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# A comprehensive analysis of operations and mass flows in postharvest processing of washed coffee

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ABSTRACT

Although coffee is one of the most valuable and widely traded agricultural commodity in the world (US$83 billion in 2017 revenue), little information exists in the scientific literature regarding coffee bean postharvest processing. In particular, sustainability analyses require information on the coffee bean mass and property changes during processing, from harvest to final consumption. In this study, a detailed analysis of the washed or wet-processed method for coffee postharvest processing is provided. Mass flow data were collected through site visits, surveys, laboratory measurements, and interviews with coffee wet and dry mill operators in several countries throughout Central America and Mexico, as well as roasters and cafés in the United States, to establish representative mass flow rates and process flow diagrams from harvest to cup. Results indicate that 100 kg of harvested coffee cherries will on average yield 2.6 kg of mass consumed by humans as exported coffee, equivalent to approximately 839 metric cups (250 ml) of drip brew coffee or 897 metric shots (30 ml) of espresso. The remaining 97.4 kg provide opportunities for development of alternative products, and other economic uses. Importantly, the data suggests that more mass is lost during depulping in practice than previously indicated by laboratory measurements. This study provides a foundation for further investigations in the fields of equipment improvement, byproduct utilization, and environmental and economic sustainability of the coffee processing and distribution chain.

## 1. Introduction

Coffee is one of the most valuable, widely traded, and consumed agricultural commodity at an estimated US$200 billion per year total industry value (Samper et al., 2017), which generated around US$83 billion in global revenue in 2017 (Voora et al., 2019). For the producing countries, the total green coffee export value including the production and postharvest phases, is around 10% (US$20 billion per year) of the total yearly industry value (Samper et al., 2017). The coffee industry supports the livelihoods of around 125 million people, especially in developing countries (Fairtrade Foundation, 2020). Over 100 coffee species exist, but only two are economically important: Arabica (*Coffea arabica*) and Robusta (*C. canephora*), representing about 60%, and 40% of global production in 2018, respectively (De Castro and Marraccini, 2006; ICO, 2020b). In the context of specialty coffees, Arabica is almost exclusively preferred due to its superior flavor (Chambers et al., 2016). On average (2015–2019), 9.5 billion kg of green coffee were produced annually. Of that, Latin America produced 59%, Asia 30%, and Africa 11% (ICO, 2020b). Coffee is then roasted, distributed and mostly consumed in developed or industrialized countries (20% in the United States) (Dicum and Luttinger, 1999). Generally, coffee is produced either by large high-tech agribusiness operations (<1% of farms, 5–10% of global production), family owned estates (<5% of farms, 30% of global production), or smallholder farms of 50,000 $m^2$ or less (95% of farms, ~60% of world production) (Browning and Moayyad, 2017). Despite coffee's popularity, most producers face economic uncertainty

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and poverty, while key aspects of the environmental and economic sustainability of the coffee industry are in question. These challenges include the coffee plant's lack of resilience in warmer temperatures, and diseases such as coffee rust (*Hemileia vastatrix*) (Davis et al., 2019).

Surprisingly, limited scientific research has assessed the unit operations and mass flows associated with coffee postharvest processing, from harvest to cup, especially in English language scientific publications. Coffee postharvest processing, which is mainly performed in production countries, requires a significant amount of work to convert a freshly harvested coffee cherry (fruit) into a finished beverage, and generates high mass flows of byproducts. While these byproducts (e.g. coffee pulp), often result in pollution that add mitigation costs to producers (Chanakya and De Alwis, 2004; Coltro et al., 2006), there are also opportunities for alternative economic uses, such as energy production, chemical compound extraction, and the production of industrial products (Esquivel and Jiménez, 2012). The global scope of the coffee sector complicates a robust elaboration of mass flows across the processing and supply chain. Postharvest processing of coffee occurs across vast divides in geography, corporate entities, culture, and language. Thus, efforts to improve economic and environmental sustainability must evaluate this complex supply chain in its entirety.

Therefore, this study provides a detailed analysis and description of Arabica coffee postharvest processing, roasting, and brewing, focused on the washed or wet-processed method. The study's first objective is to provide a detailed description of the washed coffee method in terms of a process-flow diagram, as commercially conducted in representative Central American and Mexican commercial wet and dry mills, as well as US roasteries and cafes. This process flow diagram informs on necessary equipment to process the coffee from harvest to consumption and where and how byproducts are produced. The second objective is to provide postharvest mass flow data to inform efforts aimed to increase equipment performance and the overall economic and environmental sustainability, providing a framework for further studies.

In Section 2 of this article, general background information is provided, including the composition of a coffee cherry, a detailed description of unit operations in the coffee postharvest washed (or wet processed) method, and a scientific literature review. In Section 3, data acquisition (i.e., survey – Appendix A) and statistical methodologies are discussed. In Section 4 the resulting process flow diagrams, and specific mass flow calculations are presented. Finally, Sections 5 and 6 include a discussion of the main conclusions and implications for improving coffee sustainability. In addition, a detailed English / Spanish / Portuguese glossary of common coffee post-harvesting terms is provided in Appendix B to assist international readers.

## 2. Background

### 2.1. The coffee cherry

A coffee cherry is composed of six distinct layers (Eira et al., 2006; Murthy and Madhava Naidu, 2012), as seen in Fig. 1. First, the outermost layer, known as the skin (exocarp), is thin (~0.5 mm) and has a tough, smooth surface. The skin matures from green to either red or yellow (less commonly orange) depending on the coffee variety. Second, a yellowish-white, soft, juicy, and sweet fruit flesh (outer mesocarp). Together, these two layers are referred to as pulp and are composed of carbohydrates (35–85%), soluble fibers (30.8%), minerals (3–11%) and proteins (5–11%) (Iriondo-DeHond et al., 2019). Third, a layer that strongly adheres to the interior layers after depulping is called the mucilage (inner mesocarp). The mucilage is mainly composed of water, protein, sugar, pectic, and ash (Esquivel and Jiménez, 2012). This layer surrounds and binds the coffee beans (seeds) together and it is removed either through anaerobic degradation (fermentation) or mechanically (Illy and Viani, 2005). The fourth layer is the parchment, a papery fibrous shell that covers the underlying layers. The parchment is mainly composed of (α-) cellulose, hemicellulose, lignin, and ash (Iriondo-DeHond et al., 2019). When mechanically removed in the dry mill, the parchment is referred to as the coffee hull. The fifth layer is the silverskin (epidermis), a thin, delicate, closely held layer that envelops the final layer (the green bean). It has a high fiber content and also polysaccharides (mainly sugars), protein, fat, and ash (Iriondo-DeHond et al., 2019). This layer becomes chaff during the roasting process. The innermost or sixth layer, is the endosperm, commonly known as green coffee.

The primary goal of postharvest processing in coffee-producing countries is to remove the first five layers and enough water to obtain an exportable green coffee bean at around (10 to 12)% wet basis moisture content ($MC_{wb}$). Typically, a single cherry contains two beans, but in 5–10% of cherries only one bean forms (peaberry), and similarly rare, three beans may form (Suhandy and Yulia, 2017). Finally, the

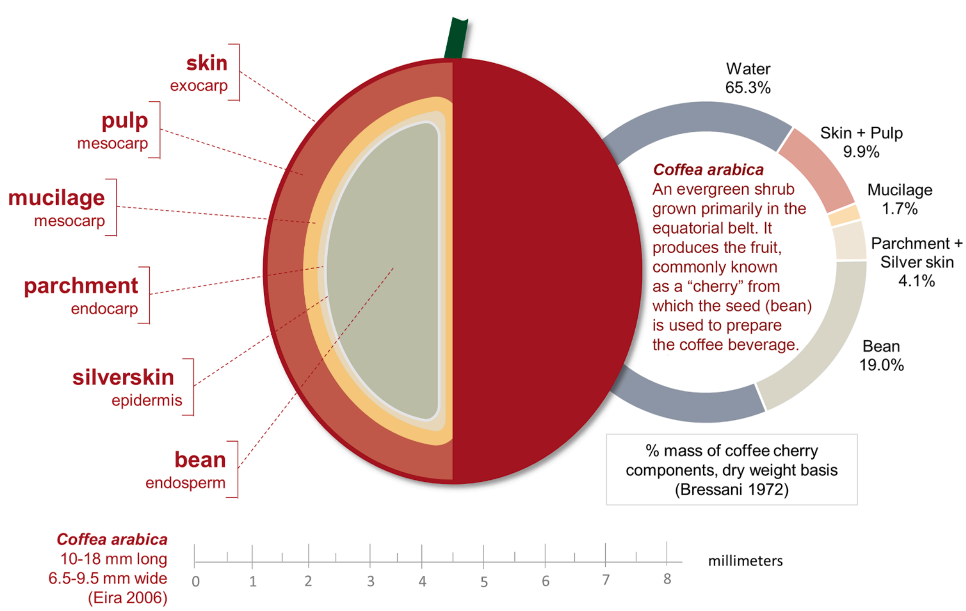



**Fig. 1.** Composition of a coffee (Coffea arabica) cherry, describing layers with botanical terms, typical size, and percent of mass on a dry-weight basis, as reported by Bressani et al. (1972). For interpretation of the references to color in this figure, the reader is referred to the web version of the article.

green coffee beans are roasted, ground, steeped in water and the extracted soluble solids are consumed in a coffee beverage (Illy and Viani, 2005). The primary chemical constituents of the coffee bean are cellulose-like polymers, minerals, sugars, lipids, tannin, polyphenols, proteins, acids, and caffeine (Mussatto et al., 2011). Although caffeine is found throughout every layer in the coffee cherry, its concentration is the highest inside the bean, ranging from 1.1 to 1.5 g/100 g dry matter (dm) basis(Duarte et al., 2010; Iriondo-DeHond et al., 2019).

