Title

Preservation And Moisture Estimation Of Green Coffee

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Preservation And Moisture Estimation Of Green Coffee

By

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THESIS

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Abstract

The maintenance of green coffee moisture content (MC_{wb}) within the ideal range (10-12%) during storage and transportation is crucial, as variations in MC_{wb} will lead to degradation in coffee quality. Prolonged storage and long-distance transportation of green coffee in conventional jute sacks exposes the coffee beans to undesirable fluctuations in temperature (T) and relative humidity (RH), which can change the physical and sensory characteristics of the coffee. Thus, the primary goal of this study was to evaluate the efficacy of commercially available desiccants for preserving the moisture content of green coffee between 10-12% MC_{wb}, when stored and transported in either hermetic packages and/or jute sacks, and to assess the corresponding impact on sensory quality. A conventional coffee storage and transportation period from Brazil to Italy with a duration of 42 days was mimicked in environmental chambers. Treatments in a 3 × 3 factorial design consisting of three packaging materials (GrainPro SuperGrain bag, GrainPro TranSafeliner, and/or jute sacks) and desiccants (Drying Beads®, $CaCl_2$, or no desiccants) at four different mass ratios of green coffee to desiccant ranging from 50 to 300 – g coffee per g desiccant were evaluated. Overall, the results indicate that hermetic packages, even without desiccants, provide a stable MC_{wb} for green coffee compared to jute sacks only, but under some conditions such as green coffee transportation, desiccants should be added to prevent MC_{wb} in excess of 12%.

In addition to controlling the MC_{wb} of green coffee, accurate measurement of MC_{wb} at the various postharvest steps is also vital. Therefore, an accurate, inexpensive prototype inline system capable of accurately measuring the MC_{wb} of green coffee beans, using a commercially available time-domain reflectometry (TDR) probe was designed and developed. TDR was applied due to its high accuracy, flexibility, robustness, and capability of providing real-time measurements. The

TDR probe was calibrated and validated with green coffee within a MC_{wb} range of 9 to 21 %. A calibration linear regression model correlating the TDR probe output (dielectric constant) to reference MC_{wb} measurements obtained by a halogen moisture analyzer, yielded a high coefficient of correlation (R^2 =0.99). Model validation yielded a high R^2, and a low Root Mean Squared Error equal to 0.93, and 0.9% MC_{wb}, subsequently. Results indicate that the TDR inline green coffee moisture estimation system has the potential to be applied in real-time, industrial-scale operations.

To my mum, Joyce Acheampong, and sister, Beauty Anokye-Bempah, thank you for your endless love, support and encouragement. I could not have done this without you.

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CHAPTER 1

1.0 Introduction

Coffee is one of the most traded agricultural commodities in the World with an estimated annual total industry value of US $200 billion, representing a significant source of income for producing and consuming countries (Voora et. al, 2019; Samper et al., 2017; ICO, 2016). Internationally, coffee is traded as green coffee beans, which is the raw, unroasted seed of the coffee plant (Eira et al., 2006). The coffee plant is an evergreen shrub that thrives in high tropical altitudes (600–1500 m) with an annual average temperature of 15–25 ◦C and abundant rainfall (Wintgens, 2004; Farah and Dos Santos, 2015). Botanically, coffee is a member of the *Rubiaceae* family and the genus *Coffea*, which is composed of 103 known species (Davis et al., 2006; Murthy and Madhava Naidu, 2012). However, only two are economically important: *C. arabica* (arabica) and *C. canephora* (robusta), representing about 75% and 25% of the World's coffee production respectively (Farah and Dos Santos, 2015; Vieira, 2008; Belitz et al., 2009). Arabica coffee is superior to robusta coffee due to its organoleptic properties and therefore has a higher price in the international specialty coffee market (Charrier and Berthaud, 1985; Gielissen and Graafland, 2009; Ferreira et al., 2019). The origin of coffee can be traced to Yemen and Ethiopia, where it was first cultivated in the 14th century, and subsequently spread to India and Sri Lanka during the 17th century, and then to Indonesia, Brazil, Colombia, Central Africa, and Central America (Smith, 1985; Alonso-Salces et al., 2009; Illy and Rinantonio, 2005).

Today, coffee is cultivated in over 50 tropical and subtropical countries with a total production of 175.6 million 60-kilogram bags during the 2020/2021 coffee production season (ICO, 2022). The five largest coffee-producing countries responsible for approximately 75% of the total World production, are as shown in Figure 1.1. Over 70% of the green coffee produced in developing countries is exported and consumed mainly in developed countries (Fig. 1.1b) (Ponte, 2002; Esquivel and Jiménez, 2012; Graham, 1912). The United States and Germany are the main importers of coffee, importing around 18% and 12% of total coffee imports respectively (Workman, 2019; Slavova and Georgieva, 2019). The imported green coffee is typically processed for local use or exported as refined products.

