Operations and Mass Flows in Postharvest Processing of Coffee: Comprehensive Case Study in Washed Coffee

By

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Abstract

Although coffee is one of the most valuable and widely traded agricultural commodities in the world, little information exists in the scientific literature regarding postharvest processing of the coffee beans. In particular, sustainability analyses require information on the coffee bean mass and property changes during processing, from harvest to final consumption. In Chapter 1 of this thesis, an overview of the coffee industry, the coffee cherry, and coffee processing methods are given. In Chapter 2, a detailed analysis of the washed (or wet-processed) method for postharvest processing of coffee is provided, as a case study. Mass flow data were collected through site visits, surveys, laboratory measurements, and interviews with coffee wet and dry mill operators 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. The results indicate that 100 kg of harvested coffee cherries will on average yield 2.6 kg of mass consumed by humans as exported coffee. The remaining 97.4 kg provide opportunities for development of alternative products, such as coffee cherry flour or 'cascara tea,' and economic uses such as energy production and fertilizers. Chapter 3 explores other processing methods, based on what was learned in Chapter 2, and provides hypothetical mass flows for each one. This analysis yields the first quantitative estimates for the relative amounts of coffee produced globally using the four main post-harvest processing techniques, with approximately 43% natural (dry), 39% washed, 12% honey (pulped natural), and 6% wet-hulled. The primary byproducts are also discussed in the context of a best use analysis. This study provides a foundation for further investigations in the fields of equipment improvement, byproduct utilization, environmental and economic sustainability of the coffee supply chain, and as a starting point for similar studies of other coffee processing methods.

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Chapter 1
Introduction & Literature Review

1.1 INTRODUCTION

Coffee is one of the most valuable and widely traded agricultural commodities, generating around $83 billion USD in global revenue in 2017 (Voora, Bermúdez, & Larrea, 2019), and supporting the livelihoods of an estimated 125 million people (Fairtrade Foundation, 2020), especially in developing countries. While over 100 species of coffee have been identified, only two are economically important: Arabica (*Coffea arabica*) representing about 60 % of global production, and Robusta (*Coffea canephora*) representing about 40 % in 2018 (De Castro & Marraccini, 2006; ICO, 2020c). In the context of specialty coffees, Arabica is almost exclusively preferred due to its superior flavor profile (Chambers et al., 2016). In terms of processing methods, coffee processed by the washed method is generally considered to provide a clean flavor which showcases the coffee bean itself while coffee processed by other methods is influenced to varying degrees by the presence of the coffee fruit and mucilage during the drying process and therefore carries additional flavors. That said, these other (non-washed) methods are becoming more popular, including in the specialty coffee context. On average (in 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 consumed mostly in developed or industrialized countries (20 % in the United States alone) (Dicum & 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 & Moayyad, 2017). Despite its immense popularity, most coffee producers face economic uncertainty or poverty, and key aspects of the environmental and economic sustainability of the coffee industry have come into question. These challenges include the coffee plant's lack of resilience in warmer temperatures, and diseases provoked by climate change, such as coffee rust (*Hemileia vastatrix*) (Davis et al., 2019).

Given the huge societal and economic impact of coffee across the world, surprisingly little scientific research has assessed the unit operations and mass flows associated with coffee postharvest processing, from the harvest to the cup, especially in English language scientific publications. Coffee postharvest processing requires a tremendous amount of work to convert a freshly harvested coffee cherry (fruit) into a finished beverage, and generates high mass flows of byproducts across the value chain. While these byproducts, such as coffee pulp, often result in pollution that add mitigation costs to producers (Chanakya & De Alwis, 2004; Coltro, Mourad, Oliveira, Baddini, & Kletecke, 2006), there are also opportunities for alternative economic uses for the byproducts, such as energy production, chemical compound extraction, and the production of industrial products (Esquivel & Jiménez, 2012). The United States Environmental Protection Agency (EPA) has published a Food Recovery Hierarchy which categorizes different uses for food waste generally. These categories are useful in categorizing options specifically for coffee byproducts, but little work has established precisely how much coffee mass ends up in each tier respectively (EPA, 2019). The global scope of the coffee sector complicates a robust elaboration of mass flows across the processing and supply chain. Coffee is typically produced in developing countries but primarily consumed in developed countries, so much of the 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.

This study addresses this gap in the literature by providing a detailed analysis and description of coffee postharvest processing, roasting, and brewing. The case study in Chapter 2 is focused on the washed or wet-processed method. The primary focus is on export grade Arabica coffee, which is typically retailed through cafes in consuming countries. The first objective of this study 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 wet mills and dry mills as well as North American roasteries and cafes. This process flow diagram informs on the equipment necessary to process the coffee from harvest to consumption and where and how byproducts are produced. The second objective is to provide mass flow data to inform efforts aimed at increasing postharvest equipment performance and the overall economic and environmental sustainability of coffee, providing a framework for further studies.

This thesis is organized as follows: In Chapter 1, an overview of the coffee industry, the coffee cherry, and coffee processing methods are given along with a review of related scientific literature. In Chapter 2, a detailed analysis of the washed (or wet-processed) method for postharvest processing of coffee is provided, as a case study. Data for mass flows and unit operations (steps) 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. This information is used to establish representative mass flow rates and process flow diagrams from harvest to cup. While it can be estimated that 39 % of coffee is processed in the washed method, the natural (dry) method represents an estimated 43 % of coffee produced (see Chapter 3). Other methods (wet-hulled and honey) make up the remainder. Chapter 3 explores these other methods, based on what was learned in Chapter 2, and provides hypothetical mass flows for each of them. It also discusses each of the primary byproducts in the context of a best use analysis for environmental sustainability. A detailed English/Spanish/Portuguese glossary of common coffee post-harvesting terms is provided in Appendix B to assist readers interested in the international scientific literature on coffee.

This thesis serves as a point of reference for potential future research into the coffee industry, with especially more scientific work being done in consuming countries, both as a means of educating consumers and as a means of forging partnerships with producers and scientists in the countries of origin. The future of coffee may depend on this kind of partnership, one focused on meeting global ecological and economic challenges and ensuring that coffee can be enjoyed by many generations to come.

1.2 BACKGROUND

1.2.1 The Coffee Cherry

A ripe coffee cherry is composed of six distinct layers (Eira et al., 2006; Murthy & Madhava Naidu, 2012), as seen in Figure 1. First, the outermost layer, generally 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, underneath the skin is a yellowish-white, soft, juicy, and sweet fruit flesh (outer mesocarp). Together, these two layers are typically 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 or the inner mesocarp. The mucilage is mainly composed of water, protein, sugar, pectic, and ash (Esquivel & Jiménez, 2012). This layer surrounds and binds the coffee beans (seeds) together and it is removed either through anaerobic degradation (fermentation) or mechanical means (Illy & 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 removed in the dry mill, this layer is sometimes referred to as the coffee hull. The fifth layer is the silver skin (epidermis), a thin, delicate, closely held layer that envelops the final layer (the 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. Finally, the innermost segment of the coffee cherry or sixth layer, is the seed, more commonly known as the coffee bean (endosperm). The primary goal of postharvest processing in coffee-producing countries is removal of the first five layers to obtain just the dried, green coffee bean for export.

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 basis (dm) (Duarte, Pereira, & Farah, 2010; Iriondo-DeHond et al., 2019). The primary chemical constituents of the bean are cellulose-like polymers, minerals, sugars, lipids, tannin, polyphenols, proteins, acids, and caffeine (Mussatto, Machado, Martins, & Teixeira, 2011).

Typically, there are two bean hemispheres in a single cherry, but in 5-10 % of cherries only a single bean forms, called a “peaberry”, and similarly rare, three beans may form (Suhandy & Yulia, 2017). Once removed from the five surrounding layers, the coffee bean, commonly known as green coffee, is roasted, ground, steeped in water and the soluble solids, which are extracted, are consumed in a coffee beverage while the remaining solids are usually discarded (Illy & Viani, 2005).

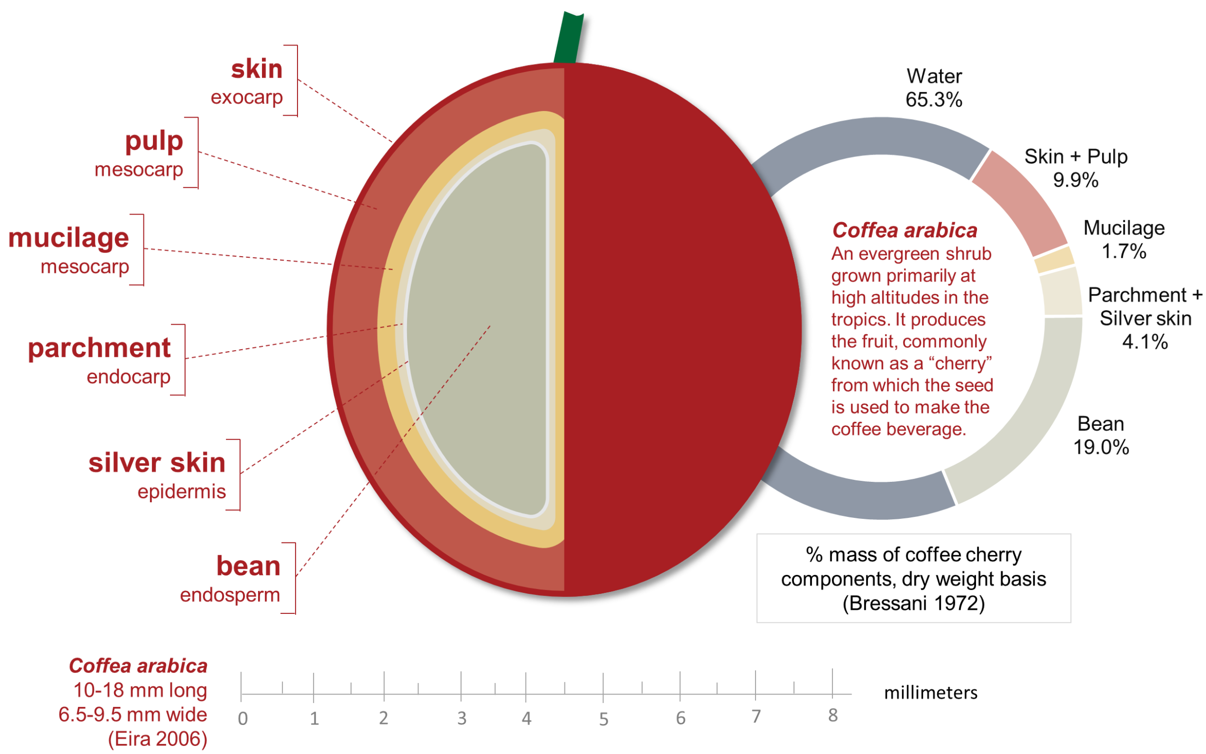


Figure 1 *Composition of a coffee cherry*, describing layers with botanical terms, typical size, and percent of mass on a dry-weight basis, as reported by Bressani (1972).

1.2.2 Methods for Processing Coffee

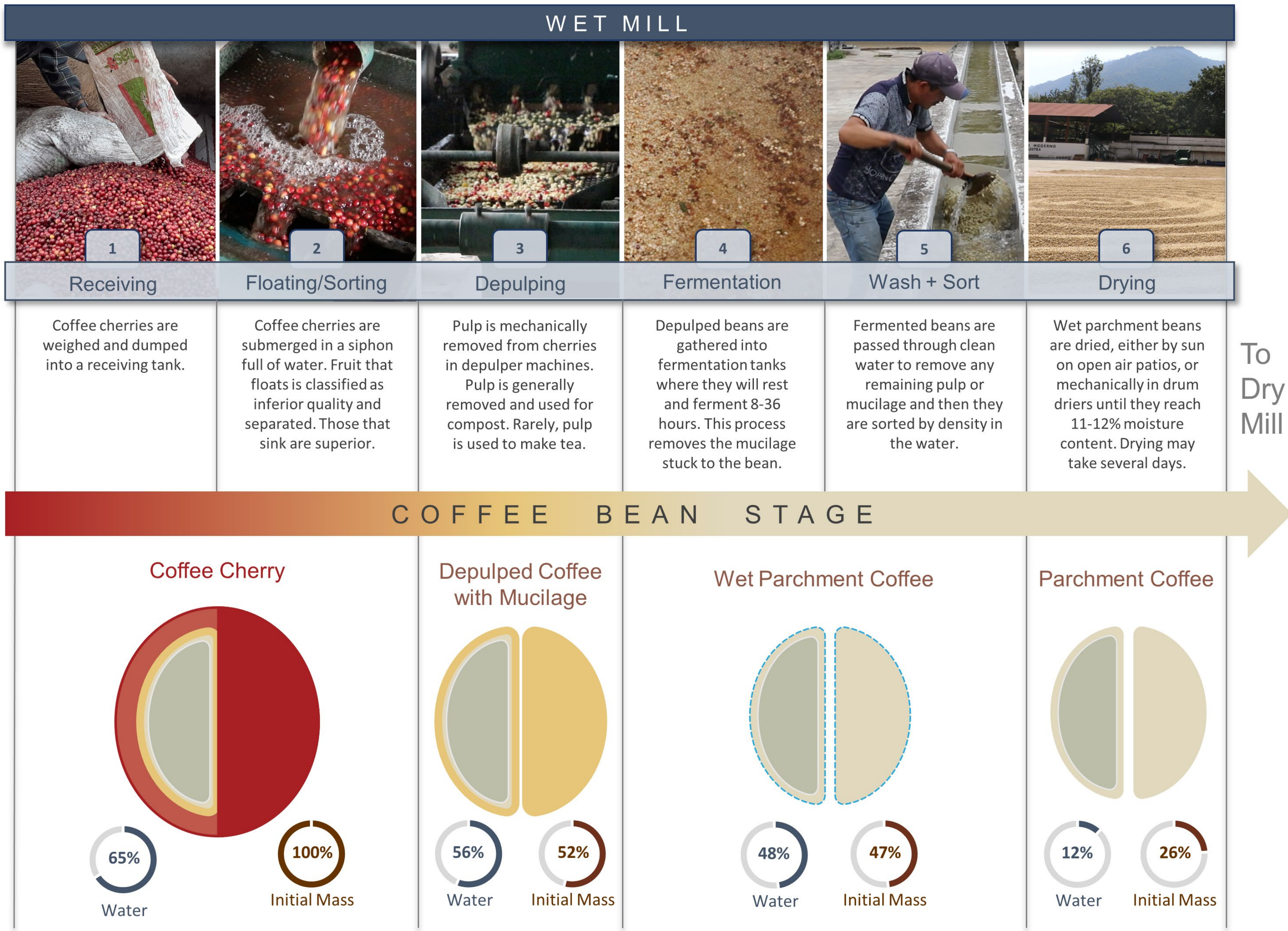
There are at least four primary methods for processing coffee, with many variations on these. Each processing method has been adapted to the places where they are performed (largely in response to environmental conditions and the availability of water) and are important, though certainly not exclusive, sources of flavor and quality in the final product. The washed method will be analyzed in Chapter 2. Other methods, which are described below, include the natural (dry), honey (semi-dry), and wet hulled methods (Evangelista, Miguel, Silva, Pinheiro, & Schwan, 2015) and will be discussed in Chapter 3.