### 2.2. Methods for processing coffee cherries

There are at least four primary methods for processing coffee, with

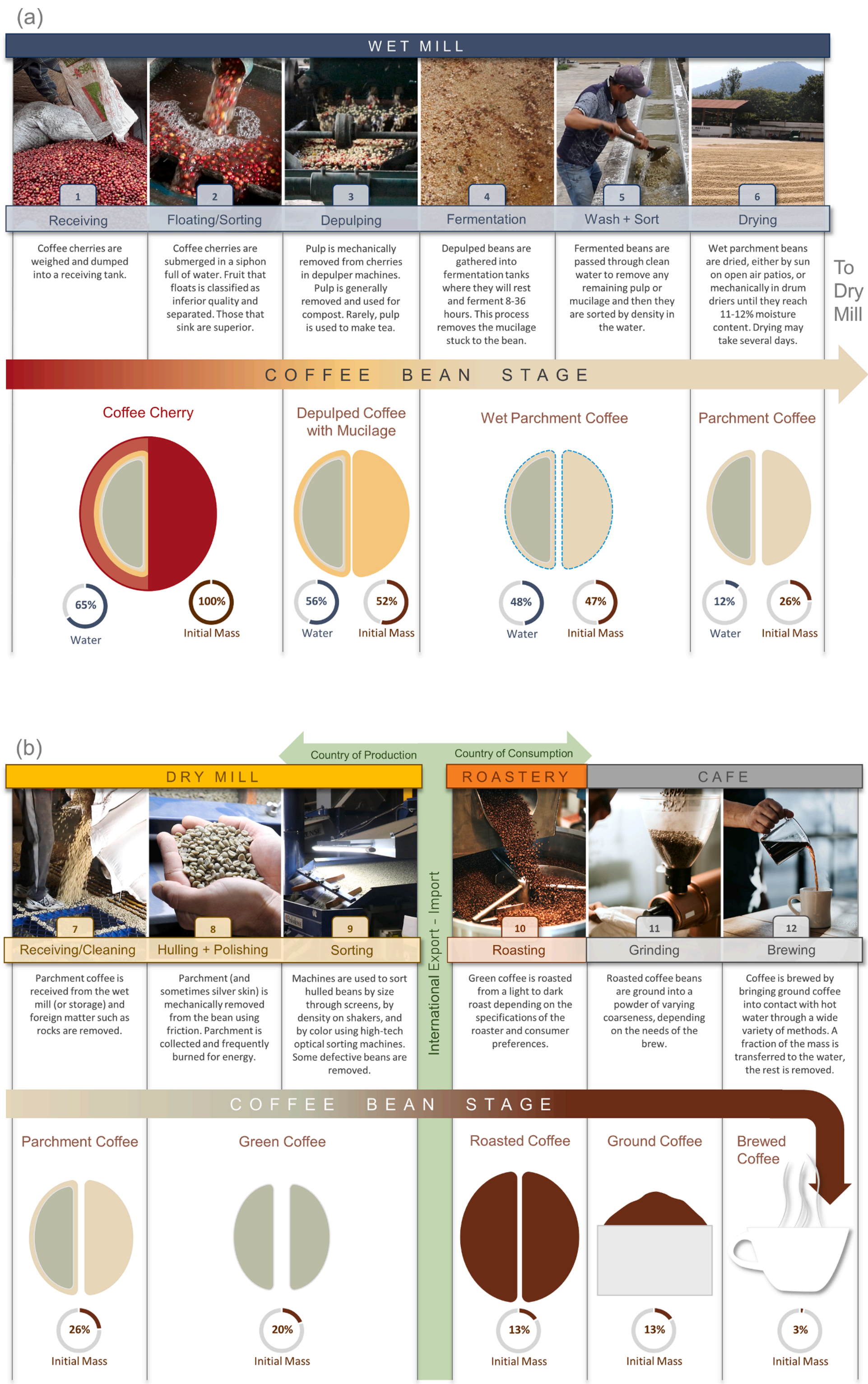



**Fig. 2.** 'Washed' processing method for coffee, describing important operations taking place in (a) the wet mill, (b) dry mill, roastery, and café phases of postharvest processing. Mass and water content as reported in Section 4.1 are displayed at the bottom. For interpretation of the references to color in this figure, the reader is referred to the web version of the article.

many variations on these. Each processing method has been adapted to the location where it performed, largely determined by environmental and economic factors. The washed method, which uses the most water, is more commonly applied in the areas of Central America, Colombian, Mexico and other regions where water and hand labor are readily available, and where partial sun drying is feasible. Although they fall outside the scope of this study, the natural/dry (e.g., Ethiopia and Brazil) and honey/semi-dry (e.g., Tanzania) methods are more common in semi-arid regions where water is less reliable and where sun drying is more practical. The wet-hulled method, on the other hand, is an adaptation to high ambient moisture conditions (e.g., Indonesia) as it reduces the amount of patio/sun drying time by removing every layer from the bean before drying is complete (Evangelista et al., 2015). The processing method applied is an important, though certainly not exclusive, source of flavor and quality in the final product.

### *2.3. Operations in the washed method*

The washed or wet processing method represents a significant percentage of World coffee production and it is the dominant method in Colombia, Central America, Hawaii and other regions throughout the world (Silva et al., 2000). The washed method has four primary phases: 1. the wet mill, 2. the dry mill, 3. the roastery, and 4. the café, which represents the point of coffee preparation for final consumption. The washed method is summarized in Fig. 2.

#### *2.3.1. Operations in the wet mill phase*

*2.3.1.1. Harvesting.* During the harvest, on farms where handpicking is performed, trained pickers select only those coffee cherries at the ideal maturity level, determined by color (depends on variety), detachment force (8–10 N), and/or °Brix (13–15) (Martínez et al., 2017). Immature (typically green-colored), off-colored (dark brown to black), shriveled, and dry coffee cherries may be hand sorted in the field and transported to the wet mill in a separate container. Upon arrival at the wet mill, the same day as harvest, the following operational steps take place (Fig. 4a).

*2.3.1.2. Receiving.* Coffee cherries are weighed and then dumped into a receiving tank where they are transported by any combination of water rails, augers, or conveyor belts to the next processing step. To properly trace each harvest lot, immature and off-colored coffee cherries, different varieties, or coffee cherries from different farms are usually processed separately.

*2.3.1.3. Floating (primary or initial density and size sorting).* Coffee cherries are typically immersed in a water siphon separator, where foreign matter (leaves, twigs, and other debris) is removed due to its proclivity to float. Coffee cherries that sink then pass through a destoner, which removes heavy foreign matter such as small stones, and then continue to the next step in the form of clean coffee cherries (generally known in Spanish as *Primeras*). Foreign matter is disposed either as garbage or organic matter for compost. During flotation, some coffee cherries also float because of their lower density due to physical quality defects, such as insect damage or unfertilized beans (empties). These cherries are considered to be inferior or non-export quality, and may be removed to a secondary quality processing stream. Alternatively, inferior quality coffee cherries are classified into one of more quality groups (generally known in Spanish as *Segundas, Natillas*, or *Terceras*), where some are immediately dried without removing the pulp and mucilage, and sold in the domestic market, mainly for instant coffee production. Inferior quality coffee beans can pass through all the same steps as the export quality beans to remove their pulp and mucilage, but through alternative processing machinery. In some wet mills, further sorting and evaluation on the basis of size using a rotary separator screen is performed to recover some of the erroneously removed export quality coffee, and these are looped back into the export quality stream.

*2.3.1.4. Depulping.* Coffee cherries are conveyed by gravity and/or water through depulping machines, which removes the pulp from the coffee beans using pressure and/or friction. There are different designs and sizes of depulping machines to meet processing capacity. Drum pulpers, which can be oriented horizontally or vertically, press or pinch coffee cherries between a plate and a grating, causing the seed to be squeezed out of the pulp. Alternatively, abrasion provided by a rough disk (disk pulper) may be used to strip the pulp off the seed. To increase throughput and/or processing capacity, it is common to see 2–4 pulpers working in parallel. The pulp is usually removed from the wet mill with an auger, or through a water channel, and dropped either onto the ground or into a truck to be transported elsewhere. Pulp is most commonly used for compost, but it can also be used as an animal feed amendment (Bressani and Gonzalez, 1978), or consumed as cascara tea. (Ciummo, 2014).