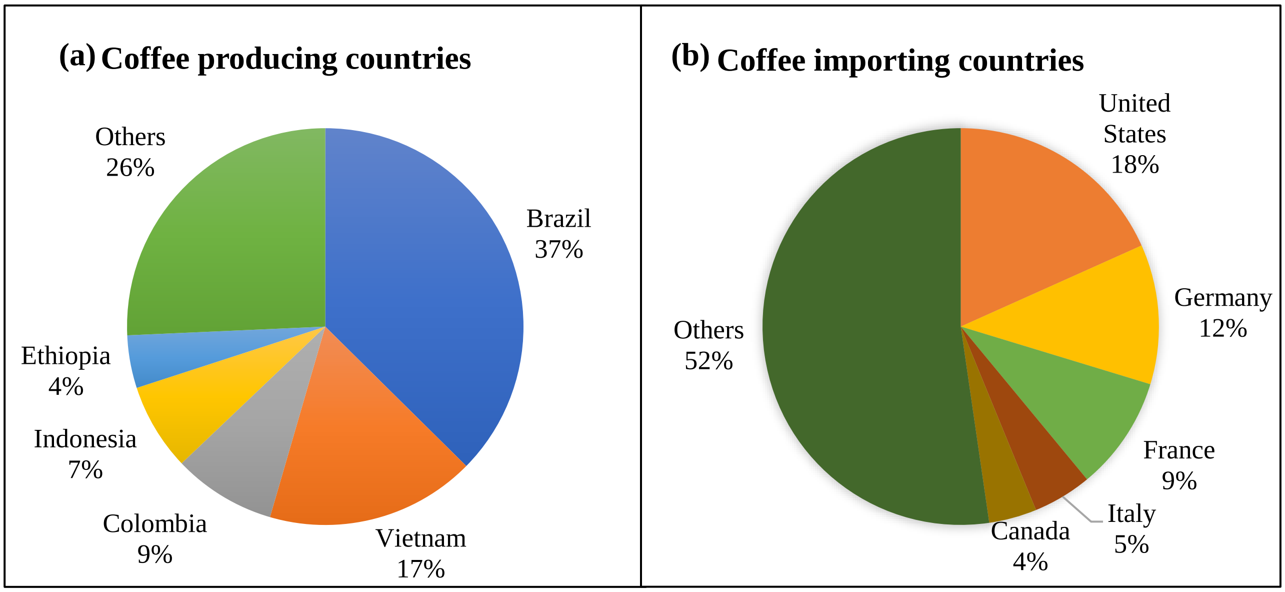

Figure 1.1. (a) Pie chart showing the five largest coffee-producing countries. Others include Honduras (3.6%), India (3.4%), Uganda (3.3%), Mexico (2.4%), and Guatemala (2.2%). (b) Pie chart showing the five largest coffee-importing countries. Others include the Netherlands (3.8%), Japan (3.8%), Belgium (3.6%), Spain (3.3%), and the United Kingdom (3.2%). For interpretation of the references to color in this figure, the reader is referred to the web version of the thesis.

The market value of coffee increases significantly with improvements in its physical and organoleptic quality (Agwanda et al., 2003; Wintgens, 2008). For instance, specialty coffee, which refers to the highest quality of coffee beans; when grown under ideal climate and conditions, shows little or no physical defects such as black beans or insect damage, and has distinctive taste and flavor, receives a premium price that is approximately 20–50% higher in comparison to regular coffee beans (Wollni and Zeller, 2007; Traore et al., 2018). Price, as well as national regulations in consuming countries, are established based on quality. Thus, much attention is paid to quality improvement and its maintenance throughout the production, postharvest, and distribution chains to maintain coffee value. Green coffee quality is influenced by a variety of factors, including pre-harvest factors such as husbandry practices (application of nutrients, mulching, pruning), coffee variety, and ecological factors (climate, rainfall, altitude), and maintained through post-harvest phases such as harvesting, processing, storage, transportation and roasting (Njoroge, 1998; Alpizar and Bertrand, 2004; Illy and Rinantonio, 2005; Farah and Donangelo, 2006; Borém et al., 2008; Barbosa et al., 2012). According to Musebe et al., (2007), pre-harvest factors determine 40% of green coffee bean quality while the remaining 60% is maintained through proper post-harvest practices. During postharvest processing, changes in physicochemical properties of coffee beans occur, and these influence the overall quality of the final product (Knopp et al., 2006; Avelino et al., 2005; Leroy et al., 2006).

Storage and transportation are among the most important postharvest steps in maintaining the quality of green coffee beans, prior to commercialization. The preservation of desirable sensory attributes and coffee quality mainly depends on its storage and transportation conditions (Ribeiro et al., 2011; Abreu et al., 2017). Variations in environmental factors such as temperature (T) and relative humidity (RH), mainly when transporting coffee from tropical producing countries to temperate importing regions, cause moisture migration between the green coffee and the ambient air due to coffee's hygroscopic nature, leading to quality deterioration (Konnman, 2016). The ideal wet basis moisture content (MC_{wb}) range for green coffee storage is 10 to 13%. Coffee beans with MC_{wb} above this range are susceptible to fungal growth that can accelerate bean degradation and can induce the accumulation of mycotoxins (Belitz et al., 2009; Illy and Rinantonio, 2005). To ensure green coffee's overall quality, attributes such as the green coffee MC_{wb} need to be controlled during storage and transportation.