1.2.2.1 Washed (or Wet-Processed) Method

The method which is the primary focus of this thesis, is known as washed or wet processing (Figure 2). This method is dominant in Colombia, Central America, and Hawaii and is present throughout the world (Silva, Schwan, Sousa Dias, & Wheals, 2000). Coffee cherries are usually hand harvested at optimum ripeness, generally determined by color (depends on variety), detachment force (8-10 N), and/or °Brix (13-15) (Martínez, Aristizábal, & Moreno, 2017). Then the coffee is taken to a wet mill where pulp is mechanically removed. Typically, depulped coffee is allowed to rest and ferment for up to 48 hours inside tanks, known as fermenters, to break down the mucilage layer, allowing it to subsequently be washed off. During this step, the microorganisms naturally present in the fermenter both degrade the mucilage and cause measurable impacts to the chemical composition of the green beans, ultimately altering their sensory profile (De Bruyn et al., 2017; Zhang, De Bruyn, Pothakos, Contreras, et al., 2019; Zhang, De Bruyn, Pothakos, Torres, et al., 2019). Alternatively, the mucilage can be removed by mechanical mucilage removers (Illy & Viani, 2005). Beans are then dried in the sun or by mechanical convective heated air drier, until they reach 10-12 % wet-basis moisture content (MC_{wb}), yielding what is known as parchment coffee (Folmer, 2017;

Schwan & Fleet, 2014). Once dry, the parchment coffee moves to the dry mill phase where the parchment, and more rarely the silver skins are mechanically removed to yield the green coffee. Higher quality (or higher value) coffee is exported while that which remains is typically transformed into instant coffee and/or consumed in domestic markets. Finally, coffee is roasted, brewed, and consumed. Therefore, in the washed processing method there are four primary phases: 1. The wet mill, 2. The dry mill, 3. The roastery, and 4. The point of coffee preparation for consumption (this is represented as the café), as seen in Figure 2.

(a)



WET MILL
1
Receiving
Coffee cherries are weighed and dumped into a receiving tank.
2
Floating/Sorting
Coffee cherries are submerged in a siphon full of water. Fruit that floats is classified as inferior quality and separated. Those that sink are superior.
3
Depulping
Pulp is mechanically removed from cherries in depulper machines. Pulp is generally removed and used for compost. Rarely, pulp is used to make tea.
4
Fermentation
Depulped beans are gathered into fermentation tanks where they will rest and ferment 8-36 hours. This process removes the mucilage stuck to the bean.
5
Wash + Sort
Fermented beans are passed through clean water to remove any remaining pulp or mucilage and then they are sorted by density in the water.
6
Drying
Wet parchment beans are dried, either by sun on open air patios, or mechanically in drum driers until they reach 11-12% moisture content. Drying may take several days.
To Dry Mill
COFFEE BEAN STAGE
Coffee Cherry
65%
Water
100%
Initial Mass
Depulped Coffee with Mucilage
56%
Water
52%
Initial Mass
Wet Parchment Coffee
48%
Water
47%
Initial Mass
Parchment Coffee
12%
Water
26%
Initial Mass

Figure 2 *Washed processing method for coffee*, describing important operations taking place in (a) the wet mill, (b) dry mill, roastery, and cafe phases of postharvest processing.

1.2.2.2 Natural (or dry) Method

An alternative method is known as the "natural" (or "dry") process, which may represent more than 40 % of all coffee produced (see Section 3.2.6) and is most common in Brazil, and some parts of Africa and Asia. The pulp and mucilage are left on the bean during drying, therefore eliminating most of the steps associated with a traditional wet mill. The dried cherries are then sent to the dry mill which removes the dried skin, pulp, mucilage, and parchment (together referred to as the "coffee husk") in a single operation. Although present, this method is much less common in Central America and Mexico and will not be discussed again until Chapter 3.

1.2.2.3 Wet Hulled Method

Also known as "semi-washed," "Sumatra processed," or "Giling Basah," wet hulling is a method employed mostly in Indonesia and consists of removing the pulp and parchment before drying the beans. This helps processors adapt to cloudy and humid weather which makes drying difficult since the coffee without its outer layers is easier to dry. After harvest, cherries are depulped as in other methods, but then after a quick pre-dry (less than 24 hours) which brings the water content down to 30-35 %, the depulped beans (with mucilage still attached) are put through a wet hulling machine which removes not only the mucilage but also the parchment layer below. Finally, the wet green coffee is transferred to drying patios where drying is completed more efficiently since the parchment has been removed. The downside is that the rough dehulling process tends to cause more damage to the green coffee than in other methods.

1.2.2.4 Honey (or pulped natural) Method

Honey produced coffees, largely from Central America and in particular Costa Rica, have found a niche in specialty markets, gaining popularity in the 2010s. The pulped natural method, an essentially identical method which has become increasingly popular in Brazil and elsewhere, will be included under this category for the purposes of this thesis. In the honey method, coffee cherries are mechanically depulped but mucilage is not removed through fermentation and washing like in the washed method, but rather placed on drying patios in their mucilage layer. The resulting parchment coffee can be described in at least three different styles: yellow, red, or black. As the coffee is drying, the mucilage (still attached) oxidizes and darkens in color. Beginning an amber color, the mucilage further oxidizes to a red-brown and finally a very dark (black) color. More mucilage left on the bean leads to darker colors due to longer drying times with black honey coffee drying with more fruit (about 100 % of mucilage remaining) than yellow honey coffee (about 25 % of mucilage). Red honey coffee has about 50 % of mucilage attached. As the coffee beans dry, yellow honey process coffee is turned more often to encourage drying, red and black are turned less often. The duration of drying is believed to help determine the amount of fruity flavors in the final roasted coffee. (Perfect Daily Grind, 2015; Trianon Coffee, 2020)

1.2.3 Coffee Byproducts as Percent of Coffee Cherry Mass

Few detailed studies have been conducted to determine mass losses at each step in the coffee postharvest processing. Extant studies reporting raw mass data are summarized in Figure 3. Bressani et al. (1972) published one of the first set of scientific measurements of the mass composition of a coffee cherry and all of its internal components. They found that from 1,000 g of fresh coffee cherries, 432 g of pulp (43.2 %) and 118 g mucilage (11.8 %) (fresh-weight basis) was removed. Second, although the study apparently did not subject the coffee to a drying step (which typically comes after mucilage removal in the washed method) 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 during a theoretical drying step equals 168 g (16.5 %).

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

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 coffee bean. Again, the methodology behind the estimation of these numbers 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 (Montilla-Pérez et al., 2008). 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, on a fresh-weight basis, the coffee 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 % of the initial harvest mass. Mass loss during the dehulling process 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 (Montilla-Pérez et al., 2008). Non-export quality coffee yielded qualitatively similar trends, with reported values differing from the above by no more than 2 % above or below the results for export quality coffee.

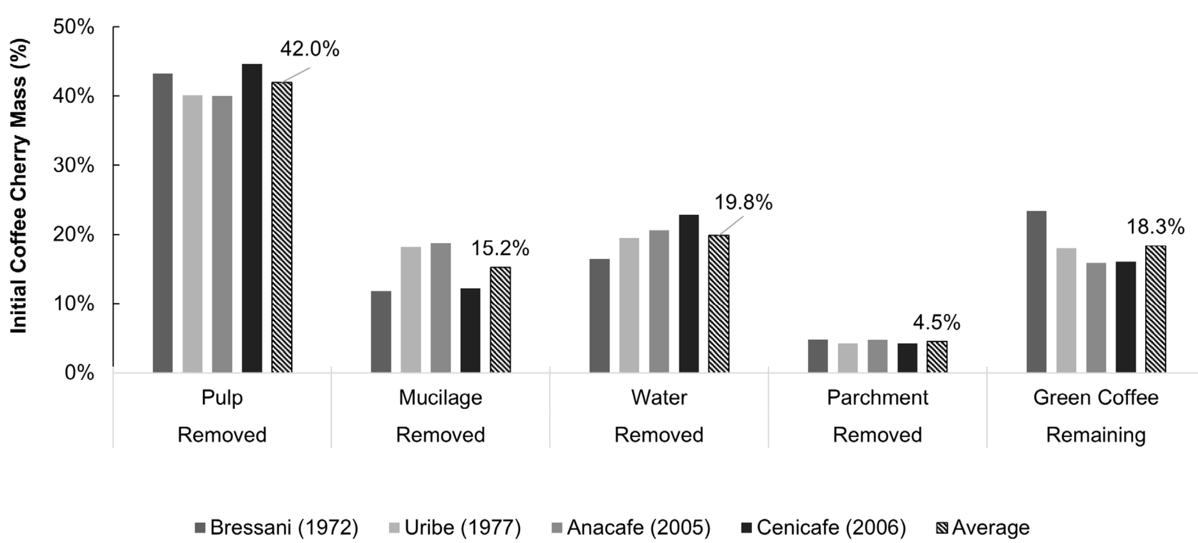


Figure 3 *Comparison of results for previous studies* showing percent of initial harvest mass lost at four key mass affecting steps in the wet and dry mill postharvest processing phases: depulping, fermentation, drying, and milling. Finally, the percentage left over as green coffee is displayed.

Chapter 2
Case Study: Operations & Mass Flows in the Washed Method

2.1 STUDY OVERVIEW

The mass percentages obtained from prior studies, as summarized in Figure 3, are informative and broadly consistent. However, none of these studies considered the postharvest process in a comprehensive way. More importantly, minimal field data was considered, and real-world effects such as material streams including foreign matter and inefficiencies in separations were excluded. Only Montilla-Pérez et al. (2008) considered variations in initial coffee cherry quality. Observations and measurements in these studies presumably represent optimum efficiency in highly controlled environments, not likely observed in the daily operations of commercial wet or dry mills. In addition, all of these studies end at the dry mill phase, and present green coffee as the final product. To the authors' knowledge, coffee roasting and brewing are not included in any extant mass flow study starting at harvest.

Toward that end, the goal for this collaborative study is to address the specific question: where does an initial harvest mass of 100 representative mass units of harvested cherries actually end up through the entire process, from harvest to cup? To answer this question, detailed surveys of wet mills and dry mills in Central America and Mexico were performed to produce representative process flow diagrams and to determine how that initial 100 kg is distributed across the entire chain. The data generated will facilitate coffee postharvest equipment improvements, sustainability and economic analyses, and focus attention on development of alternative uses for coffee processing byproducts.

2.2 MATERIALS AND METHODS

2.2.1 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. Central American countries and Mexico have traditionally been popular origins for specialty coffee buyers, with all five of the countries included in this study being among the top ten most sought after countries of origin for Specialty Coffee buyers (SCA, 2018a). The washed method is the focus of this study, due to its overwhelming prevalence 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) in Central America and Mexico. In Guatemala interviews were conducted with experts at Anacafé in Guatemala City, and then 7 wet mills, 4 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 1,500 to 2,200 meters above mean sea level (MAMSL). In Honduras 3 wet mills, and 5 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 3 wet mills and 1 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 9,072 and 317,514 kg/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 *Coffea 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 3 roasteries in Mexico and Central America.

2.2.2 Generation of representative process flow diagram

The authors personally visited a subset of 7 wet mills and 5 dry mills. At each of these site visits, qualitative process flow diagrams (PFDs) were sketched by hand to record the specific unit operations in use at each mill, 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 Software (2020). The roastery PFD relies on information from site visits in Guatemala and Mexico and consultations with industry experts in the United States. 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.

2.2.3 Acquisition of mass flow data

Detailed 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 coffee) or as a ratio of desired product to byproduct (such as coffee cherry to coffee pulp). These ratios were converted into a percent loss format. Such conversion ratios are referred to throughout this thesis as independently reported data, and are used to calculate the overall mass losses in an entire phase of processing (e.g., across the entire wet mill).

The provided conversion ratios generally did not, however, include information on mass changes at every unit operation step, 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 %) and this data is used in the analysis below (section 2.3).

2.2.4 Estimation of water content after de-pulping and 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 a representative 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-hour 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 24 samples were labeled, frozen, and sent to the Anacafé laboratory in Guatemala where water content was estimated from the samples, using the air-oven method (105 °C) for industrial testing (Reeb & Milota, 1999). After recording an initial weight, the samples were oven-dried until reaching a stable weight and the percent weight change was reported as the MC_{wb}.

2.2.5 Representative mass losses during roasting and brewing

For the roastery and café segments of the PFD, representative data was provided by private companies involved in roasting coffee in Central America, Mexico, and the United States. Available loss percentages at each step in the roasting and brewing process were reported.

Additionally, to determine mass loss represented as chaff during roasting, measurements were taken in the UC Davis Coffee Center experimental roastery. 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 which is a separate compartment attached to roaster. At the end of the roast, the chaff was weighed, recorded, and the percent loss was calculated.

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

2.2.6 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 the generally higher quality coffee that is ultimately exported, referring to that coffee as export quality, while the remaining coffee is indicated as non-export quality. There may be several quality categories for coffee in a given coffee market, and that may differ from country to country, so bifurcating coffee into these two common categories simplifies classification of the quality grades encountered throughout the world. This distinction is important as coffees destined for export not only flow through some different operational steps, but also differences in export as compared to non-export quality coffee may result in different mass losses at various steps throughout the postharvest process.

This study assumes that non-export quality coffee is primarily consumed in the country of origin (though that may not always be the case). The percent of coffee which is diverted to domestic markets in the countries studied (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 throughout this case study.

2.2.7 Mass Flow Calculations

To calculate mass losses throughout the postharvest process, a simple 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 1.2.2.1, 2.3). 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 Δm_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 $j = 1,2,3, \dots n$ represents each of the $n = 10$ distinct mass affecting steps and Δm_j is the average mass removed in step j.

To visualize the average behavior of postharvest coffee mass flows, a Sankey diagram, created using Illustrator 2020 (Adobe, USA) was generated to visually 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.

2.2.8 Descriptive statistics

A key challenge of this study was to obtain descriptive statistics for each material stream in post-harvest processing of coffee, some of which are rarely (if ever) measured at commercial operating mills. To reflect the diversity of collected data points, the progressive (cumulative) mass loss from the principal mass flow (export quality coffee) as it passed through each mass affecting step (Equation 2), 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, where 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.

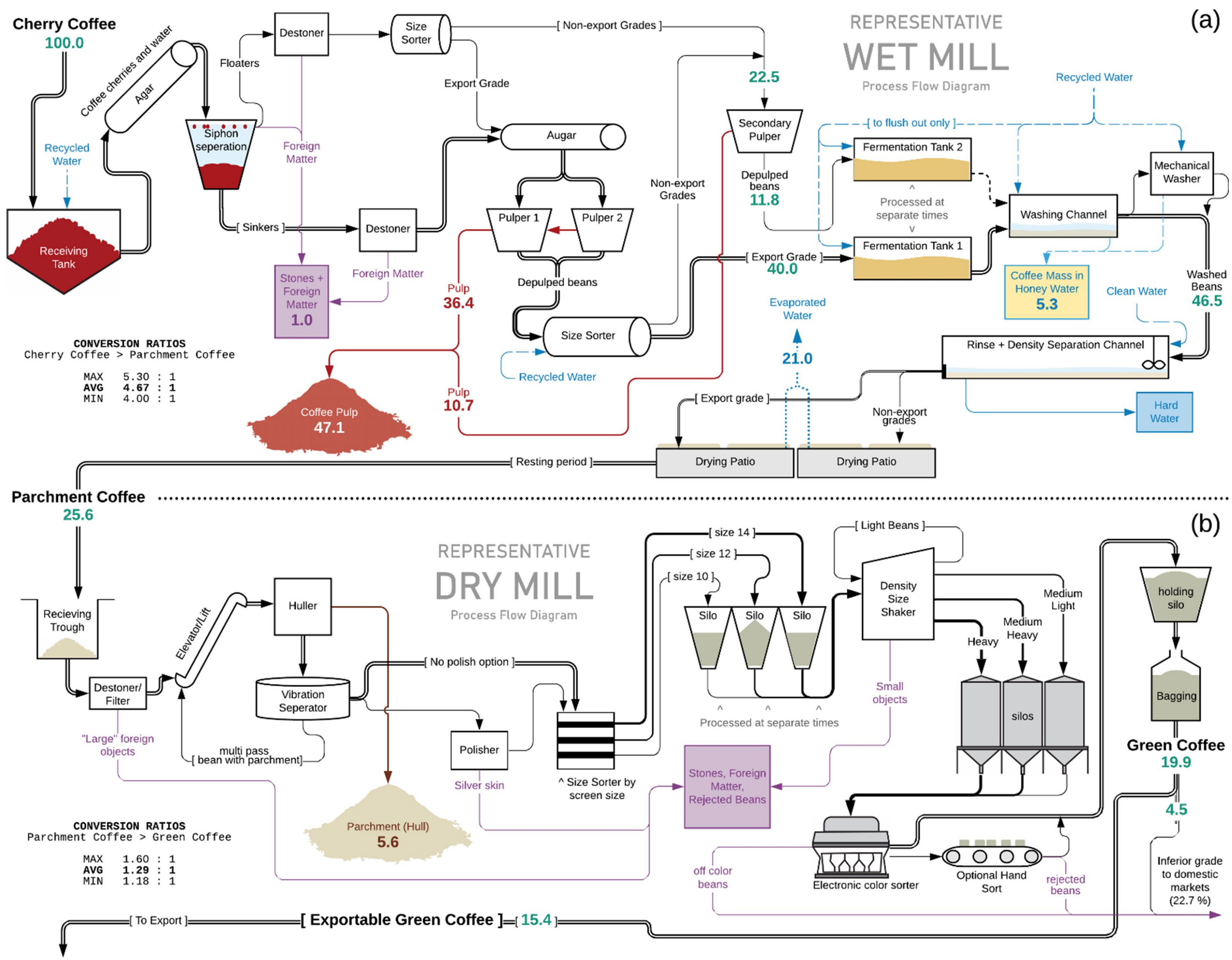
Since data sets were constructed from many sources, and each step *n* had a different sample size, to quantify the variability a propagation of errors approach was applied to estimate the standard deviation in the cumulative mass loss at step *n*,

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

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

2.3 RESULTS

The overall process flow diagram (PFD) for washed coffee is presented in Figure 4, and the corresponding Sankey diagram showing the overall mass flows is presented in Figure 5. In both figures, for clarity, only the average values of the mass flows are reported; likewise, in the following discussion of Figures 4 and 5, the statistical deviations are omitted for clarity. Detailed discussion of statistical measures of variation are deferred to later sections, where they are shown in Figures 6 and 7. The author emphasizes that while many variations exist, what is described here is typical in Central America, Mexico, and other regions of the world, and is intended to serve as a representative example of the washed or wet processed method. First, the unit operations and mass flows are described in detail, before then discussing quantification of statistical variations. Note that throughout this section, the phrase initial harvest mass means the initial 100 mass units (e.g. 100 kg) of harvested cherries at the beginning, whereas the phrase input mass means the mass input into the specific unit operation under discussion.