*2.3.1.5. Fermentation (mucilage degradation).* Depulped coffee is conveyed on conveyor belts, augers, or pushed by recycled water or in rare cases with fresh water into open-air cement or tile fermentation tanks and allowed to rest typically for 6–48 h, during which fermentation occurs (Anacafe, 2008). The microorganisms naturally present in the fermenter degrade the mucilage (which detaches from the underlying parchment layer), and cause measurable impacts to the chemical composition of the green beans, ultimately altering their sensory profile (De Bruyn et al., 2017; Zhang et al., 2019, 2019). Fermentation is performed either by a more conventional method where depulped coffee is submerged under water, or in a waterless open-air tank.

*2.3.1.6. Wash (mucilage removal) and secondary density sorting.* When fermentation is complete, coffee beans are conveyed to washing channels containing recycled water, and ultimately washed with clean water to completely remove the mucilage from what will become wet parchment coffee. Alternatively, the mucilage can be mechanically removed (Illy and Viani, 2005). Water, which was used to remove the mucilage, is referred to as "honey" or "residual" water and it is generally drained into settling ponds, or recycled for conveying and initial washing purposes. During the washing step, coffee is sorted again, where the wet parchment coffee is floated through channels (approximately 20 cm tall and 20 cm wide with varying lengths) filled with running water. The coffee flows over progressively shorter barriers placed in the channel, were distinct batches of wet parchment coffee are separated based on their density differences and separately dried (Anacafe, 2005).

*2.3.1.7. Drying.* Typically, wet parchment coffee is manually removed from the washing stage (in containers appropriate to the size of the wet mill) and spread into a singular layer onto drying patios or on raised beds, under a shade cloth, semi-transparent roofing, or on open sky. Wet parchment is periodically turned (up to 17 times per day) (Illy and Viani, 2005) with a wooden shovel (or other implement) to evenly dehydrate the coffee beans to a desired storage level equal to 10 to 12% $MC_{wb}$, yielding the dry parchment coffee. Conventional sun drying method time is mostly dependent on environmental conditions and initial moisture content, but it is frequently completed between 2 and 15 days. Alternatively, wet parchment coffee can be mechanically dried for up to 5 days, typically in large cylindrical driers (commonly known in Spanish as a "guardiola") with forced convectively heated air (40 to 60) °C, while maintaining the parchment coffee mass temperature of (40 to 45) °C (Illy and Viani, 2005). Despite being faster, mechanical drying can potentially degrade coffee quality due to damage caused by temperatures at or above 40 °C (Alves et al., 2020). Also, both conventional (sun) and mechanical drying methods can be combined. Drying is typically the final step in the wet mill phase. Upon completion, dry parchment coffee is typically stored in jute/sisal bags, or on the open air inside a warehouse, for weeks to months, or may instead be directly transported to the dry mill. This may be in the same facility or elsewhere. In Guatemala, wet mills are generally smaller and more numerous (~3000 in the country) while dry mills are larger and fewer (~50 in the country) (R. Soto, personal communication, December 12, 2019). In comparison, Costa Rica has less than 200 mills, of which the majority are typically a wet-dry mill combined operation (Wagner, 2001).

### 2.3.2. Operations in the dry mill phase

*2.3.2.1. Receiving and cleaning.* As the parchment coffee enters the dry mill, usually after being dumped manually or from a truck into a receiving trough, it is cleaned using forced air, sieves, and magnets, to remove foreign matter such as small stones or other debris. It is then conveyed throughout the dry mill using bucket lifts, conveyor belts, or pneumatically.

*2.3.2.2. Dehulling (and polishing).* Cleaned parchment coffee is passed through a dehulling machine, which uses vibration and mechanical friction to remove the outer parchment from the bean. This parchment is collected and composted, or used as a biofuel energy source in the mill, or as a heat source for mechanical driers (Illy and Viani, 2005). After dehulling, dry millers have the option to also polish the beans. The coffee polisher uses friction to remove the silverskin layer, generally using phosphor bronze bars that rotate inside a cylinder (ITC, 2012). This is done to improve the aesthetics of the beans and reduce the amount of chaff during roasting. Polishing is generally not preferred by specialty coffee buyers as it may induce an undesirable change in color and taste, reducing final quality, mainly due to frictional heat increase (ITC, 2012). Therefore, this study didn't directly consider the silverskin mass loss stream in further calculations.

*2.3.2.3. Sorting.* Sorting is typically the final step in the dry mill phase. Green coffee is sorted by size using screen size separators. Then the beans are sorted by density and size on a perforated inclined surface with air forced through the perforations from beneath called a "densiometric" or "gravity" table. Denser beans migrate to the higher end of the table. Finally, beans are sorted by color through inline electronic color sorting machines. In some mills, additional human visual-hand sorting ensures that mechanical sorting was done correctly (ITC, 2012).

Green coffee is grouped by different attributes, and usually inferior quality coffee beans are separated as lower quality beans but still exported, and highly defective coffee beans are typically sold for domestic consumption, often being transformed into instant coffee. Making batches homogenous also aids more even roasting. At the end of the sorting step, sub-samples are commonly collected and tested for flavor (cupping) and additional quality evaluation.

Ultimately, export quality green coffee is poured from holding silos into jute/sisal bags which are sized at 69 kg (Central America and Mexico), 70 kg (Colombia and Bolivia), or 60 kg (the rest of the world), or it is bulk-shipped inside plastic-lined shipping containers (21,000 kg), and transported to consumer countries (NCA, 2020). Approximately 70% of all coffee produced worldwide is exported from its country of origin (ICO, 2020a).

### 2.3.3. Operations in quality sorting

When wet and dry mills are separate facilities, it is common to ship non-export quality parchment coffee from the wet mill directly to facilities that serve local markets, including those that produce instant coffee. In wet-dry mill combined operation, the separation to domestic markets may instead occur at the end of the dry mill process. Therefore, the non-export quality coffee may be separated out at various points throughout the post-harvest process including during flotation, subsequent size and density sorting at the wet mill, as well as during density, size, and color sorting in the dry mill. These variations are seen between countries and regions.

Many factors influence the proportion and quantity of harvested coffee, destined to export markets, including but not limited to the quality of the harvest, variations in fermentation and drying practices and standards, as well as storage quality and the quality standards of international customers. Green coffee imported by consuming regions is typically stored in a dedicated warehouse prior to shipment to a roasting facility.

### 2.3.4. Operations in the roastery phase

Green coffee beans are shipped to a roastery, typically in consuming countries, where several unit operations occur including: cleaning, roasting, cooling, and packaging (Fig. 4c). Grinding may also occur at the roastery but in this representative description grinding is assigned to the café phase.

*2.3.4.1. Cleaning.* Bags (typically 60–70 kg) of green coffee beans are opened, dumped into a hopper. Despite extensive cleaning in the dry mill, small amounts of foreign material still make it to the roastery, much of it in the form of dirt and small stones. Much of this foreign material is added during the drying or dry mill stages, because the parchment and green beans are often dried or stored on the ground. In large roasters, screening to remove foreign matter occurs before and after roasting, but in smaller roasteries screening is generally only performed after roasting. In large roasteries, the green beans are weighed and mechanically transferred by belt or pneumatic conveyor to storage silos. From the storage silos, the green beans are likewise conveyed to the roaster (EPA, 1995). In smaller facilities, coffee beans are manually conveyed in bags and directly poured into the coffee roaster hoper.

*2.3.4.2. Roasting.* Roasters typically operate at temperatures between (140 to 250) °C (Illy and Viani, 2005), for a period of time ranging from a few minutes to about 30 min. Roasters are typically horizontal rotating drums that tumble the green coffee beans in a current of hot air and may rely on some combination of convection and/or conduction (depending on roaster design) to heat the coffee, however many other roaster designs exist as well. Roaster technicians use "roasting profiles", which provide guidance for a target temperature during the roasting process. At the end of the roasting cycle, water sprays are sometimes used to "quench" the beans, which ends the roasting process more quickly. There are byproducts generated from the roasting process including chaff, water vapor and other gases (EPA, 1995):

*2.3.4.2.1. Chaff is produced as the silverskin detaches from the beans.* Chaff is generally collected in a cyclone separator, expelled by the coffee roasting machine, collected in a "chaff can" or "chaff bin," and then disposed of in general waste destined for landfills, but may also be used for compost, mulch, animal bedding, or fuel.

*2.3.4.2.2. Water vapor and gasses including volatile organic compounds (VOCs).* A solid-gas or cyclone separator may be used to first remove solid particles from the exhaust and then an afterburn process completes the cleaning using a thermal oxidizer (incinerator), with temperatures reaching up to (650 to 816) °C (EPA, 1995). Cleaned gasses are ultimately released into the atmosphere.

*2.3.4.3. Equilibration (Cooling).* Following roasting, the roasted coffee is cooled to approximately 25 °C and passed through destoners which remove stones, metal fragments (using magnets), and other waste not previously removed. The destoners, in some cases, pneumatically convey the beans to a de-gasifying chamber, where the beans stabilize and dry (small amounts of water from quenching exist on the surface of the beans) and then stored in silos (EPA, 1995). In other cases, the roasted beans are immediately packaged.