Thus, Chapter 1 of this thesis focuses on describing the production, properties, and quality parameters of green coffee beans, as well as the factors that affect their quality during storage and transportation. The use of packaging materials such as hermetic packages and desiccants to preserve bean quality by maintaining the MC_{wb} during storage and transportation, and moisture content estimation methods will also be addressed.

1.1 The coffee cherry

The coffee cherry is the fresh fruit of the coffee plant. Coffee cherries are green when immature and ripen to red, yellow, or orange depending on the species (Fig. 1.2a). Fruit ripening occurs within 8–12 months after flowering (Illy and Rinantonio, 2005; Wintgens, 2004). Figure 1.2(b) shows the components of a mature coffee cherry, which consists of: (a) the external skin (exocarp), which is a monocellular layer covered with a waxy substance that protects the fruit (Eira et al., 2006; Farah and Dos Santos, 2015); (b) the mesocarp which consist of a fleshy, easily removable pulp composed mainly of carbohydrates (35–85%), soluble fibers (30%), proteins (5–11%) and minerals (3–11%), and a slimy pectinaceous layer of mucilage which contains protein, water, sugar, tannins, polyphenols, and caffeine (Janissen and Huynh, 2018; Murthy and Madhava Naidu, 2012; Iriondo-DeHond et al., 2019); (c) the endocarp or parchment, which is a thin, yellowish paper-like polysaccharide covering composed mainly of lignocellulose (Esquivel and Jiménez, 2012); (d) the silverskin or integument, which is the layer surrounding the bean (seed coat), composed of mainly polysaccharides such as cellulose and hemicelluloses, as well as protein, fat, and ash (Farah and Dos Santos, 2015); and (e) two elliptical or egg-shaped seeds (green beans) containing embryos. Typically, a single cherry contains two seeds, but 5-15% of cherries contain only one seed termed a “peaberry”, and a lower percentage (~2%) contains three seeds (Vieira, 2008).

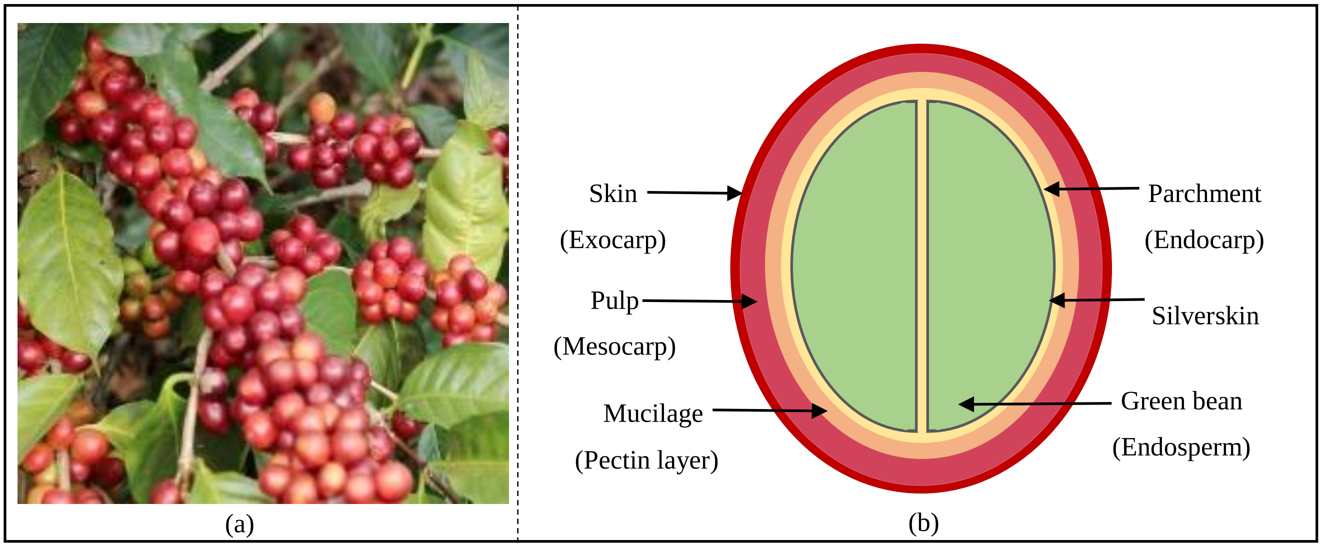

Figure 1.2 a) Coffee tree bearing ripe (red) cherries. b) Components of a coffee cherry. For interpretation of the references to color in this figure, the reader is referred to the web version of the thesis.