(a)
REPRESENTATIVE
WET MILL
Process Flow Diagram
Cherry Coffee
100.0
Recycled Water
Receiving Tank
Coffee cherries and water
Agar
Siphon seperation
Floaters
Sinkers
Destoner
Foreign Matter
Stones + Foreign Matter
1.0
Destoner
Foreign Matter
Size Sorter
Export Grade
[Non-export Grades]
Augar
Pulper 1
Pulper 2
Depulped beans
Pulp
36.4
Pulp
10.7
Coffee Pulp
47.1
Size Sorter
Recycled Water
Non-export Grades
22.5
Secondary Pulper
Depulped beans
11.8
[Export Grade]
40.0
Fermentation Tank 2
Processed at separate times
Fermentation Tank 1
[to flush out only]
Recycled Water
Washing Channel
Mechanical Washer
Coffee Mass in Honey Water
5.3
Clean Water
Washed Beans
46.5
Rinse + Density Separation Channel
Hard Water
Evaporated Water
21.0
[Export grade]
Non-export grades
Drying Patio
Drying Patio
[Resting period]
CONVERSION RATIOS
Cherry Coffee > Parchment Coffee
MAX 5.30 : 1
AVG 4.67 : 1
MIN 4.00 : 1
Parchment Coffee
25.6
(b)
REPRESENTATIVE
DRY MILL
Process Flow Diagram
Recieving Trough
Destoner/ Filter
"Large" foreign objects
Elevator/Lift
Huller
Vibration Seperator
multi pass
[bean with parchment]
Parchment (Hull)
5.6
[No polish option]
Polisher
Silver skin
^ Size Sorter by screen size
[size 14]
[size 12]
[size 10]
Silo
Silo
Silo
Processed at separate times
Stones, Foreign Matter, Rejected Beans
[Light Beans]
Density Size Shaker
Small objects
Heavy
Medium Heavy
Medium Light
silos
Electronic color sorter
Optional Hand Sort
off color beans
rejected beans
holding silo
Bagging
Green Coffee
19.9
4.5
Inferior grade to domestic markets (22.7 %)
CONVERSION RATIOS
Parchment Coffee > Green Coffee
MAX 1.60 : 1
AVG 1.29 : 1
MIN 1.18 : 1
[To Export]
[Exportable Green Coffee]
15.4

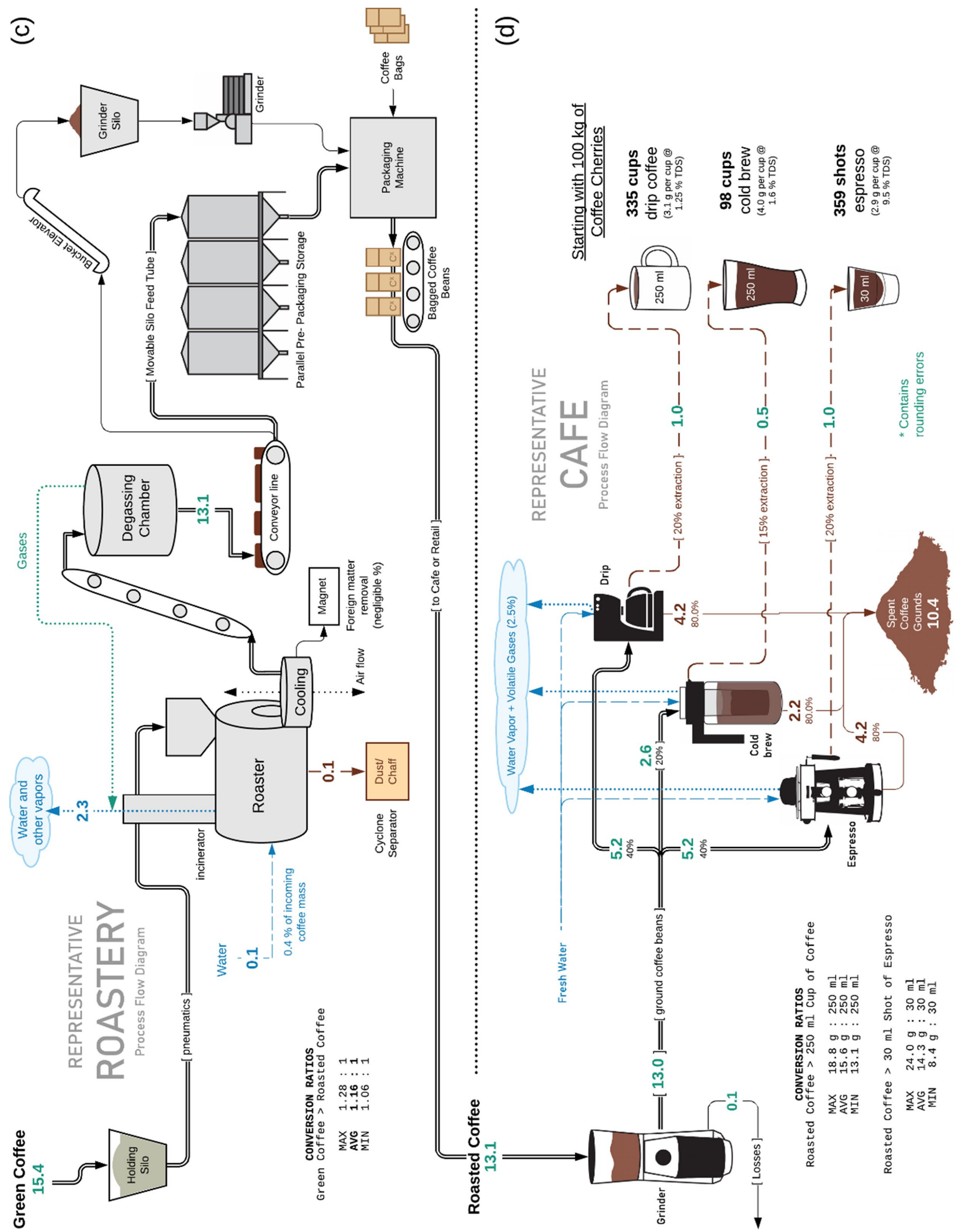


Figure 4 *Representative process flow diagram (PFD)* for the washed method of postharvest coffee processing as seen in Central America and Mexico. Inline numbers represent mass units. Phases represented are (a) wet mill process (b) dry mill process (c) roastery process (d) café process.

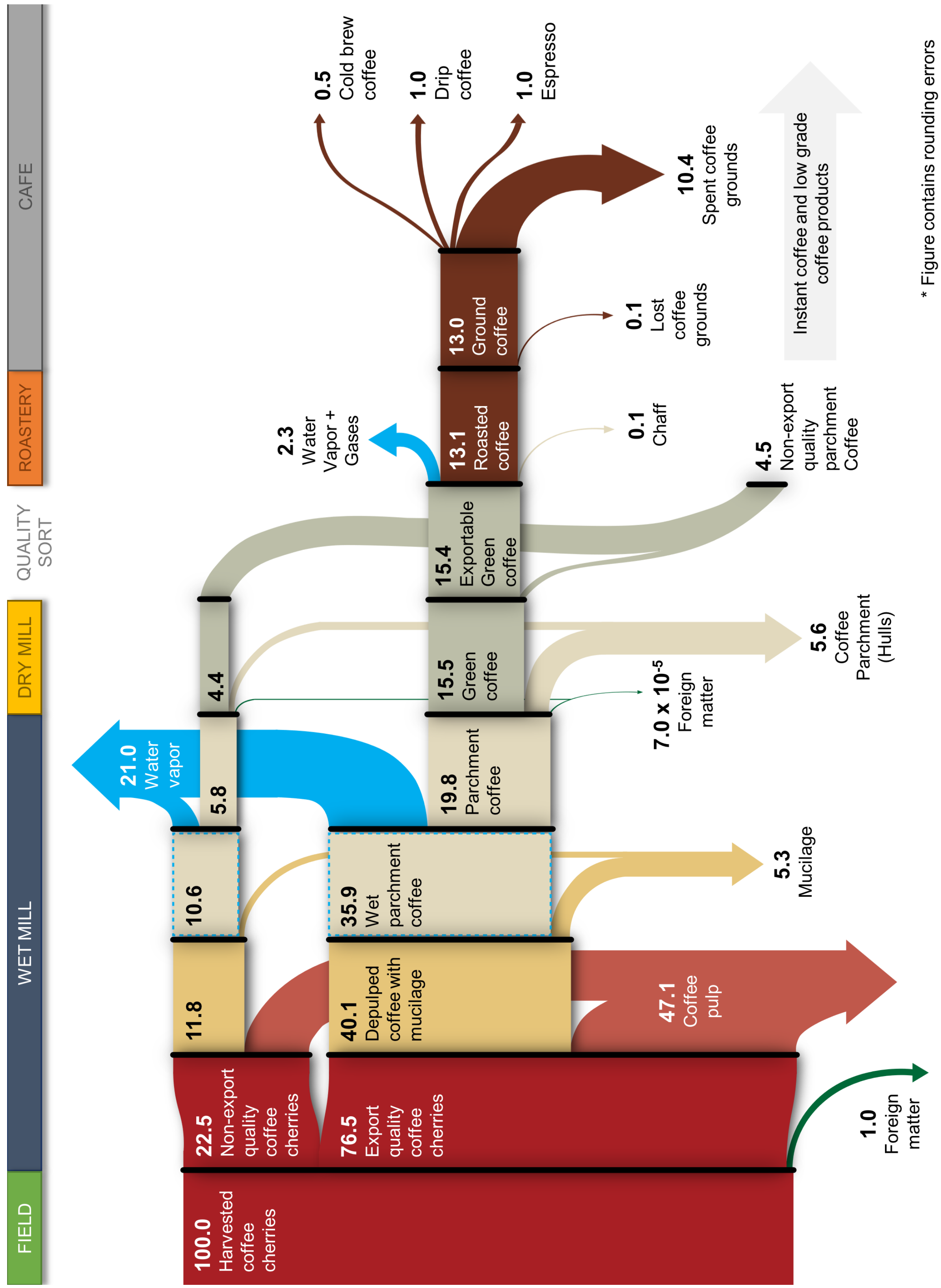


Figure 5 *Sankey diagram* for mass flows in the coffee in the washed method for postharvest processing. Numbers represented are averages; numbers might not sum due to rounding.

2.3.1 Wet Mill Phase

During the harvest, on farms where handpicking is performed, specially trained pickers select only those coffee cherries at the ideal maturity level, determined primarily by their color (and other factors outlined in section 1.2.2.1). Immature (typically green-colored), off-colored (dark brown to black), shriveled, and dry coffee cherries that are accidently harvested may be hand sorted in the field and transported to the wet mill in a separate container for separate processing. Upon arrival at the wet mill, the same day as harvest, the following operational steps take place (see PFD, Figure 4a):

2.3.1.1 Receiving: Freshly harvested 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. At this stage, coffee cherries were found to have 68.9 ± 0.9 % MC_{wb}.

2.3.1.2 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 tendency to float. Coffee cherries that sink then pass through a destoner, which removes heavy foreign matter such as small stones. Foreign matter is then disposed either as garbage or organic matter for compost. In this study, it was determined that 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 (generally known in Spanish as *Primeras*). During flotation, some coffee cherries also float because of their lower density due to physical quality defects, such as insect damage or unfertilized beans (so-called “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 national market, mainly for instant coffee production. Also, 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.

2.3.1.3 Depulping: Coffee cherries are conveyed by gravity and/or water through depulping machines, which removes the pulp (including skin) from the coffee beans using pressure and/or friction. There are different designs and sizes of depulping machines to meet the processing capacity of the particular wet mill. 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 in a “disk pulper” may be used to strip the pulp off the seed. To increase throughput and processing capacity, it is common to see 2-4 pulpers working in parallel within a single wet mill. 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 amendment for animal feed (Bressani & Gonzalez, 1978), or consumed as a tea known as “cascara tea” (Ciummo, 2014). The depulping step removes on average 47.6 % of the input mass of the cleaned coffee cherries, which represents 47.1 % of the initial harvest mass, with 51.9 % of the initial harvest mass transferred to the next step, as depulped coffee. Depulped coffee was found to have 61.8 ± 2.9 % MC_{wb}. These values are somewhat divergent from previous studies (section 1.2.3) which average 42.0 % of initial harvest mass lost; in other words, 5.1 % more mass appears to be lost during depulping in practice than is indicated by prior laboratory studies, possibly due in part to accidental losses of otherwise acceptable coffee cherries in this process which would not occur in a laboratory setting.

2.3.1.4 Fermentation (mucilage degradation): The depulped coffee is conveyed on conveyor belts, augers, or pushed by recycled water into open air cement or tile fermentation tanks and allowed to rest typically for 6-48 hours, during which fermentation occurs naturally (Anacafe, 2008). During this step the remaining mucilage is degraded via microbial processes and detaches from the underlying parchment layer. Fermentation is performed either by a more traditional method where depulped coffee is submerged under water, or in a waterless open-air fermentation tank. Fermented coffee was found to have 59.0 ± 1.4 % MC_{wb}.

2.3.1.5 Wash (mucilage removal) and secondary density sorting: When fermentation is complete, coffee beans are conveyed to the washing channels with recycled water, and ultimately washed with clean water to completely remove the mucilage from what will become wet parchment coffee. 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. 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 much smaller than indicated from prior laboratory studies, which suggested that 15.2 % of the initial mass is lost as mucilage, compared to the 5.3 % observed here (a difference of 9.9 %). During the washing step, coffee is sorted again based on its density, where the wet parchment coffee is floated through channels (approximately 20 cm tall and 20 cm wide with varying lengths according to the mill design) filled with flowing water. The coffee passes over progressively shorter barriers placed in the channel. Here, distinct batches of wet parchment coffee are separated based on differences in their density and sent to be separately dried (Anacafe, 2005). Wet parchment coffee was found to have 54.3 ± 1.8 % MC_{wb}.