*2.3.4.4. Packing.* When cool, the roasted coffee is ground (Section

2.3.5.1) or packaged as whole beans often in valve-sealed, vacuum-sealed, or modified atmosphere packaging and prepared to ship to retailers or consumers. Over the next several days, carbon dioxide and other gasses are slowly released from the roasted coffee in a process called "off gassing" or "degassing." Valve-sealed bags are preferred because they allow the gas to escape so they do not harm the coffee flavors.

### 2.3.5. Operations in the café phase

After the roastery phase, packed roasted coffee is shipped to consumers either via retailers, such as wholesalers or supermarkets, or to cafes. In this analysis the café phase represents all consumption of exported coffee, since the basic process is essentially the same wherever the coffee is brewed (Fig. 4d).

*2.3.5.1. Grinding.* Upon arrival to the point of consumption (if not before), the roasted coffee beans are ground to coarseness appropriate for the brewing method and consumer preferences, generally coarser for cold brew, medium for drip, and finer for espresso (highly variable). This is accomplished with a hand crank home grinder, retail electric grinder (throughput = 10–80 kg per h), or industrial sized grinders (throughput = 140–400 kg per h). Types of grinders include: flat disk grinders, conical burr grinders, blade grinders, and stone grinders (Folmer, 2017). In actual retail café operations, a small fraction of coffee grounds is lost, spilled, or used for "dialing in" espresso machines without being served.

*2.3.5.2. Brewing.* Approximately 28% of a roasted coffee bean mass is water-soluble solids (Lingle, 2011), however coffee is typically not fully extracted because doing so yields less desirable flavor profiles. The percentage of extracted mass in a given brew is known as the extraction yield. There are three primary methods for brewing coffee in a specialty coffee context, each with unique properties: hot brews including espresso and drip brewing, and cold brew. Many other variations exist (such as various types of pour-over brews and vacuum brews) but will not be represented in this study. Each method provides a means of bringing ground coffee into contact with water, which for hot brew is typically heated to approximately 94 °C (SCA, 2018b). Soluble solids in the ground coffee dissolve into the water. The resulting mixture (coffee beverage) is consumed. The remaining mass becomes spent coffee grounds, and is typically discarded as compost or waste.

## 2.4. Coffee byproducts as percent of coffee cherry mass

Few detailed studies have been conducted to determine mass losses at each step in coffee postharvest processing. Extant studies reporting raw mass data are summarized in Fig. 3. Bressani et al. (1972) provided one of the first laboratory measurements of the mass composition of a coffee cherry and all of its internal components, indicating that from 1000 g of fresh coffee cherries, 432 g of pulp (43.2%) and 118 g mucilage (11.8%) (fresh-weight basis) could be removed. Although this early study apparently did not subject the coffee to a wet-mill drying step, the moisture content at each physical state was provided, allowing the following wet weights to be calculated (at a theoretical 11% $MC_{wb}$): 48 g parchment (4.8%) and 234 g beans (23.4%). This calculation suggests that the water lost the drying step equals 168 g (16.5%).

Another study, which did not provide its methodology, was conducted by Uribe et al. (1977), reported similar results to Bressani et al. (1972), in that the pulp, mucilage, water loss during drying, parchment, and green coffee bean represented 40.1, 18.2,19.4, and 4.2, and 18.0% of the initial coffee cherry mass, respectively.

In 2005 the National Guatemalan Coffee Association (in Spanish: Asociación Nacional del Café (Anacafe)) produced a manual for coffee producers, which provides the mass percentages of the coffee cherry layers (Anacafe, 2005). Of the total mass of the coffee cherry, they reported that 40.0% is pulp, 18.8% is mucilage, 20.6% is typically lost in water mass during drying, 4.8% is parchment, and 15.9% is the green coffee bean. Again, the methodology behind this estimation was not provided.

A more recent study, produced by the Colombian National Center for Coffee Research (in Spanish: Centro Nacional de Investigaciones de Café (Cenecafé)) reported conversion rates from coffee cherries to parchment coffee, based on different initial cherry qualities and harvesting times. The study was conducted at an experimental mill under controlled conditions, and measurements were obtained in a laboratory. This study reported that for export quality coffee, the pulp represents 44.6% of the initial harvest mass of the cherry, 12.2% was mucilage, 22.9% represents moisture lost during the drying for a total loss of mass in the wet mill of 79.7%. Mass loss during the dehulling process (dry mill) represented an additional 4.3% of the initial harvest mass. In total, 83.9% of the initial harvest mass was removed from the cherry to produce green coffee, representing 16.1% of the initial harvest mass. Non-export quality coffee yielded qualitatively similar trends, with reported values differing from the above by no more than 2-% (Montilla-Pérez et al., 2008).

## 3. Materials and methods

### 3.1. Study aims

The mass percentages obtained from these prior studies (Fig. 3) are informative and broadly consistent. However, all of the previous studies end at the dry mill phase, and present green coffee as the final product. Most importantly, minimal field data was considered, and real-world

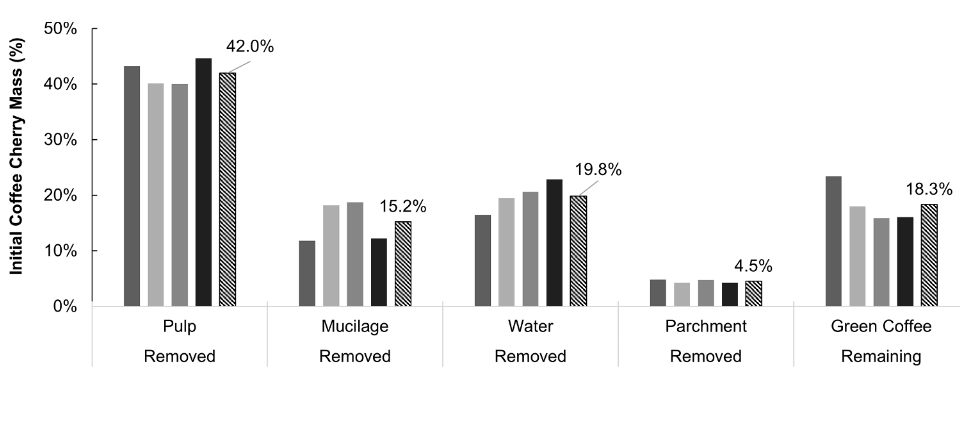



**Fig. 3.** Comparison of results for previous studies showing percent of initial harvest mass lost at four key mass affecting steps in the wet and dry mill postharvest processing phases: depulping, fermentation, drying, and milling. Finally, the percentage left over as green coffee is displayed.

effects such as material streams including foreign matter and separation inefficiencies were excluded. Only Montilla-Pérez et al. (2008) considered variations in initial coffee cherry quality. Observations and measurements in previous studies presumably represent optimum efficiency in highly controlled environments, not likely observed in commercial wet and/or dry mills. In addition, to our knowledge, coffee roasting and brewing are not included in any extant mass usage study starting at harvest.

Therefore, in this study detailed surveys of commercial wet and dry mills in Central America and Mexico, and roasters in the US were performed to produce representative process flow diagrams and to determine how an initial 100 representative mass units of freshly harvested coffee cherries is distributed across the entire chain (from harvest to consumption). The generated data facilitates coffee postharvest equipment improvements, sustainability and economic analyses, and focus attention on the development and improvement of alternative uses for coffee byproducts.

### 3.2. Study focus and locations

Focusing on export quality coffee, this study collected industry field data in Central America and Mexico. The region was chosen due both to its proximity to the United States and to its prominence in the specialty coffee industry (SCA, 2018a). The washed method is the focus of this study, due to its prevalence globally and especially in the study's region of interest.

Data collection for wet and dry mill mass loss was conducted through a combination of in-person interviews, review of historical mill records, and remote surveys (Appendix A) provided by mill hosts (mill owner, manager, or a technician). The interviewees and mills were selected from a large pool of candidates throughout the region complied through a network of industry participants associated with the UC Davis Coffee Center. Final selections were based on availability and willingness to participate in this study. In Guatemala interviews were conducted with experts at Anacafe in Guatemala City, and then seven wet mills, four dry mills, and one roastery were visited, all within a 60 km radius of Antigua Guatemala (14.56° N, 90.73° W) at elevations ranging from 1500 to 2200 m above mean sea level (MAMSL). In Honduras three wet mills, and five dry mills were surveyed within a 10 km radius of El Paraiso (13.86° N, 86.55° W), at elevations ranging from 700 to 850 MAMSL. In Nicaragua surveys were administered at three wet mills and one dry mill within 10 km of Sébaco, Nicaragua (12.85° N, 86.09° W) at elevations ranging from 450 to 800 MAMSL. In Costa Rica information was provided by experts from the Costa Rican Coffee Institute (in Spanish: Instituto del Café de Costa Rica (Icafe)) and the University of Costa Rica. Additionally, one mill in the San José Province was surveyed. In Mexico one combination wet mill, dry mill, and roastery and one stand-alone roastery were visited, both within 10 km of Tlapacoyan, Veracruz (19.96° N, 97.21° W) at elevations ranging from 400 to 500 MAMSL. The wet mills visited represent processing capacities of between 9072 and 317,514 kg per day of coffee cherries and drew from 0.2 to 95.0 million $m^2$ of land under coffee cultivation. The dry mills represented processing capacities of 10,886 to 217,724 kg/day of parchment coffee. More than 10 unique *C. arabica* varieties were processed at the mills included in this study. In all, survey data was obtained from a total of 15 wet mills, 12 dry mills, and three roasteries.