1.2 Green coffee production

Figure 1.3 shows several processing methods applied to produce green coffee. Ripe coffee cherries are harvested by selective hand-picking, non-selective stripping of whole branches, or by mechanical harvesting (Kleinwächter et al., 2015; Pimenta et al., 2018; Illy and Rinantonio, 2005). Following harvest, coffee cherries undergo sorting and primary processing to remove the skin, pulp, mucilage, and enough water to obtain exportable green coffee beans with MC_{wb} of 10-12%. The two main processing methods are the wet (washed) and dry (natural) processing methods. In wet processing, coffee cherries are mechanically depulped to remove the skin and pulp and then fermented for approximately 24–48 h to remove the mucilage layer. Alternatively, the mucilage can be mechanically removed. The resulting bean, covered by the parchment is known as the parchment coffee. Parchment coffee is then dried, conditioned, and subsequently hulled to remove the parchment and ultimately produce green coffee. This method is often used in regions with abundant availability of water and where coffee is harvested by selective picking such as Colombia, Asia, Central America, and Hawaii (Silva et al., 2008; Winkler, 2014; Rotta et al., 2021). In contrast, in dry processing, whole coffee cherries are dried without the removal of the pulp, and then mechanically hulled to remove the skin, pulp, mucilage, parchment and parts of the silverskin to produce green coffee (Mazzafera and Purcino, 1995; Taveira et al., 2015; De Bruyn et al., 2017). The dry process is commonly applied in countries where rainfall is scarce and long periods of sunshine are available for efficient drying. It is used for about 95% of Arabica coffee produced in Brazil, Ethiopia, Haiti, Indonesia, and Paraguay (Silva et al., 2008; Rothfos, 1980). More recently, other processing methods such as the wet-hulled (semi-washed) and honey processing methods have been adopted. These methods are variations of the traditional wet and dry processes. In the wet-hulled method, the skin is removed, like in the wet process, but the mucilage remains on the beans as it is dried. The wet-hulled method is unique to Indonesia where sun drying is challenging, mainly due to high humidity (Vilela et al., 2010; Poltronieri and Rossi, 2016; Brando, 2008). In the honey processing method, coffee cherries are de-pulped, and quickly sun-dried or slowly dried in the shade without the subsequent fermentation and washing step, to obtain red, yellow, or black “honey” coffee (Musebe et al., 2007; Bee et al., 2005). After processing, the green coffee is sorted according to its density, presence of defects, size, shape, and color, bagged and stored in warehouses, and/or shipped to importing countries.