2.3.1.6 Drying: Typically, wet parchment coffee is removed from the washing stage manually (in containers appropriate to the size of the milling operation) and spread out by hand onto open-air drying patios or on raised beds, under a shade cloth, semi-transparent roofing, or under open sky and spread into a singular layer. Wet parchment is periodically turned (up to 17 times per day) (Illy & Viani, 2005) with a wooden shovel (or other implement) to dehydrate the wet parchment coffee beans evenly from their initial MC_{wb} equal to 54.3 ± 1.8 % to a desired storage level equal to 10-12 % MC_{wb}, yielding the dry parchment coffee. Conventional sun drying method time and throughput is mostly dependent on environmental conditions and initial moisture content, but it frequently takes between 2 to 15 days to complete. 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), and the parchment coffee mass maintaining a temperature of (40 to 45) °C (Illy & Viani, 2005). Despite being faster, mechanical drying methods can potentially degrade coffee quality due to internal damage caused by temperatures higher than 40 °C (Alves et al., 2020). Also, both conventional (sun) and mechanical drying methods can be combined. Regardless of the drying 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 are closely in line with previous studies, which average 19.8 % of initial harvest mass (1.2 % less than this study). Drying is typically the final step in the wet mill phase of the postharvest process. Upon completion of drying, dry parchment coffee is stored until it is transferred to the dry mill.

During the wet mill phase, there is an overall mass loss of 78.4 % of the initial harvest mass (independently reported data). The solid byproducts are principally coffee pulp (47.1 % of initial harvest mass) and mucilage (which is removed in "honey water" as 5.3 % of initial harvest mass), and foreign matter (1.0 % initial harvest mass).

After the wet mill phase, parchment coffee may be stored for weeks to months, or may instead be transported directly to the dry mill. This may be in the same facility or elsewhere. In Guatemala, wet mills are generally smaller and more numerous (~3,000 in the country) while dry mills are larger and there 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), for example.

2.3.2 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. This represents an insignificant mass fraction, equal to approximately 2.7×10^{-4} % of the mass of parchment coffee, or 7.0×10^{-5} % of the initial harvest mass, with 25.6 % of the initial harvest mass passing to the next step. It is then conveyed throughout the dry mill using bucket lifts, conveyor belts, or pneumatic systems.

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 inner bean. This parchment is collected and composted, or typically used as a biofuel energy source in the mill, or as a heat source for mechanical driers (Illy & Viani, 2005). 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 19.9 % of the initial harvest mass passing on to the next step as unsorted green coffee. These findings are similar to previous studies which average a loss of 4.5 % of initial harvest mass (1.1 % less than this study). After dehulling, dry millers have the option to also polish the beans. The coffee polisher uses friction to remove the silver skin layer of the coffee bean, generally using phosphor bronze bars that rotate inside a cylinder through which the hulled beans are passed (ITC, 2012). This is done to improve the aesthetics of the beans and reduce the amount of chaff during the roasting process, but is generally not preferred by specialty coffee buyers because it is thought to reduce the quality of the bean. In certain coffees it may encourage loss of color that forms part of the aging process whereby the color and taste of green coffee deteriorate (mainly due to exposure to heat generated by friction) (ITC, 2012), and therefore this study didn't consider this mass loss stream in 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 on a perforated inclined surface with air blowing up through the perforations from beneath called a “densitometric” or “gravity” table. Denser beans migrate to the higher end of the table while less dense beans remain at the lower end. Finally, beans are sorted by color through inline electronic color sorting machines. In some mills, hand sorting by humans at the end of the process ensures that the machine sorting was done correctly (ITC, 2012). Through this sorting process, 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 local consumption. Making batches homogenous also aids more even roasting. The mass diverted to the non-export quality coffee stream at this step is estimated to be on average 4.1 % of the input mass, or 0.8 % of initial harvest mass, with 19.1 % of initial harvest mass passing to the next step as sorted green coffee. At the end of the sorting step, sub-samples are commonly collected and tested for flavor (cupping) and additional quality evaluation before export.

After sorting, export quality green coffee is poured from holding silos into jute or 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 loaded onto cargo ships to be transported to consumer countries (NCA, 2020). Approximately 70 % of all coffee produced worldwide is exported from its country of origin (ICO, 2020a).

At the end of the dry mill phase, it was determined that that there is an average total loss of 8.1 % of the initial harvest mass (independently reported data). The primary byproducts being coffee parchment (or hulls) (5.6 % of initial harvest mass), defective beans (0.8 % of initial harvest mass), and foreign matter (7.0 x 10^-5 % of initial harvest mass).

2.3.3 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. When wet and dry milling processes (phases) are performed in the same facility, the separation to domestic markets may instead occur at the end of the dry mill process. Variations are seen between countries and regions.

Many factors influence the proportion of harvested coffee which goes to export markets and how much is sent to domestic 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. This study assumes an average of 22.7 % of non-export quality coffee harvested is ultimately consumed in domestic markets (section 2.2.6), including defects removed in the dry mill reported above.

The non-export quality coffee is 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. By the end of the dry mill phase, all non-export quality coffee has been diverted to domestic markets and therefore, for the purposes of the Sankey diagram (Figure 5), the separation is visually represented after the dry mill phase, but the mass flows in the process flow diagram take the dispersed nature of the quality sorting into account.

2.3.4 Roastery Phase

After exported green coffee arrives in the country or region of consumption, it is typically stored in a dedicated warehouse prior to being shipped to a roasting facility. Although biological or chemical degradation can occur during long storage, this study assumes sufficiently short storage times such that any mass loss is negligible. Eventually the beans are shipped to a roastery where several unit operations occur: cleaning, roasting, cooling, and packaging steps (see process flow diagram, Figure 4c). Grinding may also occur at the roastery but in this representative description grinding is described the café phase.

2.3.4.1 Cleaning: Bags (typically 60-70 kg) of green coffee beans are opened, dumped into a hopper, and in large roasteries, screened to remove foreign matter. In smaller roasteries, screening is generally only performed after roasting. 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. Because this material stream is added after harvest and then removed, it doesn't affect the overall mass calculations based on the initial harvest mass. In large roasteries, the green beans are then weighed and 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 conveyed manually in bags and poured into the hopper of the coffee roaster by coffee roasting personnel.

2.3.4.2 Roasting: Roasters typically operate at temperatures between 140-250 °C (Illy & Viani, 2005), and the beans are roasted for a period of time ranging from a few minutes to about 30 minutes. 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 in each second of 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 two primary byproducts from the roasting process (EPA, 1995):

2.3.4.2.1 Chaff is produced as the remaining silver skin detaches from the beans during the roasting process as the beans increase in volume. According to data obtained through laboratory measurements of representative light, medium, and dark roasts (Agtron = 44.2 ± 4.8) (section 2.2.5), chaff represents on average 0.5

% of the input green coffee mass or 0.1 % of the initial harvest mass. 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 gases including volatile organic compounds (VOCs) are released from the coffee during the roasting and cooling process (sections 2.3.4.2 and 2.3.4.3). A solid-gas or cyclone separator may be used in this process 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 650-816 °C (EPA, 1995). Cleaned gases are released into the atmosphere. According to the previously mentioned laboratory measurements, the mass removed at this step represents on average 14.7 % of the input green coffee mass and 2.3 % of the initial harvest mass.

2.3.4.3 Cooling: Following roasting, the roasted coffee is cooled from roasting temperatures to approximately 25 °C and passed through air classifiers called destoners that remove stones, metal fragments (using magnets), and other waste not removed during prior green coffee screening (if any). 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 to storage silos. This stabilization process is called equilibration (EPA, 1995). In other cases, the roasted beans go directly to the packing step.

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 bags or vacuum-sealed bags 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. This mass loss is small (< 1 %) (Smrke, 2019) and is accounted for in the water vapor and gas material stream explained in section 2.3.4.2.2.

In the roastery phase the average total loss to the input green coffee mass was 14.8 % (independently reported), which represents 2.3 % of the initial harvest mass. The amount of mass lost during the roastery phase is most influenced by the level of roast (light vs. dark) with a dark roast having a higher mass loss than a light roast. The primary solid byproduct produced is chaff (0.1 % of initial harvest mass on average). Chaff mass percentage is variable based on how much (if any) polishing was done in the dry mill. The mass of roasted coffee which passes to the next phase represents 13.1 % of the initial harvest mass of harvested coffee cherries.

2.3.5 Café Phase

After the roastery phase, packed roasted coffee is shipped by ground transport 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 whether the coffee is brewed in a café, at home, or elsewhere (see process flow diagram, Figure 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 machinery as varied as a hand crank home grinder, to a retail electric grinder (throughput = 10-80 kg h^{-1}), to industrial sized grinders for mass production (throughput = 140-400 kg h^{-1}). Types of grinders include: flat disk grinders, conical burr grinders, blade grinders, and stone grinders (Folmer, 2017). Variability in grinders means each must be calibrated for coarseness to the requirements of the individual user and product. In actual retail café operations, a small fraction of coffee grounds is lost, spilled, or used for "dialing in" espresso machines without being served; this study estimates this to represent a loss of 1.0 %. Therefore, an average of 13.0 % of initial harvest mass passes to the next step as ground coffee.

2.3.5.2 Brewing: Approximately 28 % of a roasted coffee bean mass is made up of water-soluble solids (with the other 72 % of mass insoluble) (Lingle, 2011) however coffee is typically not fully extracted because doing so yields less desirable flavor profiles. The percentage of mass which dissolves in a given brew is the extraction yield. There are three primary methods for brewing coffee in a specialty coffee context, each with unique properties: drip brew, espresso, and cold brew. Many other variations also exist 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, with the resulting mixture being the coffee beverage which is consumed. The remaining mass becomes spent coffee grounds. It is outside the scope of this study to precisely measure the distribution of coffee beverage types prepared in consuming countries; therefore, using values qualitatively consistent with information from industry participants and economic reports, a representative breakdown of 40 % drip, 40 % espresso (including for use in espresso based drinks), and 20 % cold brew is provided to typify broadly how much coffee beverage can be produced from a given initial harvest mass. Based on the above calculations, an initial harvest mass of 100.0 kg will produce 13.0 kg of export quality ground coffee beans, which may be brewed by the methods that follow:

2.3.5.2.1 Drip brew coffee is made by allowing gravity to pull hot water through coffee grounds and then a filter. Based on industry standards (SCA, 2018b), the final coffee beverage will have on average 1.25 ± 0.1 % total dissolved solids (TDS), which in a 250 ml metric cup of coffee would represent 3.1 g of coffee mass. If 40 % (5.2 kg) of total ground coffee beans are used in drip, and the extraction yield is 20 % (typical in industry), 4 kg will become spent grounds and 1 kg will be consumed as a part of <u>335 metric cups (250 ml) of liquid beverage</u>.

2.3.5.2.2 Espresso coffee is made by forcing pressurized hot water (90 ± 2 °C) through finely ground coffee in an espresso machine (Illy & Viani, 2005). In the present study, this method is assumed to account for approximately 40 % (5.2 kg) of export quality coffee consumed and have on average 9.5 % TDS, equaling 2.9 g of coffee solids per shot (30 ml). If the extraction yield is 20 %, therefore, approximately <u>359 shots (30 ml) of espresso are produced</u>.

2.3.5.2.3 Cold brew coffee has become more popular in recent years. Coffee grounds are submerged in cold, ambient, or even warm temperature water (approximately 2-77 °C) for extended periods of time (typically 14-24 hours). Assuming an initial harvest mass of ground coffee equal to 100 kg, a TDS of 1.6 %, and an extraction yield of 15 % means it is calculated that 0.4 kg of coffee grounds are dissolved into a total of 98 metric cups (250 ml) of cold brew coffee (4 g per cup).

In the café phase, representing all exported coffee consumed regardless of location, an average of 10.5 % of the initial harvest mass was lost, the vast majority becoming spent coffee grounds (10.4 %).

2.3.6 Statistical Measures of Variations

The prior sections and Figures 4 and 5 focused on the average mass flows, but large variations at each step of the process were observed. These variations are characterized in detail in Figure 6, which shows box plots displaying the reported data for each of the mass affecting steps in the postharvest process in the top section, and the mass loss that was independently reported for the entire wet mill, dry mill, and roastery phases in the bottom section. Mass loss here is in reference to the input mass for that particular step or phase. The greatest variability was seen in the following steps: quality sort (mass diverted as non-export quality coffee), fermentation (mass lost as mucilage), drying (mass lost as water vapor), and depulping (mass lost as pulp) steps with standard deviations of 23.6, 9.2, 7.7, and 5.7 % respectively.

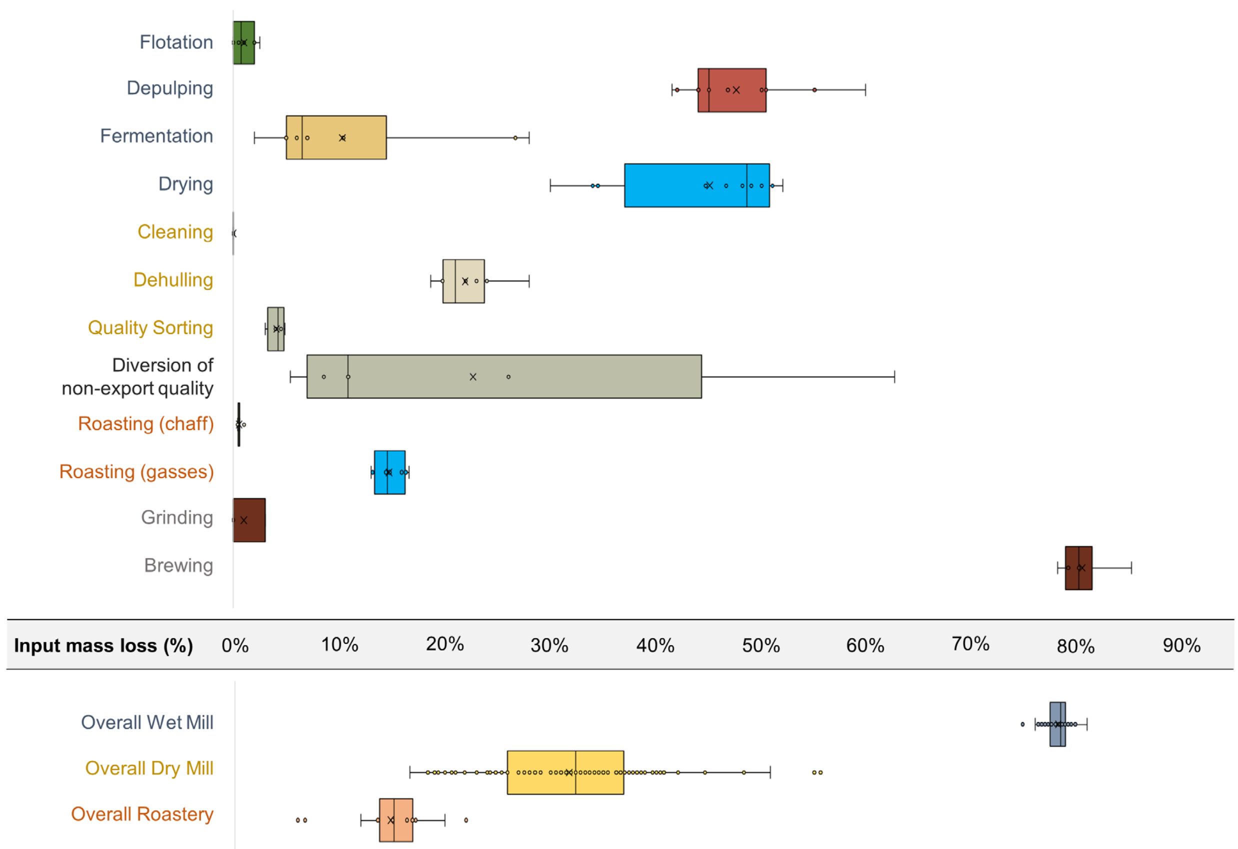
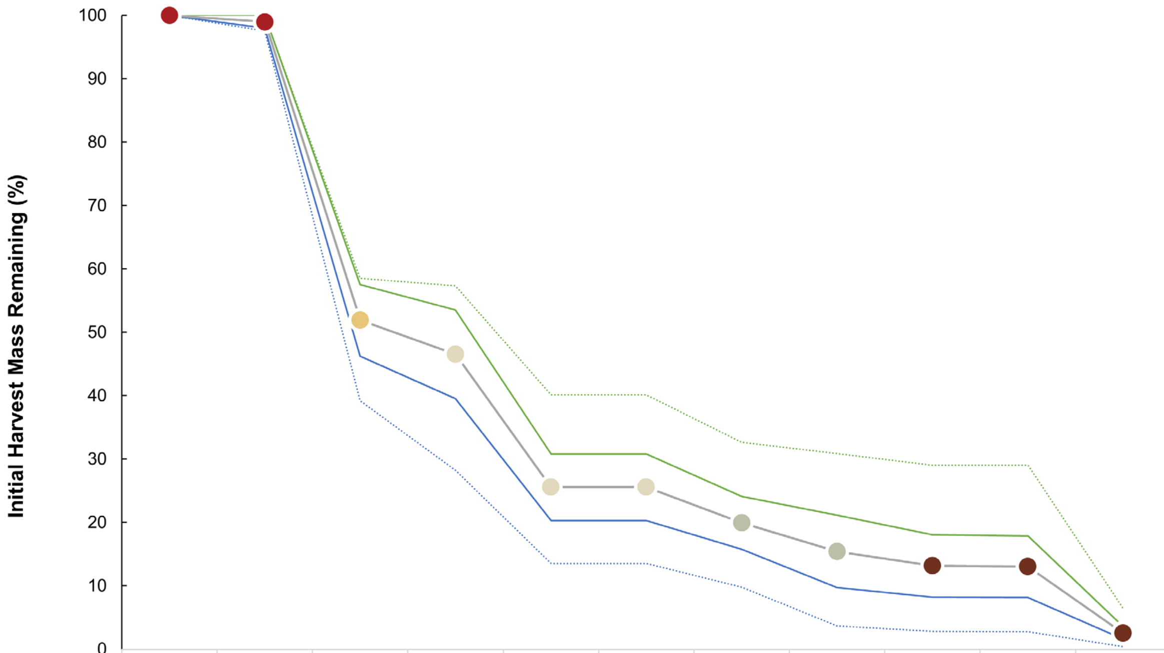