### 3.3. Generation of representative process flow diagram

The authors personally visited a subset of seven wet mills and five dry mills. At each of these site visits, qualitative process flow diagrams (PFDs) were sketched by hand to record the specific unit operations, and how the materials streams flowed through the specific mill. The mill host at each facility guided and advised on the diagrams. Each mill had a slightly different configuration; recurring features common to the majority of the mills were used to create representative PFDs using Lucidchart (Lucid Software Inc., South Jordan, UT, USA) and Adobe Illustrator 2020 (Adobe Inc., Mountain View, CA, USA). The roastery PFD relies on information from site visits in Guatemala and Mexico and consultations with industry experts in the US. The café PFD was built as a conceptual representation including the necessary steps to brew the coffee beverage. This representative harvest-to-cup technical PFD was then populated with quantitative mass flow data, as described below.

### 3.4. Acquisition of mass flow data

Historical operational records, provided by mill operators, represent 55.4% of data points for the wet and dry mill phases in this study. These raw data were most frequently provided as a mass conversion ratio from one physical state of the coffee to another (such as coffee cherries to parchment) or as a ratio of desired product to byproduct (such as coffee cherry to pulp). These ratios were converted into a percent loss format. Such conversion ratios are used to calculate the overall mass losses in an entire processing phase (e.g., across the entire wet mill).

The provided conversion ratios generally did not, however, include information on mass changes at every unit operation, including for example the mass loss during the fermentation step specifically. To fill gaps in mass flow data not typically collected, mill hosts were asked to estimate, and in some cases measure directly, averages and ranges of mass loss at specific steps. The numbers they reported make up the remainder of data points in this study (44.6%). Both types of data were used together in the analysis below (Section 4).

### 3.5. Estimation of water content after de-pulping and fermentation

A particularly important mass flow involves mass loss during fermentation. To estimate water content of coffee in different physical states before and after fermentation, three replicates of approximately 100 g samples were collected, from representative steps within a wet mill process in Guatemala during December 2019, and sealed in plastic zip-lock bags. Samples were taken from each of the following steps in the postharvest process: right after harvest (cherry), immediately after depulping (depulped), and after an approximately 24-h fermentation (wet parchment). Furthermore, samples were taken from 3 different quality grades at each step: export quality (Spanish: primeras) and non-export quality (Spanish: segundas and natas). The resulting samples were anonymously labeled, randomized, frozen, and sent to the Anacafé laboratory in Guatemala where water content was estimated and reported as the $MC_{wb}$, using the air-oven method (105 °C) for industrial testing (Reeb and Milota, 1999).

### 3.6. Representative mass losses during roasting and brewing

For the roastery and café (brewing) segments, data was provided by private companies in Central America, Mexico, and the US. Additionally, to determine mass loss represented as chaff during roasting, which is not typically collected in commercial application, measurements were taken in the UC Davis Coffee Center experimental roastery (Davis, CA). Two different Guatemalan green coffees were roasted on a 1 kg Probatino coffee roasting machine (Probat, Germany/Brazil) to three different roast levels (light, medium, and dark (Agtron = 44.2 ± 4.8)) with two replicates each (12 total trials). Before each trial, the roaster was thoroughly cleaned of any chaff and the green coffee was weighed. The starting bean temperature for each trial was approximately 177 °C. While the coffee roasted, generated chaff was collected in the chaff can. At the end of the roast, roasted coffee, and the chaff were weighed and recorded.

For the café phase, industry standards for extraction yield, total dissolved solids, and ideal brewing water temperature were used in mass flow calculations and descriptions of brewing steps (Illy and Viani, 2005; SCA, 2018b) (SCA, 2018b). The percentages of coffee used in different types of coffee beverages were broadly inferred from economic data reported by the Specialty Coffee Association (SCA, 2018a) and from conversations with industry experts. Given the high variation in style of coffee beverage preparation, the breakdown by beverage type is intended to be representative rather than definitive.

### 3.7. Coffee quality grades

Though complex and varied, standards for green coffee quality exist throughout the world. Generally speaking, only beans of sufficiently high quality are exported, with lower quality beans typically sold domestically. For the purposes of this study, the focus is primarily on export quality coffee, while the remaining is indicated as non-export quality. There may be several quality categories for coffee in a given coffee market, and that may differ by country. So, bifurcating coffee into these two common categories simplifies classification of the worldwide quality grades. This distinction is important as coffees destined for export flows through different operational steps, and may also result in different mass losses throughout the postharvest process.

This study assumes that non-export quality coffee is primarily consumed in the country of origin. The percent of coffee which is diverted to domestic markets (non-export quality) in Guatemala, Honduras, Nicaragua, Costa Rica, and Mexico was on average 22.7%. While the global average, including all processing methods for 2015–2019 was 30.7% (ICO, 2020a). Since data for this study was drawn from the five countries mentioned, 22.7% will be used as the percent of non-export quality coffee throughout this study.

### 3.8. Mass flow calculations

To calculate mass losses throughout the postharvest process, a mass conservation approach was applied. Successive mass affecting steps ($n$) in the coffee postharvest process are drawn from what is typically seen in the washed method (Sections 2.3, 4.1-5). Initial harvest mass ($m_{init}$) is defined as 100 representative mass units of freshly harvested coffee cherries. At each step $n$ a percentage of mass is removed and the fraction of mass which remains is defined as the input mass for the following step ($m_{n+1}$). The mass removed in a given step is calculated as

$$\Delta m_n = m_n \cdot y_n, \tag{1}$$

where $\Delta m_n$ is the average mass removed at a given step, $m_n$ is the average input mass at a given step, and $y_n$ is the average percent mass loss in a given step (input mass basis). Likewise, the cumulative remaining mass ($m_{n,cum}$) at any mass affecting step ($n$) in the postharvest process, in reference to $m_{init}$, is given by

$$m_{n,cum} = m_{init} - \sum_{j=1}^{j=n} \Delta m_j, \tag{2}$$

where the index $j = 1,2,3,\ldots n$ represents each of the $n = 10$ distinct mass affecting steps and $\Delta m_j$ is the average mass removed in step $j$.

To visualize the average behavior of postharvest coffee mass flows, a Sankey diagram, created using Adobe Illustrator 2020 was generated to illustrate the relative quantities of mass in each mass stream, using the mean values calculated from data obtained for each mass affecting step. Likewise, the PFDs were calculated using the mean mass flow rates.

### 3.9. Descriptive statistics

A key challenge of this study was to obtain descriptive statistics from each mass-affecting step (Eq. (2)), many of which are rarely (if ever) measured at commercial operations. The progressive (cumulative) mass loss from the principal mass flow (export quality coffee) as it passed through each mass affecting step, was further characterized by the maximum, mean, minimum, and standard deviation of mass remaining after each mass affecting step.

The variability in mass loss percentage data collected for each postharvest mass affecting step is displayed in a series of boxplots.

Since data sets were constructed from many sources, and each step ($n$) had a different sample size, to quantify the variability a propagation of errors approach was applied to estimate the standard deviation in the cumulative mass loss at step $n$,

$$\sigma_{m_{n,cum}} = m_{n,cum} \cdot \sqrt{\left(\frac{\sigma_{m_n}}{m_n}\right)^2 + \left(\frac{\sigma_{y_n}}{y_n}\right)^2} \tag{3}$$

where, $\sigma_{m_{n,cum}}$ is the cumulative standard deviation of the mass remaining at an operational step ($n$), and $\sigma$ denotes the standard deviation of the respective quantity.

## 4. Results

The overall process flow diagram (PFD) with its corresponding Sankey diagram showing the overall mass flows for washed coffee (or wet processed) are presented in Figs. 4 and 5, respectively. In both figures, for clarity, only the average mass flow values are reported and the statistical deviations are omitted. Discussion of statistical measures of variation are deferred to later sections, and shown in Figs. 6 and 7. Many variations exist, but what is described here is typical to Central America, Mexico, and other regions of the World, and is intended to serve as a representative example. The unit operations described in Section 2.3 are referenced to organize the remaining of this article. Throughout this section, the phrase “initial harvest mass” means the initial 100 kgs (or other mass basis) of freshly harvested cherries, whereas the phrase “input mass” signifies the mass input into a specific unit operation.

### 4.1. Wet mill

During the wet mill phase, there is an overall mass loss of 74.4% of the initial harvest mass. The solid byproducts are coffee pulp (47.1% of initial harvest mass) and mucilage (removed in “honey water” as 5.3% of initial harvest mass), and foreign matter (1.0% initial harvest mass).

#### 4.1.1. Harvest

For the propose of this study, it is assumed that a representative 100 kg of initial harvest mass is delivered to the wet mill.

#### 4.1.2. Receiving

At this stage, coffee cherries were found to have 68.9 ± 0.9% $MC_{wb}$.