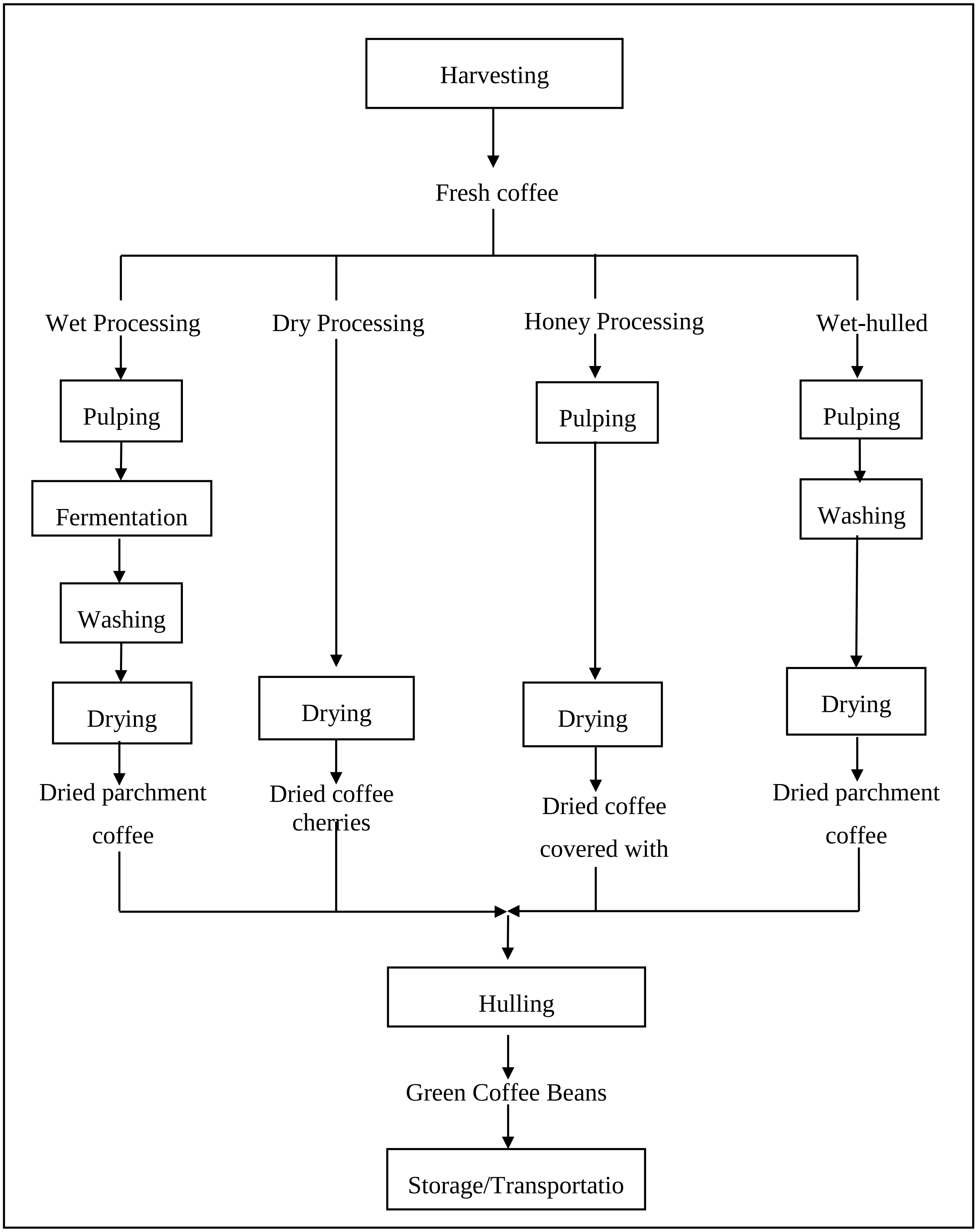

Figure 1.3. Schematic representation of common coffee processing methods

1.3 Green coffee bean properties

The physical and chemical properties of green coffee beans vary significantly depending on the variety, origin, climate conditions, as well as the applied processing method (Mussatto et al., 2011; Wrigley, 1988). Generally, green coffee beans are approximately 10 mm long and 6 mm wide, with weight ranging between 0.17 and 0.40 g, at 12-13 % MC_{wb} (Wintgens, 2004). With regards to shape and color, arabica green coffee beans tend to be flat and blue-green to grey-green with uniform color, while robusta beans tend to be more rounded in shape, brownish, and non-uniform color (Clifford, 1985; Ismail et al., 2013; Jokanović et al., 2012). Caffeine is the most known chemical component in coffee, accounting for 1 to 4% (dry basis), with 0.8-1.4% in arabica, and 1.7-4.0% in robusta (Belitz et al., 2009; Dessalegn et al., 2008; Paulo Mazzafera and Silvarolla, 2010). However, the green coffee bean is composed of other chemical constituents, including carbohydrates, proteins, lipids, water, vitamins, tannins, minerals, and free amino acids. Soluble carbohydrates, such as monosaccharides fructose, glucose, galactose and arabinose, oligosaccharides sucrose, raffinose, and stachyose, as well as insoluble polysaccharides like cellulose and hemicelluloses, make up approximately 49% of a green bean's dry weight (Murkovic and Derler, 2006; Arya and Rao, 2007). Proteins and free amino acids such as alanine, arginine, cysteine, glutamic acid, histidine, isoleucine, lysine, methionine, proline, and valine constitute 10%-13% of green coffee by dry weight (Grembecka et al., 2007; Dos Santos and De Oliveira, 2001). Water is also an important constituent, accounting for 10-13% of the green bean's dry weight. In addition, lipids, primarily triglycerides, average approximately 19% w/w, together with minerals (~4% w/w) including potassium, magnesium, calcium, sodium, iron, zinc, cobalt, lead, molybdenum, and copper, and volatile acids such as chlorogenic acid (7-12% w/w) (Clifford and

Jarvis, 1988; Gonzalez-Rios et al., 2007; Deshpande, 2003). Table 1.1 shows the chemical composition of green coffee beans of arabica and robusta varieties.

Table 1.1. Chemical composition of Arabica and Robusta green coffee

	Average content (%, dry basis)		
Component	Arabica	Robusta	Constituents
Carbohydrates/sugars	55-65.5	40-55.5	
Monosaccharides	0.2-0.5		Glucose, Fructose, galactose, arabinose
Oligosaccharides	6-9	3-7	Sucrose (>90%), raffinose (0-0.9%), stachyose (0-0.13%)
Polysaccharides	3-4		Galactose (55-65%), mannose (10-20%), arabinose (20-35%), glucose (0-2%)
Hemicelluloses	5-10	3-4	Galactose (65-75%), mannose (0-10%), arabinose (25-30%)
Cellulose, β (1-4) mannan	41-43	32-40	
Acids and phenols			
Volatile acids	0.1		
Nonvolatile aliphatic acids	2-2.9	1.3-2.2	Citric acid, malic acid, quinic acid
Chlorogenic acid	6.7-9.2	7.1-12.1	Mono-, dicaffeoyl-, and feruloylquinic acid
Lignin	1-3		
Lipids	15-18	8-12	
Wax	0.2-0.3		
Oil	7.7-17.7		
Nitrogen compounds	11-15		
Free amino acids	0.2-0/8		
Proteins	8.5-12		
Caffeine	0.8-1.4	1.7-4.0	Traces of theobromine and theophylline
Trigonelline	0.6-1.2	0.3-0.9	
Minerals (ash, k and P)	3-5.4		

Source: Belitz et al., 2009.

1.4. Green coffee quality parameters

Green coffee quality assessment is of major importance to producers, distributors, and roasters, as it determines its market price, storage stability, and export potential (Wintgens, 2008). Determination of green coffee quality can be grouped into four main categories: Removal of foreign matter (e.g., rocks), grading based on physical attributes, organoleptic sensory evaluation of the roasted coffee, and chemical or analytical measurements. Grading or sorting involves separating the beans according to density, size, shape, color, and defective beans. Sensory evaluation focuses on determining the subjective flavor profile typically by trained cuppers, and analytical or chemical measurements mainly involve the determination of moisture content, and water activity (a_w) of the green coffee beans (Feria-Morales, 2002; Wintgens, 2004).