Figure 6 *Boxplots* for data representing mass loss percentages, with reference to the input mass, at each mass affecting step in the washed method. Overall mass loss in the wet mill, dry mill, and roastery phases from independently reported data is also provided.

An alternative way to visualize the variability in the mass flows is shown in Figure 7, which shows the range observed in cumulative mass loss versus processing step, with reference to the initial harvest mass. The average values accord with Figure 5, but the minimum and maximum observations as well as the standard deviation, with propagated errors as calculated in Equation 3 are also presented.



	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

Figure 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 Equation 3) are also displayed. The amount shown is the mass remaining after all mass in previous steps is removed.

2.4 DISCUSSION AND CONCLUSIONS

Coffee postharvest processes and related distribution chains are exceptionally complex. It was determined that 100.0 kg of harvested coffee cherries will on average yield 2.6 kg of mass (2.6 %) consumed by humans as export quality coffee. The washed processing method includes the following steps: depulping, fermentation, and drying in the wet mill; hulling and sorting in the dry mill; roasting, cooling, and packing in the roastery; and finally grinding and brewing in the café phase. In total the washed method has at least 10 mass affecting, 7 sorting, and more than 30 operations overall (Figure 4) that are typically performed on coffee destined for export markets, with the majority taking place in the country of origin. This process also produces at least 5 solid byproducts, including: pulp, mucilage (honey water), coffee parchment, chaff (silver skin), and spent grounds which together represent more than 96 % of initial harvest mass. This study describes and quantifies these byproduct mass flow streams in detail (both in Chapter 2 and Chapter 3). Many uses for these byproducts are being studied and implemented, however, much opportunity for further research and development exist in improving the economic and ecological sustainability of the coffee industry. This is foundational information for understanding both the environmental impact of existing practices and alternative options for diverting these byproducts towards more beneficial uses.

Generally, these results corroborate the major trends already known for postharvest processing via the washed method. Mass loss during the depulping and drying are the largest causes of mass loss, though other steps are not insignificant. One key finding of this study was that mass loss during the depulping step was 5.1 % higher in commercial practice than what was reported in previous laboratory measurements. Given the quantities of pulp produced annually, this amount might seem "small," but globally it corresponds to a very significant total mass. 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 some other cause. Furthermore, a large source of variability in the postharvest process comes from the percentage of coffee that is exported verses locally 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.

Chapter 3
Review of All Processing Methods and Future Studies

3.1 OVERVIEW

The case study presented in Chapter 2 focused exclusively on the washed method for coffee processing, which represents a significant proportion of coffee postharvest processing worldwide, however, coffee produced through other methods (section 1.2.2) are also significant, especially the natural (or dry) method which may represent more than 40 % of coffee processed globally (see section 3.2.6). Therefore, the value of using the framework from this case study to analyze and estimate byproduct mass flows from other processing methods is compelling. The remainder of this chapter will look more broadly at the coffee industry as a whole, using total production numbers, all processing methods, and numbers derived from those totals. It will not be restricted to only export quality coffees which have passed through the washed method as seen in the case study of Chapter 2. As such, it will not account for domestic consumption as in Chapter 2 but instead will include that stream in all totals, therefore increasing the amount reported as passing through the roastery and café phases and ultimately being consumed by humans. These new estimates should be considered as global estimates rather than Central American washed coffee as in Chapter 2.

3.1.1 Assumptions About Instant (Soluble) Coffee

For the purposes of this chapter, it is assumed that all coffee mass destined for domestic consumption globally (30.7 % average in 2015-2019) will be converted into instant coffee. Though it is known that some non-instant coffee is produced and/or consumed in the domestic markets of coffee producing countries and some instant coffee is produced and/or consumed in export markets, this assumption is the most reasonable available to the author without access to proprietary information. Furthermore, a preliminary review of available statistics available through the USDA Foreign Agricultural Service (USDA FAS, 2020) generally supports this percentage. Since specific processing data was not available, and it is known that the instant coffee industry seeks to maximize extraction of soluble solids, it is assumed that the extraction yield of coffee solids in the production of instant coffee is 30 %. This would represent a near maximum efficiency in the removal of soluble solids from the coffee bean. In practice, the extraction yield may be less than 30 %, but it does provide an upper bound on actual soluble coffee mass consumed by humans. This is roughly in line with what is reported by Mussatto et al. (2011).

Applying the above assumptions to the mass loss formula developed in Chapter 2, it can be estimated that on average 3.8 % (1.8 billion kg) of all coffee mass harvested globally will be consumed by humans annually with 1.6 % (740 million kg) being in the form of instant coffee. If foreign matter is neglected as a byproduct, this number becomes 3.9 %. If there are 7.8 billion people on earth (Worldometer, 2020), that is 77 cups (250 ml) of drip coffee for every person on earth each year or 1.6 billion cups consumed on earth per day.

3.2 NATURAL, WET-HULLED AND HONEY PROCESSING METHODS

3.2.1 Explanation of Methods

The numbers presented below are estimates for the various coffee processing methods based on the information gathered for the case study in Chapter 2, using many of the same assumptions applied in the washed method. While the information does appear to broadly agree with what is known about these methods, further study and data from the natural, wet-hulled, and honey processing methods would be welcome to refine these numbers and provide a complete view of mass flows in the coffee industry at large. As previously stated, these analyses do not attempt to represent mass which is diverted to domestic consumption, coffee which is made into instant coffee, nor how much is consumed in each type of coffee beverage, but rather assumes that all coffee passes through a single, unseparated flow and traditional brewing methods. Each of the following methods will be explored, analyzing the mass flows in reference to an initial harvest mass of 100 kg, as in the case study.

3.2.2 Natural (Dry) Method

The natural process (Section 1.2.2.2) does not include depulping and mucilage removal steps, but rather allows the coffee fruit to dry on the bean before the dehulling process then removes the entire husk (dried fruit and parchment) from the bean. Therefore, the byproducts from this method are substantially different than the washed method. Rather than fresh pulp and wet mucilage byproducts, the dry matter from these two coffee components is removed as a single coffee husk.

Bressani et al. (1972) found that coffee pulp had a dry matter (dm) content of 22.9 %. The mucilage had a dm content of 14.4 %. Using the framework of 100 kg of coffee cherries harvested it can be concluded that approximately 18.4 kg of the initial harvest mass would be removed as coffee husk (which agrees with Murthy et al. (2012)), while 60.6 kg would be removed as water vapor during the drying process as described in the hypothetical Sankey diagram in Figure 8. Again, since domestic consumption (estimated to be 22.7 % in Chapter 2) is ignored in this analysis, all of the initial harvest mass is assumed to pass through the entire process and therefore the final percent of mass consumed by humans is calculated as 3.3 % rather than 2.6 %. The underlying efficiencies have not changed.

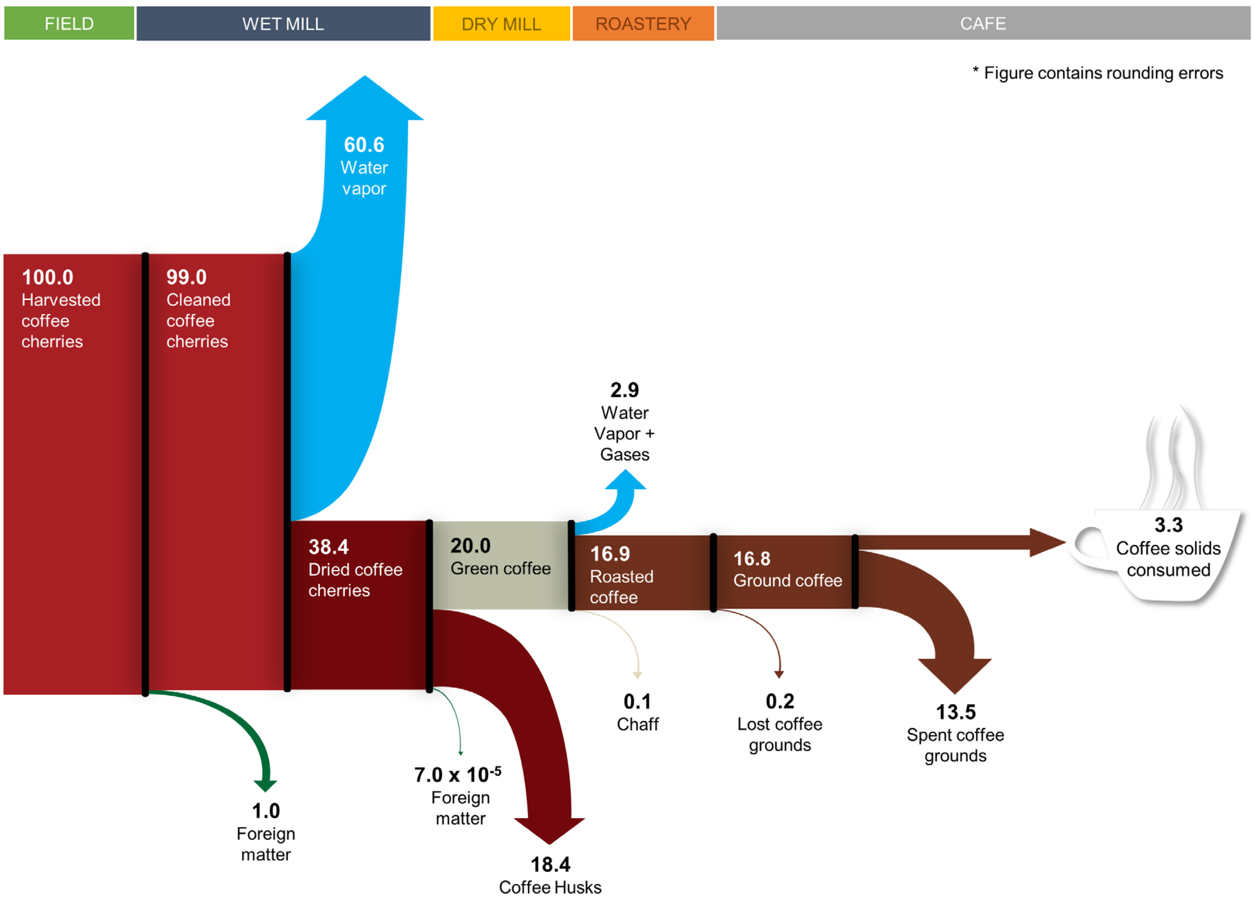


Figure 8 *Hypothetical Sankey diagram for mass flows in the coffee in the* ***natural method*** for postharvest processing. Numbers represented are estimates; numbers might not sum due to rounding.

3.2.3 Wet-hulled Method

The wet hulled method (described in section *1.2.2.3)*, primarily performed in Indonesia, produces the same pulp byproduct as the washed method, but rather than fully drying, a partial drying is done (down to about 30 % moisture content) and then wet coffee hulls are produced as the mucilage and parchment are removed while still moist. Estimated mass flows are presented in Figure 9. This method, used mostly in wet climate, removes the most mass before drying of any method.

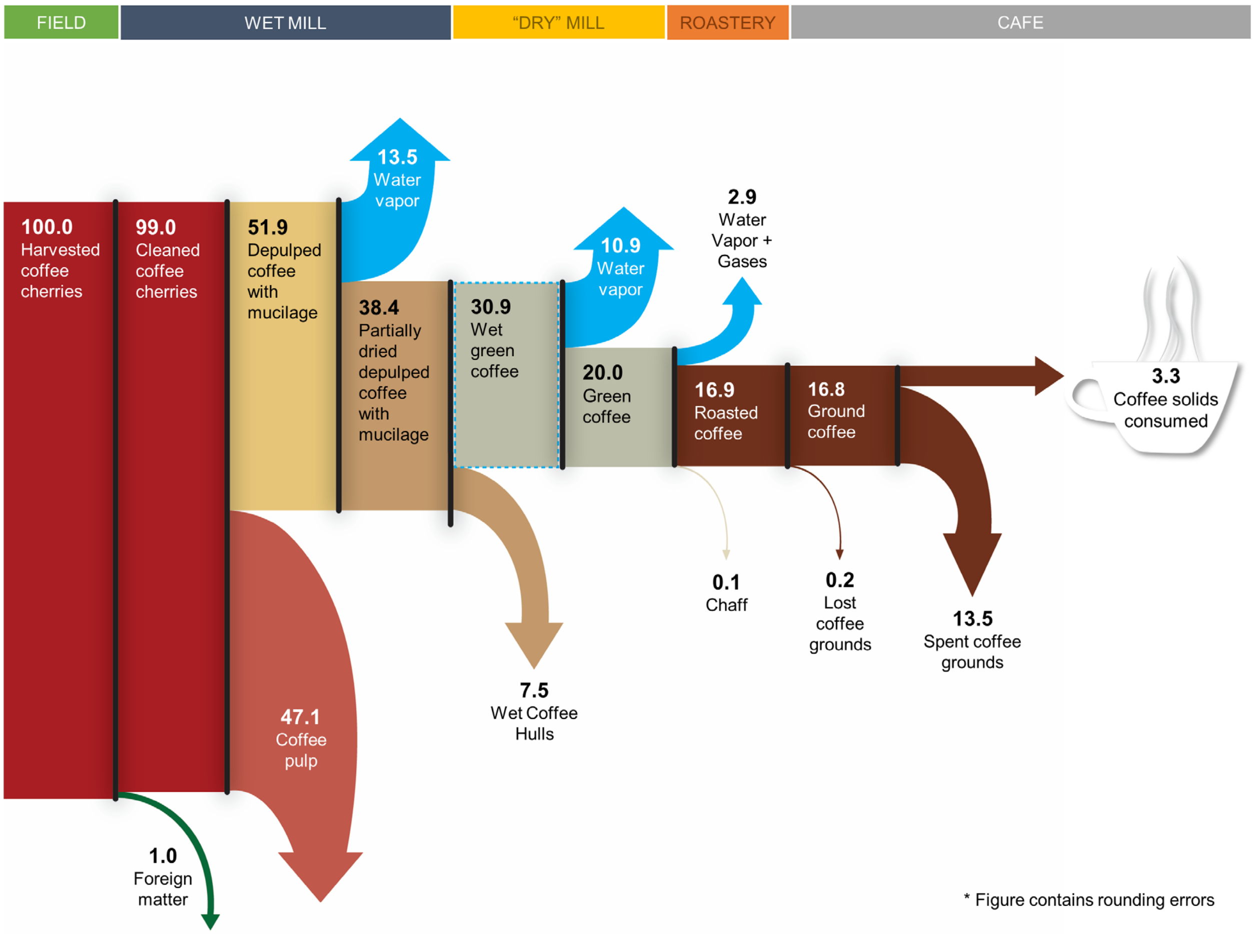


Figure 9 *Hypothetical Sankey diagram for mass flows in the* ***wet-hulled*** *method* for postharvest processing. Numbers represented are estimates; numbers might not sum due to rounding.