#### 4.1.3. Floating

Foreign matter represents on average 1.0% of the initial harvest mass, with 99.0% of the initial harvest mass continuing to the next step in the form of clean coffee cherries.

#### 4.1.4. Depulping

This step removes on average 47.6% of the clean coffee cherries input mass, which represents 47.1% of the initial harvested mass. Ultimately, 51.9% of the initial harvest mass is transferred to the next step, as depulped coffee. Depulped coffee was found to have 61.8 ± 2.9% $MC_{wb}$. These values differ from previous findings as described in Section 2.4, which average 42.0% of initial harvest mass lost. In other words, 5.1% more mass appears to be lost during depulping in commercial practical application in comparison to prior laboratory studies.

#### 4.1.5. Fermentation (mucilage degradation)

Fermented coffee was found to have 59.0 ± 1.4% $MC_{wb}$. Previous studies have not reported this value, which reflects a loss on coffee moisture during fermentation, probably due to natural dehydration and mass losses through the mucilage degradation and removal.

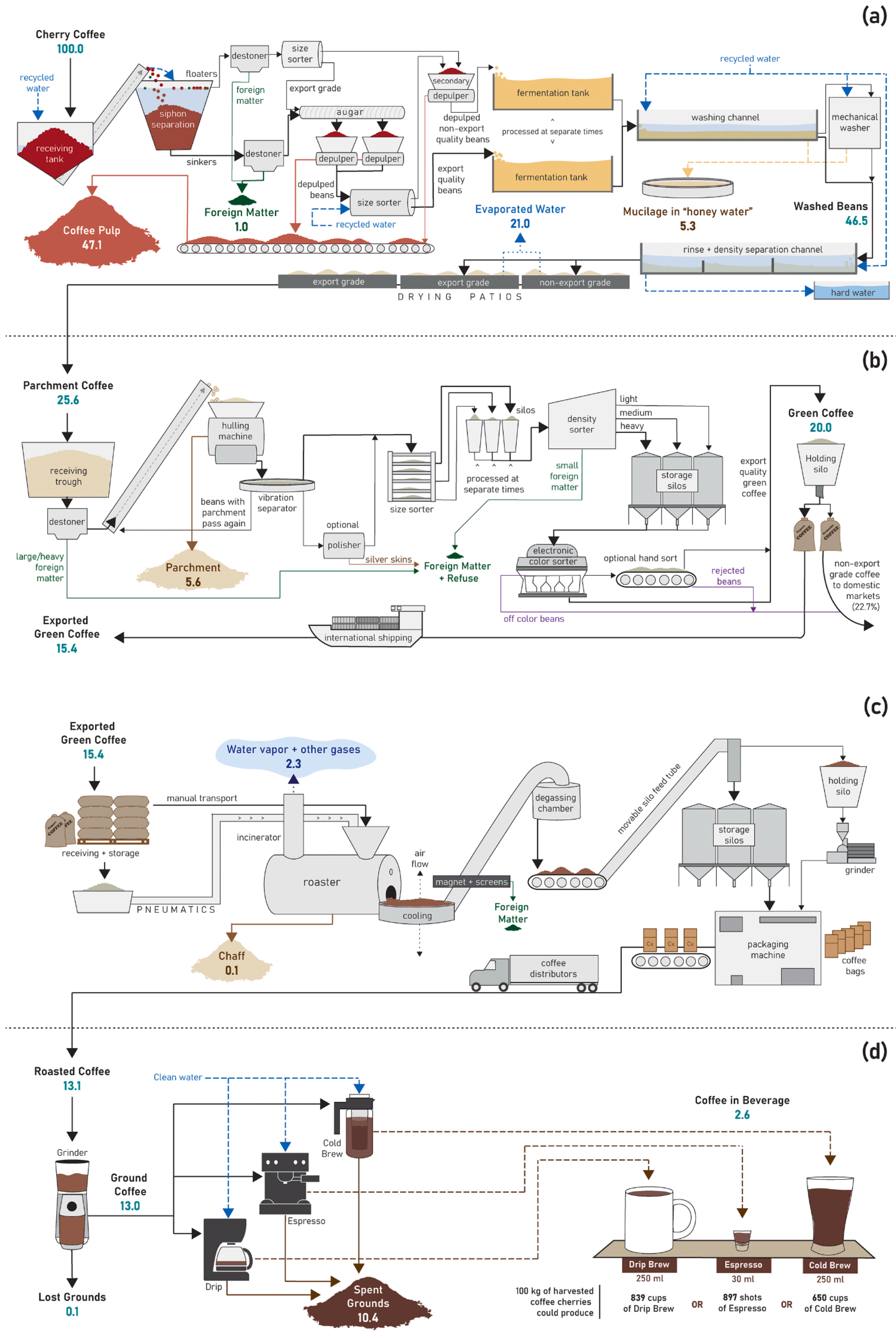



**Fig. 4.** Representative process flow diagram (PFD) for the washed method of postharvest coffee processing as seen in Central America and Mexico. Inline numbers represent mass units (and also, in this case, a percentage of the initial harvest mass). Some numbers do not sum due to rounding. Phases represented are: (a) wet mill, (b) dry mill, (c) roastery (d), and café processes. For interpretation of the references to color in this figure, the reader is referred to the web version of the article.

### *4.1.6. Wash (mucilage removal) and secondary density sorting*

On average, it was found that at this stage there is a mass loss of 10.3% from the input depulped coffee mass or 5.3% loss from the initial harvest mass, with 46.5% of the initial harvest mass transferred to the next step as wet parchment coffee. Notably, the mass of removed mucilage is smaller in commercial application in comparison to reported laboratory studies (Section 2.4), which suggested that 15.2% of the initial mass is lost as mucilage (9.9% difference). This observation suggests that commercial methods are not as efficient in terms of completely removing the mucilage. Wet parchment coffee was found to have 54.3 ± 1.8% $MC_{wb}$.

### *4.1.7. Drying*

Wet parchment coffee is dried to a desired storage level equal to (10 to 12)% $MC_{wb}$. Regardless of the method used, the average input mass loss at this step is 45.1%, which represents 21.0% of the initial harvest mass, with 25.6% of the initial harvest mass moving to the next step as dry parchment coffee. These findings accord with laboratory studies, which average 19.8% of initial harvest mass (1.2% less than this study).

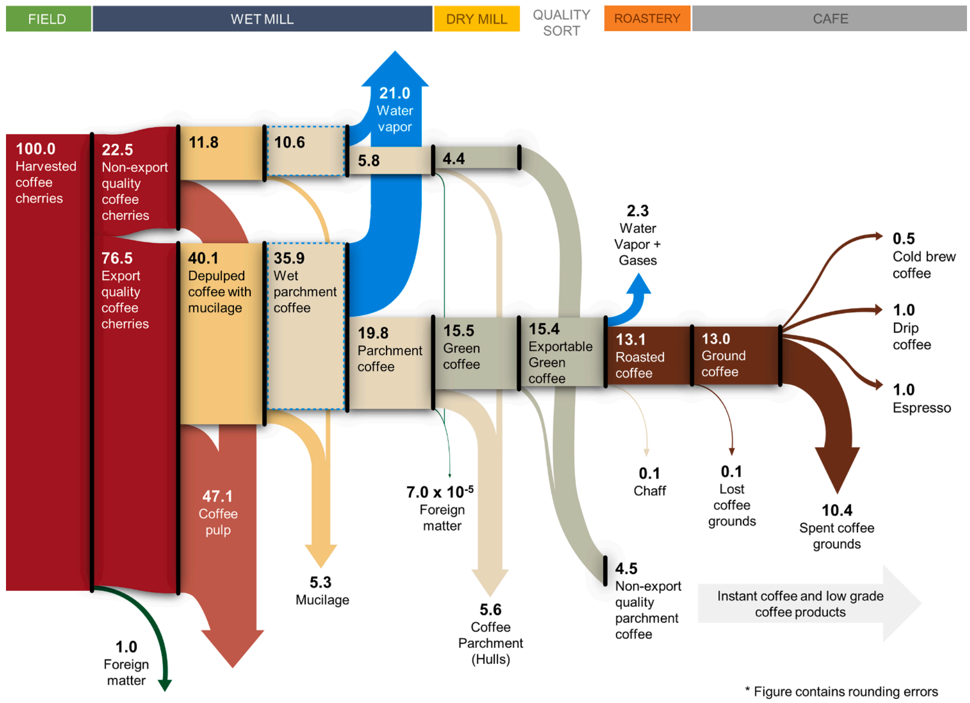



**Fig. 5.** Sankey diagram for mass flows in the coffee in the washed method for postharvest processing. Numbers represented are averages; so, might not sum to 100 due to rounding. For interpretation of the references to color in this figure, the reader is referred to the web version of the article.