1.4.1 Green coffee grading

Green coffee is separated by size, as a higher price can be received for larger coffee beans, and to enable more efficient roasting (uniform size of beans allow for a uniform roasting) (Clarke, 1987; Ghosh, 1966). Coffee graders typically use perforated plate screens with apertures of specified dimensions, to separate coffee beans according to their size and shape (Njoroge, 1998; Haile and Hee Kang, 2020). Bean size is usually expressed as a percentage of beans retained above or passing through the plate screens, and the screen aperture is commonly expressed in 1/64th of an inch (0.4mm). Depending on the production region, bean size can be specified by using designations (e.g., medium, large, bold), letters (e.g., Kenya AA), or numbers (e.g., Cameroon Grade 2) as shown in Table 1.2 (Illy and Rinantonio, 2005; Coste and Cambrony, 1992; Pimenta et al., 2018). Regarding shape, the coffee receives the denomination of flat or regular (beans that have one flat and one concave surface), and peaberries (round shape). High-quality coffee beans should be of nearly equal size and be similarly shaped (Mutua, 2000). Green coffee is also sorted by density to separate beans of light density and to remove dust and other light particles. Density sorting is done by pneumatic sorting which consists of the use of an upward current of air or by a gravimetric table (Vincent, 1987).

Table 1.2: Coffee Grading-Sizes

1/64 inch	mm	Classification	Central America and Mexico	Colombia	Africa and India
20	8	Very large	Superior	Supremo	AA
19.5	7.75	Very large	Superior	Supremo	AA
19	7.5	Very large	Superior	Supremo	AA
18.5	7.25	Large	Superior	Supremo	AA
18	7	Large	Superior	Supremo	A
17	6.75	Large	Superior	Supremo	A
16	6.5	Medium	Segundas	Excelso	B
15	6	Medium	Segundas	Excelso	B
14	5.5	Small	Terceras	Excelso	C
13	5.25	Shells	Caracol		PB
12	5	Shells	Caracol		PB
11	4.5	Shells	Caracolli		PB
10	4	Shells	Caracolli		PB
9	3.5	Shells	Caracolillo		PB
8	3	Shells	Caracolillo		PB

Source: www.coffeeresearch.org, www.rocc.coffee

The color of green coffee beans has significant economic importance as discolored beans are associated with a lower market price (Borém et al., 2013). The ISO (ISO 4149,2005) stipulates the categorization of green coffee color in the terms; blueish, greenish, grayish-green, olive-green, whiteish, yellowish, and brownish. A green-bluish color is perceived as a sign of high quality and freshness, while a yellowish color is a sign of old and low-quality coffee (Vilela et al., 2010; Ribeiro et al., 2011). Green coffee color is determined by visual inspection, by spectrophotometers, or though inline color vision sorters (Illy and Rinantonio, 2005).

The number of defective beans is also an important factor in green coffee bean quality assessment. Large amounts of defective beans in a sample can cause off-flavors and lesser homogeneity in the final roasted product, thus reducing the quality of the coffee (Franca et al., 2005). The ISO has established a standard (ISO 10470) that describes green coffee defects as foreign materials of non-coffee (e.g., stones/sticks) and non-bean (e.g., husks) origin, abnormal beans regarding shape and visual appearance, such as black beans (coffee beans that are partially or totally black), stinker beans (over-fermented or improperly dried beans), immature beans, broken and insect-damaged beans (Leroy et al., 2006; Bee et al., 2005; Mancha Agresti et al., 2008). Destoners are used by graders to remove stones and foreign materials from the coffee. The assessment of the defective beans is done by hand or electronic sorting by grouping, and counting the number of defective beans in a given amount of coffee, typically in 300–500 g, or 1000 g of green coffee beans (Wintgens, 2004; Portugal-Zambrano et al., 2017; De Oliveira et al., 2016). The International Coffee Organization (ICO) recommends that a maximum of 86 defects per 300 g for Arabica coffee and 150 defects per 300 g for Robusta coffee should not be exceeded for export purposes (ICO, 2018). Based on the grading results by density, size, shape, color, and number of defects, the coffee is then classified into or assigned an overall grade.

1.4.2 Sensory evaluation (Cup profile)

Sensory evaluation of green coffee is done through cupping or cup tasting, which is the standard method to assess the final quality of coffee in its final form or roasted beans (Lingle and Menon, 2017). In cupping, a sample of green coffee beans is roasted, ground, brewed, and evaluated by a trained taster or "cupper". The cupper then assigns subjective sensory scores on key quality attributes including flavor, aroma, sweetness, acidity, cleanness of cup, balance, and uniformity (Feria-Morales, 2002).

Currently, there is no universal standard for grading and classifying green coffee. Producing countries, trading organizations, and private companies have developed their own classification and grade charts, which are often also used to set minimum standards for export (ICO, 2018; R. Clarke, 2012; Banks, 2005). For example, the Specialty Coffee Association of America (SCAA), has a green coffee grading system to be used by its members. According to the SCAA, specialty coffee is a term used to refer to coffees that can be distinguished on the basis of high quality and uniqueness of origin (Lingle and Menon, 2017). To be considered specialty, under the SCAA grading, a coffee batch must have less than 5 defects for every 350 g (12 ounces) of green coffee beans, and score 80 points or above on a 100 point sensory evaluation scale by a certified cupper (SCAA, 2006).