3.2.4 Honey (pulped natural) Method

The honey method (section 1.2.2.4), also produces the same pulp byproduct as in the washed method, but the mucilage is dried onto the bean and then removed in the hulling process. Using the findings in chapter 2, the various byproducts are estimated and represented in Figure 10. The primary trade-off here with regard to byproducts is the reduction of the honey water in favor of more mass in the form of coffee husks.

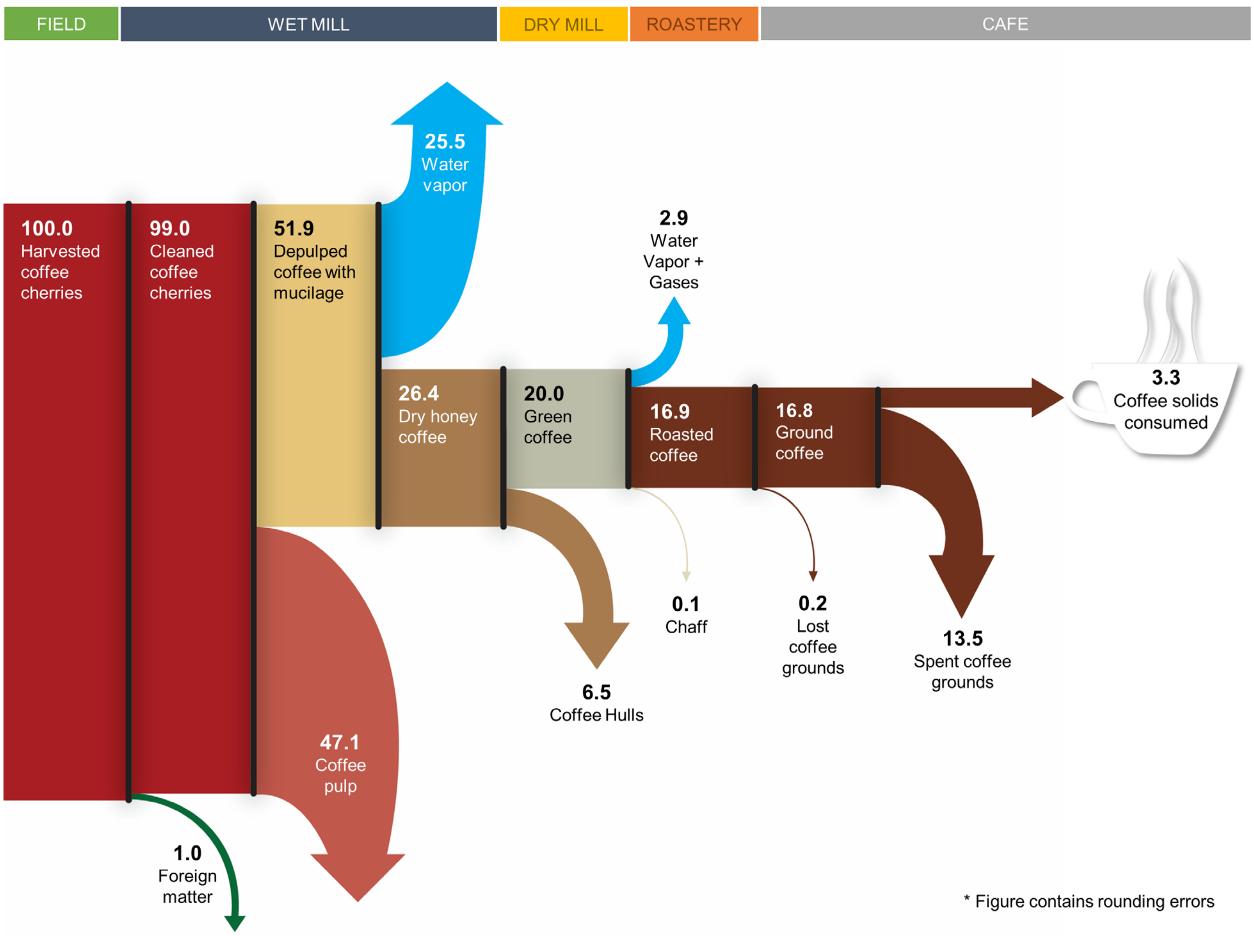


Figure 10 *Hypothetical Sankey diagram for mass flows in the* ***honey*** *method* for postharvest processing. Numbers represented are estimates; numbers might not sum due to rounding.

3.2.5 Comparison of Methods

When comparing the percent of initial harvest mass which ends up in each byproduct mass flow during the wet and dry mill phases in each of the four methods, as can be seen in Figure 11, a few major differences can be identified. The washed method produces a byproduct stream for each layer of the coffee cherry: Pulp, mucilage, parchment and bean. The natural method combines all waste products into a single fraction, husks, and is the only method that does not produce fresh pulp. The wet-hulled method is the reverse of the natural in that it *only* produces fresh pulp since everything is removed from the bean before drying is completed. The honey method finds middle ground in removing the pulp while wet but then drying the mucilage on the bean so that it is removed in the dry mill as husk. While the same mass components are removed in all four methods, the waste streams vary in two ways: (1) whether the mass comes off wet or dry and (2) which mass components are combined together. As a point of clarification, while the amount of water vapor is represented as equal in each of the methods in Figure 11, it is removed at different stages, as shown in the respected Sankey diagrams in the previous sections. Therefore, the totals will not be the same as in the Sankey diagrams because the Sankey diagrams represent fresh weight masses while Figure 11 is comparing dry weights.

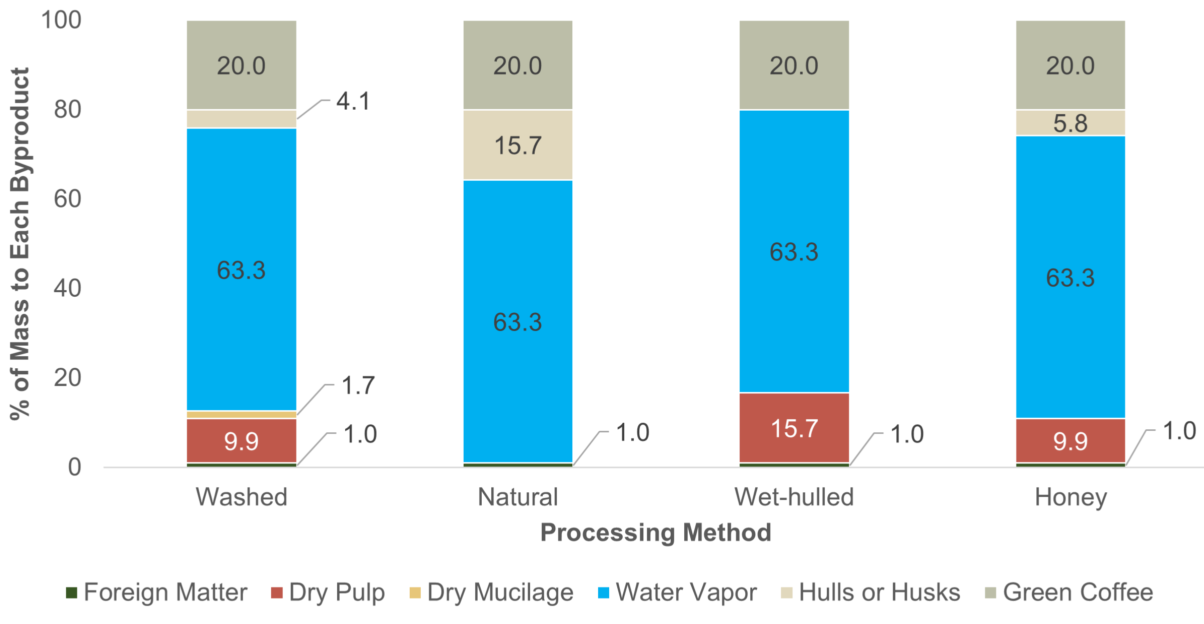


Figure 11 *Estimated percent mass of byproducts (reference to initial harvest mass) produced in each processing method,* accounting for byproducts produced in the wet and dry mill phases. All estimates are inferred from data collected on the washed method and are measured on a dry weight basis.

3.2.6 Estimation of Processing Method Percentages

In order to apply the mass flow percentages presented in Figure 11 to real world production numbers, it is necessary to estimate what percentage of world coffee production is processed through each of the washed, natural (dry), wet-hulled, and honey methods. General statistics outlining these relative percentages are not readily available. Therefore, in order to estimate these percentages, the following method was used: Production information, averaged over 2015-2019, for the 55 primary coffee producing countries provided by the International Coffee Organization (ICO, 2020c), was referenced to estimate the relative and then total quantities of Arabica vs. Robusta coffee produced. Each country was assigned a percentage of 0, 25, 75, or 100 % for each type of coffee based on indications of predominant types provided in the ICO data. Where only “A” is listed alone, 100 % Arabica was assigned to that country. Where “A” proceeds “R”, as in “A/R”, 75 % is assigned to Arabica and 25 % is assigned to Robusta. The same is true in reverse for “R” alone or “R” proceeding “A” as can be seen in Table 1. This crude method produced Arabica and Robusta production totals that were within 4.3 % of global totals provided by the ICO. The percentages for 14 countries (representing 32.0 % of global production) were adjusted to reflect more detailed information available on the websites of three coffee importers: Mercanta, Cafe Imports, and Olam Specialty Coffee as well as the United States Department of Agriculture Foreign Agricultural Service (USDA FAS) (Cafe Imports, 2020; Mercanta, 2020; Olam Specialty Coffee, 2020; USDA FAS, 2020). These improved estimates totaled to within 2.0 % of known worldwide statistics and were used as a baseline for further analysis below.

Country	Average Total Production (kg) 2015-2019	ICO Designation: Arabica vs. Robusta	Estimated % Produced (ICO)		Estimated kg Produced (ICO)		Estimated % Produced (Adjusted)		Estimated kg Produced (Adjusted)	
			Arabica	Robusta	Arabica	Robusta	Arabica	Robusta	Arabica	Robusta
Brazil	3,343,539,360	(A/R)	75%	25%	2,507,654,520	835,884,840	75%	25%	2,507,654,520	835,884,840
Viet Nam	1,678,061,489	(R/A)	25%	75%	419,515,372	1,258,546,117	10%	90%	167,806,149	1,510,255,340
Colombia	835,902,584	(A)	100%	0%	835,902,584	-	100%	0%	835,902,584	-
Indonesia	664,112,262	(R/A)	25%	75%	166,028,066	498,084,197	25%	75%	166,028,066	498,084,197
Ethiopia	429,794,081	(A)	100%	0%	429,794,081	-	100%	0%	429,794,081	-
Honduras	400,782,456	(A)	100%	0%	400,782,456	-	100%	0%	400,782,456	-
India	342,681,174	(R/A)	25%	75%	85,670,294	257,010,881	27%	73%	91,381,646	251,299,528
Uganda	259,883,748	(R/A)	25%	75%	64,970,937	194,912,811	23%	77%	60,639,541	199,244,207
Peru	227,425,007	(A)	100%	0%	227,425,007	-	100%	0%	227,425,007	-
Mexico	226,548,210	(A/R)	75%	25%	169,911,158	56,637,053	82%	18%	185,769,532	40,778,678
Guatemala	217,734,316	(A/R)	75%	25%	163,300,737	54,433,579	82%	18%	177,816,358	39,917,958
Nicaragua	140,531,615	(A)	100%	0%	140,531,615	-	99%	1%	139,594,737	936,877
Côte d'Ivoire	91,232,688	(R)	0%	100%	-	91,232,688	0%	100%	-	91,232,688
Costa Rica	87,293,604	(A)	100%	0%	87,293,604	-	100%	0%	87,293,604	-
Tanzania	53,846,341	(A/R)	75%	25%	40,384,756	13,461,585	75%	25%	40,384,756	13,461,585
Papua New Guinea	52,139,977	(A/R)	75%	25%	39,104,983	13,034,994	82%	18%	42,580,981	9,558,996
Kenya	48,979,607	(A)	100%	0%	48,979,607	-	100%	0%	48,979,607	-
El Salvador	40,326,412	(A)	100%	0%	40,326,412	-	88%	13%	35,285,610	5,040,801
Thailand	39,175,810	(R/A)	25%	75%	9,793,952	29,381,857	13%	88%	4,896,976	34,278,833
Ecuador	37,895,554	(A/R)	75%	25%	28,421,665	9,473,888	75%	25%	28,421,665	9,473,888
ALL OTHER	294,119,534		48%	52%	140,757,206	153,362,329	51%	49%	149,160,621	144,958,913
TOTAL	**9,512,005,828**				**6,046,549,010**	**3,465,456,818**			**5,827,598,498**	**3,684,407,330**
				% of Total:	63.6%	36.4%			61.3%	38.7%
				Actual ICO Totals:	59.3%	40.7%			59.3%	40.7%
				Difference:	4.3%	-4.3%			2.0%	-2.0%

Table 1 Simplified table of estimates for relative production of Arabica vs. Robusta coffee by country.

It was then assumed, as a baseline, that all Robusta coffee was processed through the natural method and Arabica was processed using the washed method. Information available on the websites referenced in the previous paragraph was then reviewed and qualitative information was quantified into estimated percentages. For example, “almost all” might be rendered 90 % while “some” might be rendered 20 % and “experimenting with” might become 5 % depending on the context. While crude, this method provides improved estimates. These percentages were averaged between the various sources and then applied to the 24 countries (representing 78.6% of global coffee production) for which information exist. All 55 countries were also grouped into 10 regions and where possible regional averages were calculated. These averages were averaged with the baseline numbers in 14 addition countries (representing 1.1 % of global production) where direct information was not available. The remaining 17 countries (representing 20.3 % of global production rely on baseline Arabica vs. Robusta information alone.

These production numbers were summed to provide global estimates. Following these steps, it was estimated that of the entire global production of coffee, approximately 39 % was produced by the washed method, 43 % via the natural (dry) method (influenced heavily by Brazil), 12 % by the honey (or pulped natural) method, and 6 % by the wet-hulled method. These estimates, while clearly imprecise, represent the best information known to the author and will serve as a framework for the rest of this discussion. These estimates are meant to serve as a basis for initial analysis and would need to be rigorously revised if precision is required outside the context of this thesis.

