improvements of the processes need to be developed to make them both technically and economically viable. For composting, an increased use of green amendments produced on-farm from coffee residues would help in minimizing the deleterious facets of residue disposal, *i.e.* transportation to (long) distance, decontamination costs, and environmental impacts. In addition, the use of compost could help in maintaining the carbon stocks in the cultivated soils in the frame of a regenerative agriculture.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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