1.4.3 Analytical measurements

1.4.3.1 Wet basis moisture content (MCwb)

Moisture content, which is the percentage by weight of water in a food product, is an important quality parameter of green coffee as it affects the physical, chemical, and sensory characteristics of the final product (Konnman, 2016; Reh et al., 2006). It has been established that green coffee should be dried to an ideal MC_{wb} range of 10-12% to ensure proper bean quality preservation (Vincent, 1987; Clarke, 1985; Bucheli et al., 2000; Vilela et al., 2010). Coffee beans with MC_{wb} above 12% are subject to a high risk of oxidation and the formation of fungi and therefore mycotoxins, which can lead to the development of off-flavors and accelerate bean quality degradation and affect their safety (Romani et al., 2000; Wintgens, 2004). Broissin-Vargas et al. (2018) reported that a high MC_{wb} (12.5%) enables the production of Ochratoxin A (OTA) mycotoxin at a concentration of around 5.1 μg/kg. Similarly, Suárez-Quiroz et al. (2004) observed that 13% MC_{wb} was the limit for spoilage of green coffee due to fungal growth. Furthermore, an increase in MC_{wb} leads to the loss of color in green coffee beans or whitening, which depreciates the beans appearance and leads to an inferior cup quality (Ribeiro et al., 2011). MC_{wb} below 10% leads to shrunken and brittle coffee beans that tend to break up during handling. The ICO resolution 407 recommends that coffee should not be exported when the MC_{wb} is outside of the ideal range (Leroy et al., 2006).

The standard method for determining moisture content is the thermogravimetric method or oven drying method. This method involves drying coffee samples (5-100 g) at 105 °C for 16 hrs in a convection oven and calculating the wet or dry basis moisture content, as specified in equations (1) and (2) (ISO 1446, 2001).

$$MC_{wb}(\%) = \frac{w_i - w_f}{w_i} \text{ x } 100 \quad (1)$$

$$MC_{db}(\%) = \frac{w_i - w_f}{w_f} \text{ x } 100 \quad (2)$$

Where MC_{wb} is the wet basis moisture content, MC_{db} is the dry basis moisture content, w_i is the initial weight of the coffee sample and w_f is the final weight of the sample after drying.

The major drawback associated with the oven drying method is that it is destructive and time-consuming. Thus, alternate indirect methods such as near-infrared spectroscopy (NIRS), hyperspectral imaging, microwave-based, resistance or conductance, capacitance methods (e.g. Dickey-John GAC-2500 moisture meter, and AgraTronix-Coffee Moisture Tester), and time-domain reflectometry (TDR) methods have been developed for rapidly and non-destructively estimate MC_{wb} (Adnan et al., 2017; Caporaso et al., 2018; Toledo et al., 2008). Indirect methods typically measure changes in electrical or structural properties of the coffee beans to predict MC_{wb}, and are calibrated based on the standard thermogravimetric method (Mendonça et al., 2007). The most common commercially available equipment to indirectly estimate the moisture of green coffee, are as shown in Figure 1.4.

1.4.3.2 Water activity (A_w)

Water activity (A_w) is a measurement of water availability in coffee, which ranges between 0 and 1, is defined as the ratio of partial pressure of water in the coffee beans to the vapor pressure of pure water at the same temperature and pressure, known as the headspace equilibrium RH (Barbosa-Cánovas et al., 2008; Nielsen et al., 2013). Equipment used to measure the A_w of green coffee include METER Aqualab 4TE water activity meter, Rotronic water activity meter and the

DryCard^{TM}, which is a humidity indicator that estimates A_w (Thompson et al., 2017) (Fig. 1.5). According to the ICO, properly dried green coffee should have a A_w of between 0.55 and 0.60. A_w determines the lower limit of available water for microbial growth and other biochemical reaction thus, it can be used to predict the shelf stability of green coffee. A_w is an accurate and important quality indicator of green coffee (Konnman, 2016; Fretheim, 2014; Fontana, 2008). A_w correlates with MC_{wb} hence, A_w is not typically measured in coffee production regions, as they mainly rely on MC_{wb} measurements (Fretheim, 2008).