Country	Avg. Total Production (1000 kg) 2015-2019	Baseline Estimated Relative %				Adjusted Estimated Relative %				Adjusted Production Estimates (1000 kg)			
		Washed	Natural	Honey	Wet-hulled	Washed	Natural	Honey	Wet-hulled	Washed	Natural	Honey	Wet-hulled
Brazil	3,343,539	75.0%	25.0%	0.0%	0.0%	13.3%	56.7%	30.0%	0.0%	445,805	1,894,672	1,003,062	-
Viet Nam	1,678,061	10.0%	90.0%	0.0%	0.0%	5.0%	90.0%	5.0%	0.0%	83,903	1,510,255	83,903	-
Colombia	835,903	100.0%	0.0%	0.0%	0.0%	93.3%	1.7%	5.0%	0.0%	780,176	13,932	41,795	-
Indonesia	664,112	25.0%	75.0%	0.0%	0.0%	11.7%	0.0%	0.0%	88.3%	77,480	-	-	586,632
Ethiopia	429,794	100.0%	0.0%	0.0%	0.0%	50.0%	50.0%	0.0%	0.0%	214,897	214,897	-	-
Honduras	400,782	100.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	400,782	-	-	-
India	342,681	26.7%	73.3%	0.0%	0.0%	50.0%	50.0%	0.0%	0.0%	171,341	171,341	-	-
Uganda	259,884	23.3%	76.7%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	259,884	-	-	-
Peru	227,425	100.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	227,425	-	-	-
Mexico	226,548	82.0%	18.0%	0.0%	0.0%	93.3%	5.0%	1.7%	0.0%	211,445	11,327	3,776	-
Guatemala	217,734	81.7%	18.3%	0.0%	0.0%	96.7%	1.7%	1.7%	0.0%	210,477	3,629	3,629	-
Nicaragua	140,532	99.3%	0.7%	0.0%	0.0%	92.5%	3.8%	3.8%	0.0%	129,992	5,270	5,270	-
Côte d'Ivoire	91,233	0.0%	100.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	-	91,233	-	-
Costa Rica	87,294	100.0%	0.0%	0.0%	0.0%	83.3%	3.3%	13.3%	0.0%	72,745	2,910	11,639	-
Tanzania	53,846	75.0%	25.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	53,846	-	-	-
Papua New Guinea	52,140	81.7%	18.3%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	52,140	-	-	-
Kenya	48,980	100.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	48,980	-	-	-
El Salvador	40,326	87.5%	12.5%	0.0%	0.0%	90.0%	5.0%	5.0%	0.0%	36,294	2,016	2,016	-
Thailand	39,176	12.5%	87.5%	0.0%	0.0%	12.5%	87.5%	0.0%	0.0%	4,897	34,279	-	-
Ecuador	37,896	75.0%	25.0%	0.0%	0.0%	60.0%	35.0%	5.0%	0.0%	22,737	13,263	1,895	-
OTHER (weighted)	294,120	51.0%	49.0%	0.0%	0.0%	58.8%	41.0%	0.2%	0.0%	172,817	120,619	663	-
TOTAL	**9,512,006**									**3,678,061**	**4,089,644**	**1,157,648**	**586,632**
									Relative production under each method by mass:	**39%**	**43%**	**12%**	**6%**
										Washed	Natural	Honey	Wet-hulled

Table 2 Simplified table of estimates for relative production by processing method and by country.

3.2.7 Estimated Masses of Byproducts Produced

The average annual global production of green coffee over the last 5 years (2015-2019) was 9.5 billion kg (ICO, 2020a). Using the findings of the case study in Chapter 2, it can be estimated that approximately 47.7 billion kg of coffee material was therefore harvested annually. Of that, approximately 26.0 billion kg became solid byproducts (not including water vapor and other gasses).

With estimates for mass loss percentages in each process (Figure 11) combined with the relative prevalence of the four processing methods (Section 3.2.6) and the total production numbers (previous paragraph), it becomes possible to estimate the approximate total mass produced of each byproduct in each of the methods. These estimates are displayed in Figure 12.

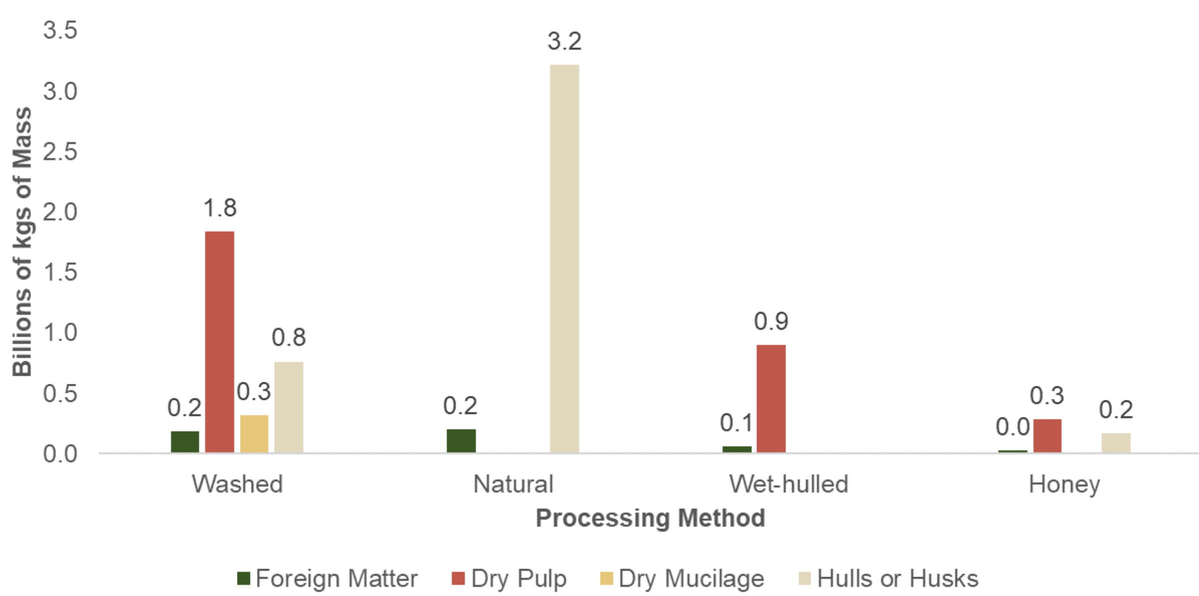


Figure 12 *Estimated total mass of solid byproducts produced in each processing method,* accounting for byproducts produced in the wet and dry mill phases of postharvest processing. All estimates are inferred from data collected on the washed method. Byproducts for the Roastery and Café phases are excluded.

The remaining byproducts produced (in the roastery and café phases) are assumed to be the same for each of the methods with the exception of spent coffee, which is the byproduct of instant coffee production and, although produced in instant coffee factories, this essentially replaces spent coffee grounds in the café phase when looking at the instant coffee stream. Taking the previously described losses into account, as well as published statistics (ICO, 2020c), it is known that the roastery phase starts with on average 9.5 billion kg of green coffee worldwide. During roasting, 50 million kg of chaff is produced (not including 1.4 billion kg of volatile gases). In the café phase 60 million kg of lost grounds, 4.5 billion kg of spend coffee grounds and 1.7 billion kg of spent coffee are believed to be produced on average per year.

3.3 REVIEW OF BYPRODUCTS

One framework that can be used to evaluate the best use of these byproducts is the United States Environmental Protection Agency (EPA) Food Recovery Hierarchy (FRH), which identifies and prioritizes six actions that can be taken to prevent and divert food losses and food byproducts in the production of food products. The tiers from most preferred to least preferred are as follows: 1. source reduction, 2. feed hungry people, 3. feed animals, 4. industrial uses, 5. composting, and 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. This will be discussed below in further detail.

Statistics presented below are averages calculated from the case study presented in chapter 2. Initial global harvest mass is defined as the average total mass of coffee cherries (plus foreign matter) harvested in the entire world, without regard for country, variety of coffee, or which processing method will be used. Rather than using a hypothetical quantity (100 kg for example) as in Chapter 2, initial global harvest mass refers to a calculated number based on known statistics, which is 47.7 billion kg. This is used to perform the calculations regarding the total mass of byproducts.

3.3.1 Foreign Matter

Foreign matter such as leaves, twigs, stones etc. which are brought in with the coffee harvest represent approximately 480 million kg of material annually (1.0 % of initial global harvest mass). This material is discarded or composted (FRH tiers 6 and 5). While the quantity is notable this there have been essentially no efforts to analyze this material for alternative uses or even to describe its components. In fact, as far as the author is aware, this may be the first study to quantify this material stream in any meaningful way. Therefore, further discussion of this byproduct will be limited. Foreign matter is removed in all processing methods, though the difference in percentage (if any) for each is unknown and depends largely on the harvesting methods employed.

3.3.2 Fresh Pulp

Fresh (wet) coffee pulp, produced in the washed, wet-hulled, and honey methods, represents approximately 12.8 billion kg (26.9 % of initial global harvest mass) annually. It has been used, and extensively studied for a diverse set of potential uses. Currently, the vast majority of pulp is composted (FRH tier 5) (Anacafe, 2008). Research has shown that there is potential to divert this material to tier 4 for uses such energy production (Parascanu, Puig-Gamero, Soreanu, Valverde,

& Sanchez-Silva, 2019), wastewater cleaning agents (Gómez Aguilar, Rodríguez Miranda, Esteban Muñoz, & Betancur P., 2019), and biomolecule extraction (Ruesgas-Ramón et al., 2020; Santos da Silveira et al., 2019; Torres-Valenzuela, Ballesteros-Gómez, & Rubio, 2020). Coffee pulp is rich in carbohydrates, proteins and minerals (especially potassium) and it also contains appreciable amounts of tannins, polyphenols and caffeine. The organic components present in coffee pulp (dry weight) includes tannins 1.80–8.56 %, total pectic substances 6.5 %, reducing sugars 12.4 %, non-reducing sugars 2.0 %, caffeine 1.3 %, chlorogenic acid 2.6 %, and total caffeic acid 1.6 % (Murthy & Madhava Naidu, 2012). So far, direct use of these by-products for animal feed (tier 3) has not been possible due to the anti-physiological and antinutritional factors (e.g., tannins and caffeine) present (Esquivel & Jiménez, 2012). Regardless, coffee pulp has the potential for even more preferred diversion to tier 2 for use as human food products: beverages including tea (Ciummo, 2014), alcoholic beverages, and flour ("The Coffee Cherry Co.," 2020). Achievement of FRH tier 1, "source reduction" seems to be unrealistic as a postharvest practice, though may be possible in an agronomic context, by producing different coffee varieties which have less pulp as a percentage of total cherry mass for example. With pulp being the biggest byproduct by mass, it provides the most material for redirection. Although from an environmental standpoint, the fact that most pulp is composted is not particularly harmful (in fact it can be highly beneficial as an organic fertilizer for coffee fields), it presents many opportunities for the production of more economically sustainable products and may therefore be one of the best opportunities to stabilize the income of coffee farmers which would have a net positive effect in the overall sustainability of the coffee industry.

3.3.3 Mucilage (Honey Water)

Mucilage (the solid component of honey water), produced in the washed method (and to a lesser extent in other methods), contains approximately 1.0 billion kg (2.1 % of initial global harvest mass) of solid material. Given that it is almost exclusively managed under FRH tier 6, it is in the worst position currently. It has been a major cause of water pollution in coffee producing regions until recent legislation in many countries has implemented more strict standards in controlling this waste stream. Despite its negative environmental impact, very little research has been done on alternative uses for this material stream. Although this is a smaller byproduct stream in terms of mass, finding alternative uses for this may provide the highest return on investment in terms of environmental benefits.

3.3.4 Parchment and/or Husks

Coffee parchment or coffee husks, which are removed after the drying step in essentially all coffee processing methods, represent a combined 5.4 billion kg of material annually, or 11.4 % of initial global harvest mass. It is assumed that the majority of this mass is currently used for energy (burning) or compost, therefore residing in FRH tiers 4 and 5. These byproducts contain many potentially useful compounds that might be used in industrial applications, but so far research into alternative uses has been limited.

3.3.5 Chaff

Coffee chaff (which is detached and/or burned coffee silver skin), is a byproduct of the roasting process, and represents approximately 50 million kg of mass (0.1 % of initial global harvest mass). It is assumed that the majority of this material enters waste streams represented in FRH tier 6, while some is also used for compost (tier 5) or is burned for energy (tier 4). Studies have shown that chaff has some antioxidant activity and high levels of total fiber and may therefore be used as a functional additive in foods (tier 2) (Murthy & Madhava Naidu, 2012).

3.3.6 Spent Grounds

Globally, according to this study, an estimated 4.5 billion kg of spent coffee grounds are produced annually (9.3 % of initial global harvest mass). At a commercial scale, coffee grounds are typically sent directly to landfills (FRH tier 6). Decomposing coffee grounds emit methane, a potent greenhouse gas. Spent coffee grounds are one of the most significant solid byproducts by mass with potentially high value (bio-bean, 2019). Approximately 28 % of a roasted coffee bean is made up of soluble solids (Lingle, 2011) while a typical extraction yield for drip, espresso, and cold brew coffees is 15-20 %, so even though they are purposely avoided due to flavor considerations, up to 46 % of the original water soluble 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 energy production (bio-bean, 2019). These uses, and others yet developed, may divert large quantities of waste from landfills up to compost (tier 5) or industrial uses (tiers 4).

3.3.7 Spent Coffee (Instant Coffee Production)

According to this study, an estimated 1.7 billion kg of spent coffee is produced annually (3.6 % of initial global harvest mass). This byproduct of instant coffee production is similar in many ways to spent coffee grounds produced by traditional coffee brewing and has much of the same potential described in the previous section. The disposal of spent coffee is a major problem encountered by the industry. Historically, disposal or utilization of spent coffee has included sewer discharge, sanitary land fill, incineration (FRH tier 6), cattle feed (FRH tier 3), and as fillers and adsorbents in thermosetting material (FRH tier 4) (Ramalakshmi et al., 2008). When combined with spent coffee grounds, it is estimated that 6.2 billion kg are produced which generally agrees with Tokimoto et al. (2004). This represents a combined 13 % of initial global harvest mass.

3.3.8 Estimated Current Tier Distribution

Taking the above discussion on byproducts and tiers into account, Figure 13 indicates where byproducts are probably being used now, categorized by byproduct. The author emphasizes that these are rough estimates based on the experience and knowledge of the researchers and does not constitute the findings of a scientific study.

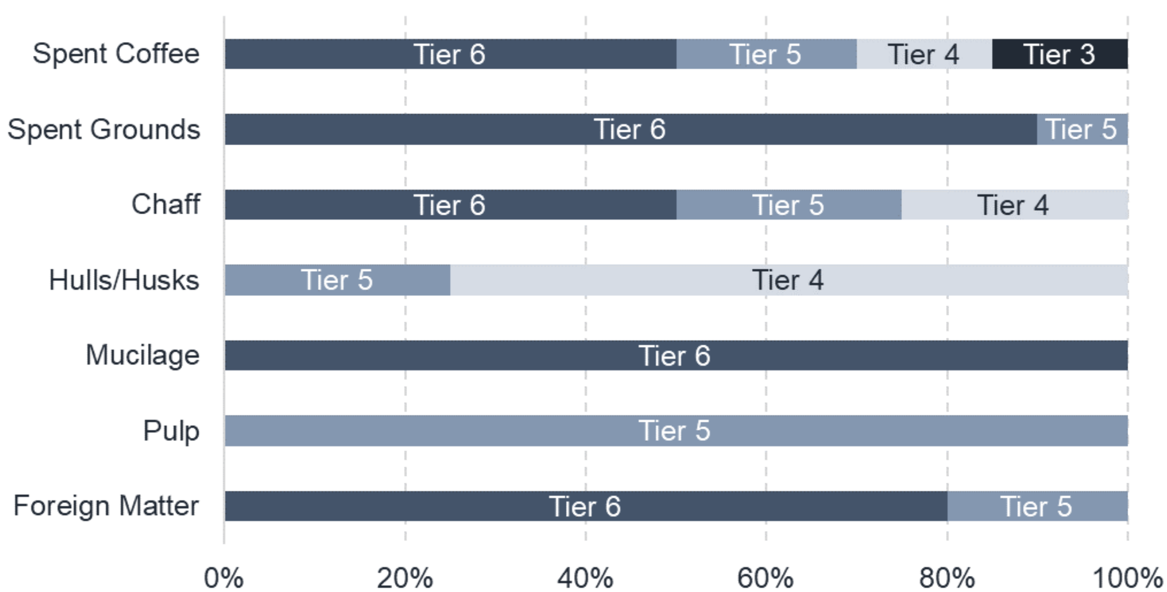


Figure 13 *Estimated percent of mass destined for each FRH tier by byproduct.* Estimates based on preliminary review of available information on the topic as described in Section 3.3.