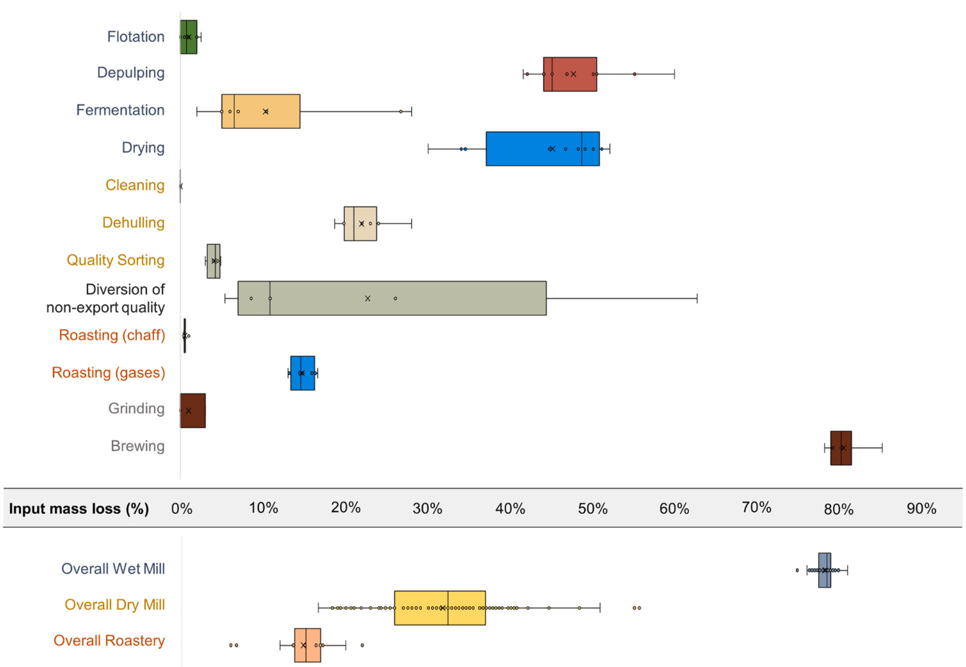



**Fig. 6.** Boxplots for data representing mass loss percentages, with reference to the input mass, at each mass affecting step in the washed method. Overall mass loss in the wet mill, dry mill, and roastery phases is also provided. The edges of the boxes represent the 25th and 75th percentiles, the line inside the box represents the median, and the whiskers denote the range of the observed values. A data point is considered an outlier if it exceeds a distance of 1.5 times the interquartile range below the 1st quartile, or 1.5 times the interquartile range above the 3rd quartile. For interpretation of the references to color in this figure, the reader is referred to the web version of the article.

## 4.2. *Dry mill*

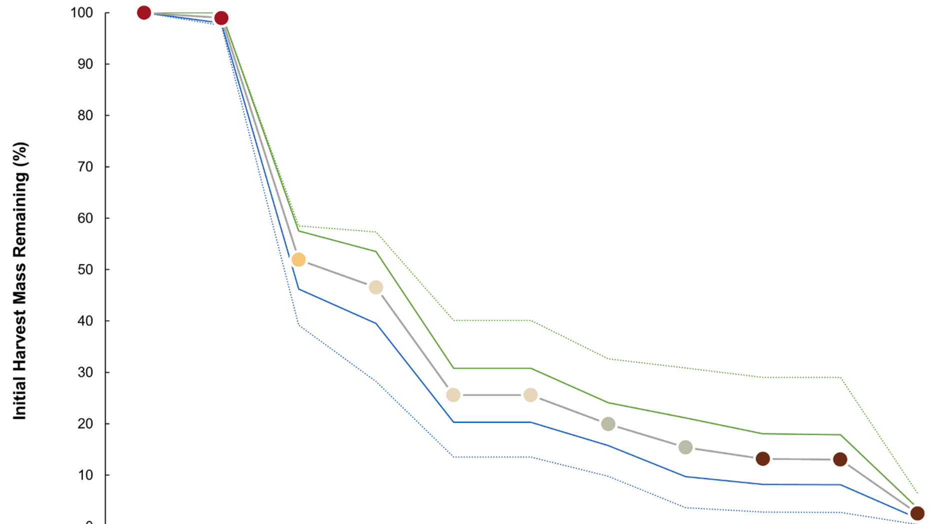
At the end of the dry mill phase, there is an average total loss of 5.7% of the initial harvest mass. The primary byproducts being coffee parchment (hulls) or 5.6% of initial harvest mass, and foreign matter ($7.0 \times 10^{-5}$% of initial harvest mass).

### 4.2.1. *Receiving and cleaning*

Removed foreign matter represents an insignificant mass fraction, equal to about $2.7 \times 10^{-4}$% of the mass of parchment coffee, or $7.0 \times 10^{-5}$% of the initial harvest mass, with 25.6% of the initial harvest mass transitioning to the next step.

### 4.2.2. *Dehulling (and polishing)*

The removed parchment represents on average 21.9% of the input mass of the dry parchment coffee and 5.6% of the initial harvest mass, with 20.0% of the initial harvest mass moved to the next step as unsorted green coffee. These findings are similar to laboratory scale studies, which average a loss of 4.5% of initial harvest mass (1.1% less than this study).




| | Harvest | Floating | Depulping | Ferm. + Wash | Drying | Cleaning | Dehulling | Quality Sort | Roasting | Grinding | Brewing |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Max | 100.0 | 100.0 | 58.5 | 57.3 | 40.1 | 40.1 | 32.6 | 30.9 | 29.0 | 29.0 | 6.4 |
| Mean + σ | 100.0 | 100.0 | 57.6 | 53.5 | 30.8 | 30.8 | 24.1 | 21.1 | 18.0 | 17.9 | 3.6 |
| Mean | 100.0 | 99.0 | 51.9 | 46.5 | 25.6 | 25.6 | 19.9 | 15.4 | 13.1 | 13.0 | 2.6 |
| Mean - σ | 100.0 | 98.0 | 46.2 | 39.5 | 20.3 | 20.3 | 15.8 | 9.7 | 8.2 | 8.1 | 1.6 |
| Min | 100.0 | 97.5 | 39.2 | 28.2 | 13.5 | 13.5 | 9.8 | 3.6 | 2.8 | 2.8 | 0.4 |

Mass Affecting Steps

**Fig. 7.** *Cumulative mass loss* during the washed method. Mean, max, and min values are displayed for each mass affecting step, from harvest to consumption. The standard deviation with propagated errors (as calculated in Eq. (3)) are also displayed. The amount shown is the mass remaining after all mass in previous steps is removed. For interpretation of the references to color in this figure, the reader is referred to the web version of the article.

#### *4.2.3. Sorting*

In this step, the mass diverted to the non-export quality coffee is estimated to be on average 4.1% of the input mass, or 0.8% of initial harvest mass, however this quantity is included in the quality sort phase (Section 4.3).

### *4.3. Quality sorting*

This study assumes an average of 22.7% of non-export quality coffee harvested is ultimately consumed in domestic markets (Section 3.7). By the end of the dry mill phase, typically all non-export quality coffee is diverted to domestic markets and therefore, for the purposes of the Sankey diagram (Fig. 5), the separation is visually represented after the dry mill phase, but the mass flows in the process flow diagram reflects the dispersed nature of the quality sorting step. Although biological or chemical degradation can occur during long storage between the dry mill and roastery phases, this study assumes proper handling and storage times such that mass loss is negligible.

### *4.4. Roastery*

In the roastery phase the average total loss was 2.4% of the initial harvest mass. The amount of mass lost is most influenced by the level of roast with a dark roast (i.e., Agtron <40) yielding a higher mass loss than a light roast (i.e., Agtron >55). The primary solid byproduct produced is chaff (0.1% of initial harvest mass on average). Chaff mass loss is variable based on how much (if any) polishing is performed. Using an average mass loss associated with a medium roast, the mass of roasted coffee that passes to the café phase is 13.1% of the initial harvested mass.

#### *4.4.1. Cleaning*

It is known that material is removed during cleaning when green coffee enters the roastery, but because of the original cleaning steps at the wet mill, most of the foreign material collected at harvest is removed. More foreign material, however, is inadvertently added to the coffee beans during fermentation, patio drying, and storage. This material added after the harvest (e.g., stones, and strings from jute/sisal bags) is removed during the final cleaning, and does not affect the overall mass flow calculation of interest here. It will therefore be neglected.

#### *4.4.2. Roasting*

There are two primary byproducts from the roasting process:

*4.4.2.1. Chaff.* Represents on average 0.5% of the input green coffee mass or 0.1% of the initial harvest mass.

*4.4.2.2. Water vapor and gasses.* Mass removed at this step represents on average 14.7% of the input green coffee mass, and 2.3% of the initial harvest mass.

#### *4.4.3. Cooling and packing*

This mass loss is small (< 1%) (Smrke, 2019) and is accounted for in the water vapor and gas material stream explained in section 4.4.2.2.

### *4.5. Café*

For the purpose of this study, the café phase signifies exported coffee consumption (Fig. 4d). An average of 10.5% of the initial harvest mass is lost, the vast majority becoming spent coffee grounds (10.4%).

#### *4.5.1. Grinding*

In commercial retail café operations, a small fraction of coffee grounds is lost, spilled, or used for "dialing in" espresso machines without being served at around 1.0% loss. Therefore, an average of 13.0% of initial harvest mass passes to the next step as ground coffee.