If the information in Figure 13 is applied to each of the processing methods individually, differences are revealed with regard to the distribution of FRH tiers under which byproducts are managed (Figure 14). This is accomplished by distributing the mass loss at each step into the various tiers according to the percentages presented in Figure 13.

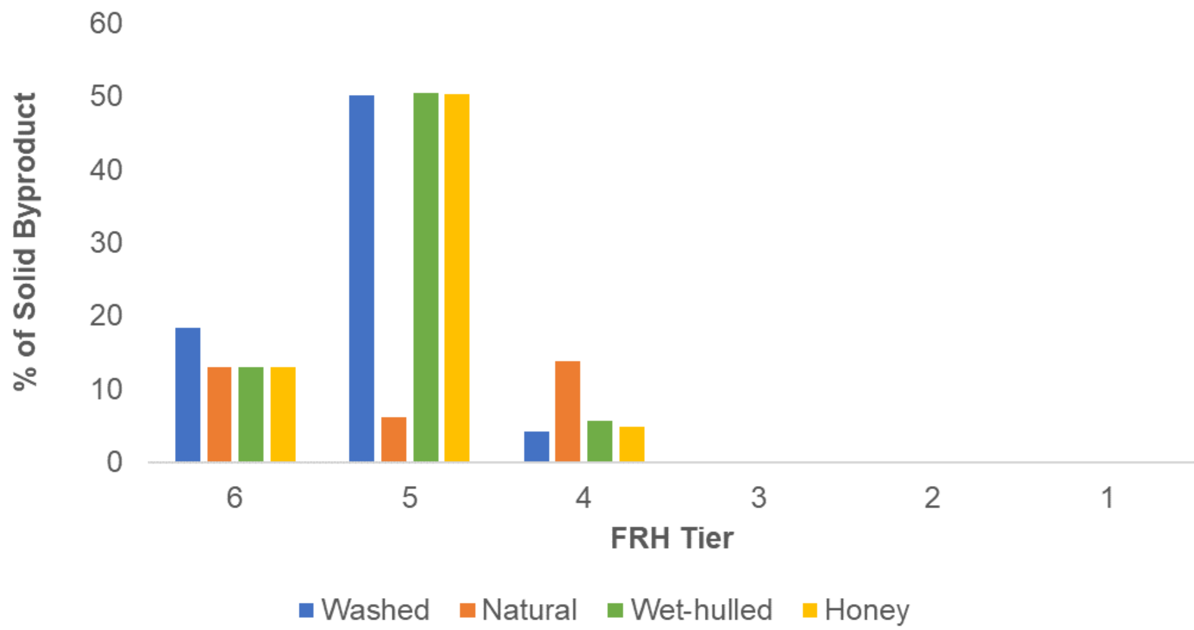


Figure 14 *Estimated total mass of byproducts managed in each FRH tier by processing method.* Calculated by multiplying the tier estimates in Figure 13 by the byproduct mass flow estimates in Chapter 2 and Section 3.2.

Once this is established, weighted averages can be calculated for each processing method. The average therefore represents the average tier under which the byproducts of a given processing method are managed. Based on the information so far presented in this thesis, the averages are as follows: the washed method is 5.19, the natural method is 4.98, the wet-hulled method is 5.11, and the honey method is 5.12. In other words, the washed method had the most material on average managed under less desirable tiers, the natural method had the best overall profile with regard to the tiers, while the wet-hulled and honey methods fell close together and in the middle. This difference can be largely attributed to the presence of “honey water” or “residual water” most prominent in the washed method, which as of now is estimated to fall almost exclusively under tier 6. This byproduct represents approximately 1 billion kg of solid material mixed with many billions of liters of now contaminated water. While this thesis only looks at byproducts, the input and use of water in this method is also a major environmental concern in some contexts. The washed method is appreciated due to its clean flavor profile and adaption to more humid climates than the natural method, yet it is the least desirable method in terms of the FRH. If consumers continue to demand this processing method, more efforts need to be made to address the concerns raised here.

3.3.9 Potential for Improvement

Considering the above, it can be calculated that of the 26.0 billion kg of byproducts produced in coffee processing, approximately 28 % falls under tier 6, 53 % under tier 5, 18 % under tier 4 of the FRH, while there is little significant contribution to tiers 1-3. Generally speaking, this clearly leaves room for improvement. Based on the alternative uses being presently studied (mentioned above), it may be possible to hypothetically improve those numbers significantly. Research has already shown promise in redirecting some byproducts, such as potentially using chaff as a food additive or spent coffee grounds as fuel for energy generation for example. More research and, of course, adoption by producers will also require a ready market for the value-added products produced using coffee byproducts, something that may already be emerging. It is conceivable that billions of kilograms of materials could be put to more environmentally friendly and/or economically beneficial purposes even with a modest adoption of these alternative uses satisfying the needs of both producers and consumers seeking to make a positive environmental and social impact in the coffee industry.

Aside from putting byproducts to better use, it is also conceivable that a transition away from the washed method to other methods could reconfigure the global byproduct profile (Figure 14) in positive ways. This would certainly require an adjustment in flavor expectations on the part of consumers, but may be welcomed as a means of reducing pollution as well as resource and energy consumption. This approach however may be more challenging to achieve on the producer level as entire regions are tooled for the washed method. Alternatively, new technologies may emerge to mitigate or eliminate the environmental and economic problems presented here, in turn keeping the watched method viable.

3.4 FUTURE RESEARCH

3.4.1 Varietal & Quality Differences

Aside from the myriad research questions already implied in the discussion of byproducts, further opportunities exist as well. It may be useful, for example, to analyze the differences between *Coffea arabica* varieties. It is known that coffee varieties do show physiological difference with regard to size, color, etc. and while this study takes average processing numbers from more than 10 varieties together, it does not present data separated by variety. Additionally, differences in export quality versus non-export quality were not sufficiently explored in this thesis and may also prove to be sufficiently significant to warrant a closer look and the reconfiguration of some processes to aid improvements in postharvest processing.

3.4.2 Equipment Differences

Further separations could be made by comparing the efficiencies of different types of coffee processing equipment or methods used (even within the washed method) in different countries. Even on the limited number of visits the author made to mills in Central America, numerous variations were observed in the types of equipment used by processors, and indeed, which type of equipment to employ in their operations is among the most pressing concerns of coffee processors today.

3.4.3 Instant Coffee

One aspect of the coffee industry that was not the focus of this thesis, yet deserves considerably more attention, is that of instant coffee production. While the exact size of the instant coffee industry, in terms of percent of coffee mass dedicated to it, is not easily estimated, it is without doubt a very considerable size (this study uses 30.7%). A large part of the world population considers instant coffee as their primary form of consuming coffee driving billions of dollars in sales. Much of the coffee destined for domestic markets and indeed export markets as well, is used in the production of instant coffee. A full study of mass flows for this aspect of coffee processing would be very useful in completing the mass flow picture presented in this thesis.

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Appendices

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

UCDAVIS
COFFEE CENTER

This survey seeks to quantify all the material streams involved in postharvest coffee processing to in sustainablility and efficiency throughout the industry. **All responses to this survey are confidential.**

Coffee Postharvest Mass Balance Survey

		Report one or more	
DRY MILL	Mass	Volume	Percent

DEHULLING

a. How much mass is lost during hull removal?

b. How is this measured? ___________

c. What do you do with the hulls?

POLISHING

a. How much mass is lost during silverskin removal?

b. How is this measured? ___________

SORTING

a. What kind of sorting do you do and at which stage(s)? Stage(s)

◯ Size ___________

◯ Density ___________

◯ Color ___________

◯ Foreign matter ___________

◯ Other _______________ ___________

b. What grades do you use and what % of beans go to each?

UCDAVIS
COFFEE CENTER

This survey seeks to quantify all the material streams involved in postharvest coffee processing to in sustainablility and efficiency throughout the industry. **All responses to this survey are confidential.**

Coffee Postharvest Mass Balance Survey

Basic Information:

What cultivars do you process here (% of each): ____________

What is your operational season: ____________

How many farms do you service: ____________

How many hectares does that represent? ____________

What is the designed processing capacity of the mill? ____________

What type of mill is this? (circle one) Private Cooperative

Operation Statistics:

Total coffee cherries received per season on average (pounds): ____________

Total water consumed on average per season (liters): ____________

Total coffee pulp produced on average per season (pounds): ____________

Total waste water produced on average per season (liters): ____________

Total green coffee beans produced on average per season (lbs): ____________

Report one or more

WET MILL

WET MILL	Mass	Volume	Percent
FLOATING			
a. How much coffee is rejected/removed on average?			
b. How much water is used per 100 pounds of cherries?			

c. How is this measured? ________

DEPULPING

	Mass	Volume	Percent
a. How much pulp is removed from 100 pounds of cherry coffee?			

b. How is this measured? __________

c. Where does the pulp go? ________________

d. Is it reused or disposed of? ________________

e. Do you treat the pulp in any way? If so, how and how much? ____

FERMENTATION

a. Do you use a dry or wet fermentation process?

◯ Dry

◯ Wet

	Mass	Volume	Percent
i. If wet, how much water is used per 100 lbs. of de-pulped coffee beans?			

ii. Is anything besides water added? ________

iii. How is this measured? __________

WASHING

	Mass	Volume	Percent
a. How much water is used per 100 pounds of coffee beans?			

b. How many times are the beans washed? ____

c. Where does the mucilage water go? ________________

d. Are any beans removed at this time?

◯ No ◯ Yes

	Mass	Volume	Percent
i. If yes, what percentage by weight on average?			

e. How is this measured? __________

f. What is the typical Brix of your wastewater? ________________

DRYING

	Mass	Volume	Percent
a. How much mass is lost during the drying process?			

b. How is this measured? __________

c. What is your method of drying? ____________

SORTING

a. What kind of sorting do you do and at which stage(s)? Stage(s)

◯ Size ____________

◯ Density ____________

◯ Color ____________

◯ Foreign matter ____________

◯ Other ________________ ____________

b. What grades do you use and what % of beans go to each?

____

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

BOTANICAL COMPONENTS

English	Spanish	Portuguese	Botanical	Definition
skin	piel	casca	exocarp	Outtermost layer of the coffee cherry, can be red or yellow.
pulp	pulpa	polpa	mesocarp	Flesh of the fruit of the coffee bean.
mucilage	mucílago	mucilagem	mesocarp	Part of the pulp which sticks to the bean after depulping.
parchment	pergamino	pergaminho	endocarp	Papery wrap around beans which remains after drying process.
silver skin	cascarilla	película prateada	epidermis, spermoderm	Light, semitransparent layer which encases the bean.
bean	grano	grão / semente	endosperm	The seed of the coffee cherry which is roasted, ground, and brewed to drink.

WEIGHTS & MEASURES

English	Spanish	Portuguese	SI units	Significance
hundredweight	quintal (qq)	quintal	45.36 kg	Standard measure of weight for farm and mill operations in coffee industry.
bag	bolsa	saca	60 kg	Standard measure for coffee exports and imports on international markets.
cup	taza	xícara	250 ml	This paper uses metric cups when discussing quantities of drip coffee.
espresso shot	taza de espresso / expreso	expresso	30 ml	This paper uses this quantity to approximate a standard 1 oz. espresso shot.

GENERAL COFFEE TERMS

English	Spanish	Portuguese	Definition
Arabica coffee	café arábica	**café arábica**	*Coffea arabica* is the most important commercially produced species of coffee in the world and is almost exclusively preferred by the specialty coffee industry for its superior flavor profile.
strictly hard beans	**estrictamente duro**	N/A	Top quality coffee beans grown at altitudes 1370 m (4500 feet) above sea level or higher.
mild coffee	café suave / café ligero	café suave	Wet.processed Arabica coffee.
export quality	primeros / excelso (Colombia)	N/A	Top quality green coffee beans, acceptable on export markets
secondary quality	segundos / pasillas	N/A	Inferior quality beans, typically sold in domestic markets

WASHED METHOD TERMS

English	Spanish	Portuguese	Definition
wet mill	beneficio húmedo	processamento / preparo por via úmida	Facilities and equipment used to remove skin, pulp, and mucilage from coffee cherry.
floating	flotación	flutuação/flotação	Process of submerging harvested coffee cherries in water. Superior quality cherries are more dense and sink, inferior quality cherries float and are separated into a different processing stream.
depulping	despulpado	despolpagem	Mechanical removal of skin and pulp shortly after arrival at the wet mill and just before fermentation.
fermentation	fermentación	fermentação	Processes after depulping where coffee beans with mucilage are allowed to sit in a tank, either in open air (aerobic) or under water (anaerobic) for typically 8-36 hours to allow mucilage to break down for removal.
honey water	**agua residual / agua miel**	água residual	Water removed from coffee fermentation tanks after the fermentation process is completed. This water contains a large percentage of the musilage which has been removed from the coffee beans.
drying	secado	secagem	Process of reducing the water content of wet parchment coffee beans to 11-12%, either in mechanical driers or sun drying on either open air or covered patios.
dry mill	beneficio seco	processamento / preparo por via seca	Facilities and equipment used to remove parchment and sometimes silverskin as well as sort by density, size, and color.
(de)hulling	processo de trilla / descascarar/ almacenamiento	descascamento	Process of mechanically removing the parchment (and optionally the silver skin) of dry parchment coffee.
hull	cáscara	casca	The parchment (and possibly silver skin) which has been removed from the coffee bean. It can be burned for energy.
sorting / classification	clasificación	separação / classificação	Mechanical or hand sorting of beans based on size, density, and/or color.
roaster(y)	tostador	torrefador	Facilities and equipment used to roast green coffee beans to consumer preference.
roasting	tostado	torrefação de café	Process of heating green coffee beans to activate maillard reactions and resulting in dehydration, increased volume, and change of color in the bean.
café; coffee shop	cafetería	cafeteria / padaria	Retail location where specialty coffee is prepared on site for consumption.
grinding	molienda	moagem de café	Process of mechanically reducing whole roasted coffee beans to a course powder in preparation for brewing and consumption.
brewing	preparación del café	fazer café	Retail location where specialty coffee is prepared on site for consumption.

STAGES OF THE COFFEE BEAN

English	Spanish	Portuguese	Definition
coffee	café	café	General term for the fruits (cherries) and seeds (beans) of plants of the genus Coffea, as well as products from these fruits and seeds in different stages of processing and use.
cherry coffee	café cereza / café maduro / fruto del café	café cereja	The fruit of the coffee plant.
depulped coffee	café en baba	café despolpado	Coffee beans with skin and pulp removed, mucilage remains attached (pre-fermentation).
wet parchment coffee; fermented coffee	café lavado	café lavado	Coffee beans immediately after fermentation and wash process. Mucilage removed, bean still wet.
parchment coffee (dry)	café pergamino (seco)	café pergaminho	Dried coffee (11-12% moisture content) with parchment and silver skin remaining attached to the bean.
dried coffee cherry	café cereza seco	café cereja seco	The full fruit of the coffee plant, dried to 11-12% moisture content through the dry or "natural" processing method.
green coffee	café oro / café almendra / café verde	café verde	Coffee in the naked bean form (i.e. from which the silverskin has been removed) before roasting.
coffee bean	grano de café	grão de café	Commercial term designating the dried seed of the coffee plant.
roasted coffee	café tostado	café torrado	Green coffee roasted to any degree.
ground coffee	café molido	café moído	Roasted coffee beans ground into a powder of varying levels of coarseness.
brewed coffee; liquid coffee	café preparado	café fresco	The water-soluble solids derived from roasted coffee and put into liquid form.
soluble coffee	café soluble	Café solúvel	The dried water-soluble solids derived from roasted coffee.
decaffeinated coffee	café descafeinado	Café descafeinado	Green, roasted or soluble coffee from which caffeine has been extracted.
washed coffee; wet processed coffee	café lavado / café procesado en húmedo	café processado por via úmida	Green coffee prepared by wet processing of the fruit.
unwashed coffee; dry processed coffee	café sin lavar / café procesado en seco	café processado por via seca	Green coffee prepared by dry processing of the fruit. The term "natural coffee" is also used for this product.