#### *4.5.2. Brewing*

Based on the findings in this study, in terms of weight, an initial harvest mass of 100.0 kg will produce 13.0 kg of export quality ground coffee beans ready to be brewed. It is beyond the scope of this study to precisely measure the distribution of coffee beverage types prepared in consuming countries; therefore, estimations of the amount of coffee beverages that can be produced from a given initial harvest mass will be based on information provided by industry participants and economic reports (SCA, 2018a), and are exclusively exemplary. It is therefore assumed that approximately 40% (5.2 kg) of the coffee grounds are consumed as drip brew coffee, approximately 40% (5.2 kg) are consumed as espresso and/or espresso-based drinks, and approximately 20% (2.6 kg) are consumed as cold brew.

*4.5.2.1. Drip brew.* The final coffee beverage contains on average 1.25% total dissolved solids (TDS) (SCA, 2018b), which in a 250 ml metric cup of coffee represents 3.1 g of coffee mass. Based on a typical industry extraction yield equal to 20%, then 4.2 kg of ground coffee will become spent grounds and 1.0 kg will be consumed as a part of 335metric cups (250 ml) of liquid beverage.

*4.5.2.2. Espresso.* The final espresso shot (30 ml) contains on average 9.5% TDS (SCA, 2018b) or 2.9 g of coffee mass. Based on a typical industry extraction yield of 20%, approximately 359 shots (30 ml) of espresso are produced .

*4.5.2.3. Cold brew.* A metric cup (250 ml) of cold brew contains around 1.6% TDS (SCA, 2018b), and therefore an extraction yield of 15% yields around 0.4 kg of coffee grounds which are dissolved into 98 metric cups (250 ml) of cold brew coffee (4 g per metric cup).

### *4.6. Statistical measures of variations*

Large variations within each coffee postharvest processing mass affecting step were observed. These variations are detailed in Fig. 6, which shows box plots displaying the reported data for each mass affecting step in the top section, as well the entire mass loss as reported by the wet mill, dry mill, and roaster phases in the bottom section. Mass loss is referred to the input mass for a particular step or phase. The greatest variability was seen in the following steps: quality sort, fermentation, drying, and depulping steps with standard deviations of 23.6, 9.2, 7.7, and 5.7% respectively.

An alternative way to visualize the variability in the mass flows is shown in Fig. 7, which displays the cumulative mass loss versus processing step in reference to the initial harvested mass. The average values accord with Fig. 5, but the minimum and maximum observations as well as the propagated error standard deviation (Eq. (3)) are also included.

## 5. Discussion

This study's findings demonstrated that around 2.6% of the total coffee mass produced at harvest is consumed by humans as a final export-quality product. This means that 97.4% of harvested fresh coffee material ultimately becomes a byproduct, or lower-quality product across the coffee supply chain, including none-export or domestic consumed coffee. This study defined and detailed each of these flows, and is intended to provide data to better understand environmental impact of existing practices for disposing of this material, as well as alternative options for diverting these byproducts towards more beneficial uses.

Generally, the results corroborate the major trends already known for postharvest processing via the washed method, but also considering real-world commercial applications. Mass loss during the depulping and drying are the largest causes of mass loss in the postharvest process, though other steps are not insignificant. One key finding is that mass loss during the depulping step is 47.1% in commercial practice, which is 5.1% higher than the average of 42% reported in previous laboratory measurements (Anacafe, 2005; Bressani et al., 1972; Montilla-Pérez et al., 2008; Uribe, 1977). Given the quantities of pulp produced annually, this amount might seem "small", but globally it corresponds to a difference of about 650 million kg. Further research may ascertain the reasons for this difference, whether inefficiencies in depulping practices, variability in the ratio of fruit to seed mass in the coffee varieties tested, or other causes. In addition, this is possibly due, in part, to accidental losses of otherwise acceptable coffee cherries that would not occur in a laboratory setting. Furthermore, a large source of variability in the postharvest process comes from the percentage of coffee that is exported versus domestically consumed in a given country. While numerous factors likely contribute to this variability, further research may reveal whether these differences are either caused by or have an effect on the mass loss efficiencies of the various postharvest processes used throughout coffee producing regions. The harvesting method may also play a role in these results with mechanical harvesting collecting more foreign matter and more variability in coffee cherry ripeness versus hand harvesting. All of these sources of variability are excellent topics for future research.

The average annual global production of green coffee over the last 5 years (2015–2019) was 9.5 billion kg, with 6.9 billion kg being export quality (ICO, 2020a). Using the findings of this study, it can be estimated that approximately 47.7 billion kg of coffee cherries were harvested annually. Of that, when considering all processing methods, approximately 26.0 billion kg became solid byproducts (not including water vapor and other gasses).

One framework that can be applied to the byproduct challenge is the United States Environmental Protection Agency (EPA) Food Recovery Hierarchy (FRH), which identifies and prioritizes six actions that organizations can take to prevent and divert food losses and food byproducts. The tiers from most preferred to least preferred are as follows: FRH tier 1 – source reduction, FRH tier 2 – feed hungry people, FRH tier 3 – feed animals, FRH tier 4 – industrial uses, FRH tier 5 – composting, and FRH tier 6 – landfill/incineration (EPA, 2019). While most of the byproducts of coffee production are not generally edible, there are many opportunities to move current waste management practices up the hierarchy at each point in the coffee supply chain, as discussed below.

Coffee pulp, which represents around 12.8 billion kg annually, has been studied for alternative uses including compost (Anacafe, 2008), energy production (Parascanu et al., 2019), food products (for animals and humans), beverages like tea and alcohol, flour ("The Coffee Cherry Co.," 2020), as a wastewater cleaning agent (Gómez A., et al., 2019), and for biomolecule extraction (Ruesgas-Ramón et al., 2020; Santos da Silveira et al., 2019; Torres-Valenzuela et al., 2020). With pulp being the largest byproduct by mass, it shows potential on diverting its disposal to several levels of the FRH, but today the vast majority of pulp is still composted (FRH tier 5) (Anacafe, 2008). Further diversion of pulp to uses listed above could elevate the byproduct to FRH tiers 4 or even 2, which would aid efforts to find economically and ecologically feasible uses for the pulp stream and therefore improve the overall sustainability of the coffee industry.

Mucilage, produced in the washed method and to a lesser extent in other coffee processing methods, represents approximately 1.0 billion kg of solid material annually. Given that it is almost exclusively managed under FRH tier 6, it is currently in the worst position. Mucilage washed as "honey water" is a major cause of water pollution in coffee producing regions. Efforts to reduce this pollutant have catalyzed the development of alternative wastewater treatment technologies, and legislation to implement stricter standards in controlling this waste stream (Ijanu et al., 2020; Zambrano-Franco et al., 2006). Despite its negative environmental impact, very little research has investigated alternative uses for mucilage. Although this is a smaller byproduct stream in terms of mass, finding alternative uses may provide the highest return on investment in terms of environmental sustainability. Coffee parchment and silverskin (chaff), together representing approximately 5.5 billion kg, almost exclusively managed under FRH tiers 4, 5, and 6, likewise have received very little scientific attention and therefore many opportunities for further research exist.

Globally, according to this study, an estimated 4.5 billion kg of spent coffee grounds are produced annually. At a commercial scale, coffee grounds are typically disposed directly to landfills (FRH tier 6). Spent coffee grounds are one of the most significant solid byproducts by mass with potentially high value. Approximately 28% of a roasted coffee bean is made up of soluble solids (Lingle, 2011), though a typical extraction yield for drip, espresso, and cold brew coffees is 15–22% to optimize flavor (SCA, 2018b). Thus, up to 46% of the original soluble solids and potentially beneficial compounds found in the brewed coffee drink are still present in the spent grounds, among many other non-soluble components. Spent grounds are highly suitable as a component in composting and also industrial products such as for green energy production, including biodiesel (Blinová et al., 2017; & Kondamudi et al., 2008), and biogas (Kim et al., 2017; & Li et al., 2015). These uses, and others yet developed, may divert large quantities of coffee ground waste from landfills up to compost (FRH tier 5) or industrial uses (FRH tiers 4).

## 6. Conclusions

Coffee postharvest processes and its related distribution chains are very complex. The fact that only a small fraction of harvested coffee mass is consumed by humans (2.6% for washed export-quality coffee) suggests that challenges and opportunities exist in the management and potential valorization of 26 billion kg of coffee byproducts annually. Each operational step (as many as 30) within the coffee postharvest processing phase, as reflected in the coffee postharvest PFD, directly affects the production of byproducts. Every step should be considered as a potential opportunity for future studies by the coffee industry, the scientific community, and related stakeholders to advocate for a higher environmental and economic sustainability of the coffee industry, as a whole. The data provided here serves as a foundation for other studies, including but not exclusive to the in-depth study of other and alternative processing methods, the development of new coffee postharvest equipment, and the evaluation of potential improvements on current equipment.

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## Declaration of Competing Interest

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## Appendicies

### Appendix A

English version (original in Spanish) of survey administered to wet and dry mill hosts.

### Appendix B

Common terms used in coffee industry with definitions and Spanish and Portuguese language equivalents.

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