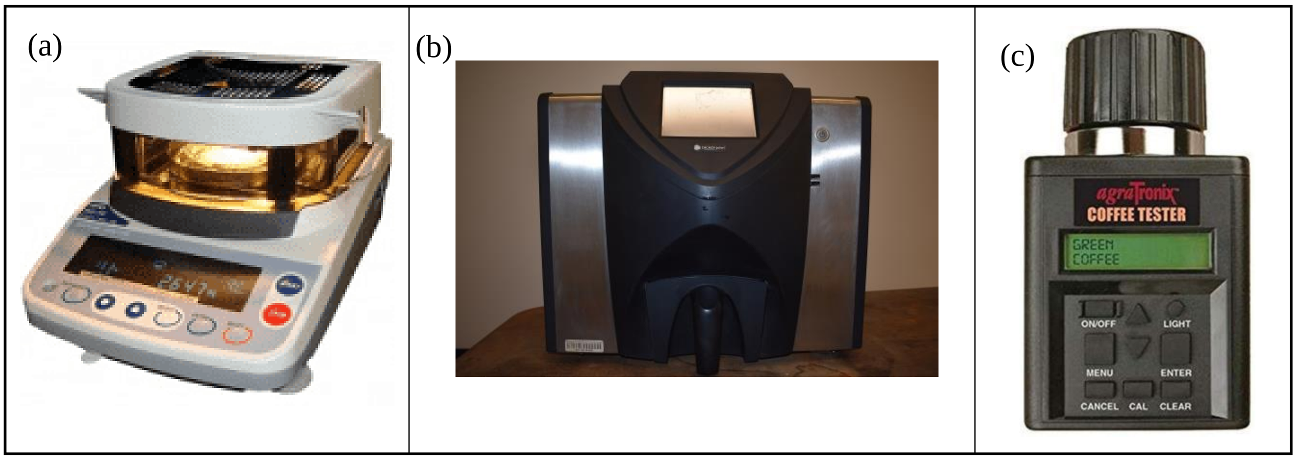

Figure 1.4. Pictures of typical equipment to determine green coffee moisture content, including (a) Halogen moisture meter Ohaus Torbal A&D weighing Mettler Toledo Sartorius. (b) Dickey-john GAC 2500. (c) AgraTronix moisture meter. For interpretation of the references to color in this figure, the reader is referred to the web version of the thesis.

(a) (b) (c)

Figure 1.5. Pictures of commonly used water activity meters for green coffee: (a) A picture of an AquaLab 4TE water activity meter. (b) A picture of a Rotroni water activity meter. (c) Picture of the DryCard^{TM}. For interpretation of the references to color in this figure, the reader is referred to the web version of the thesis.

1.5 Green coffee storage and transportation

Storage and transportation are crucial steps that influences coffee commercialization and quality. Since coffee is a seasonal crop, storage is necessary to ensure adequate supply between harvest season and year-round consumption (Wintgens, 2004). Green coffee is stored in producing countries for up to 3 years, and also for a few weeks to months, in consuming countries before roasting (Birch, 1985; Belitz et al., 2009; Illy Andrea, 2005). According to Bucheli and Taniwaki, (2010), green coffee transportation takes from a few days up to three months depending on the origin and destination of the coffee. During storage and transportation, factors such as storage time, T and RH, and packaging may cause significant changes in the physical and chemical composition of the coffee, leading to its quality deterioration (Broissin-Vargas et al., 2018; Sivetz and Desrosier, 1984).

1.5.1 Factors that influence green coffee quality during storage and transportation

1.5.1.1 Temperature (T) and Relative Humidity (RH)

Environmental conditions, mainly T and RH are important during green coffee storage and transportation, as these directly affect coffee quality. The optimum T and RH ranges for green coffee storage are 20-26 ^{o}C and 50-70 %, respectively (Bucheli et al., 1998; Illy and Rinantonio, 2005; Nobre et al., 2007). Coffee beans are hygroscopic, which equilibrate their moisture content with surrounding environmental conditions (Brando, 2008). Thus, fluctuations in T and RH lead to changes in the coffee MC_{wb}, which in turn, cause quality deterioration. At low RH (<50%), the coffee beans lose moisture, which directly relates to a loss of volatiles and compounds that relate to coffee aroma and flavor (Harris and Miller, 2008). On the other hand, an increase in RH (>70%) causes the coffee beans to absorb moisture from the environment, which lead to quality degradation as described in section 1.4.3.1 (De Bruin, 2010; Scheidig et al., 2007).

Several studies have investigated the effects of T and RH on the quality of green coffee beans during storage (R. J. Clarke, 1987; Saath et al., 2014; Ribeiro et al., 2011; Broissin-Vargas et al., 2018; Bucheli et al., 1998). Palacios-Cabrera et al. (2004) determined that fluctuations in storage T favored OTA production in green coffee, mainly due to condensation and changes in MC_{wb} and A_w of the coffee beans. High RH in combination with T variations might induce water condensation in the surface of coffee beans potentially contributing to microbiological. Shipping green coffee from producing to importing countries exposes beans to significant variations in T and RH that can lead to moisture transfer into or outside the coffee (Gheorghe, 2012; Jones and Faas, 2020). Palacios-Cabrera et al. (2007) studied the effect of T and RH variations over one and a half months of industrial scale storage and maritime transportation, showing that, T varied over a 16°C range (~10-26°C) and RH varied over a 15% range (~70-85%). This variability in environmental conditions led to water condensation inside the shipping containers, coffee bags, which ultimately induced fungal growth and the production of OTA.

1.5.1.2 Storage and transportation time

During storage and transportation, undesirable chemical changes occur due to oxidation and other biochemical processes (Rendón et al., 2014; Abreu et al., 2019; Ismail et al., 2013). Prolonged storage of green coffee, even under favorable storage conditions, leads to a decrease in coffee quality, including a loss in color and flavor of the beans (Selmar et al., 2008). Scheidig et al. (2007) and Abreu et al. (2017) studied the storage of commercial green coffee beans under optimum storage conditions for up to 3 years and noted significant changes in cup quality (i.e. flatness) and loss in color. Green coffee storage under optimum storage conditions shouldn't exceed one year. After one year, quality is generally reduced, and changes in color, flavor, and aroma become evident and undesirable (Bucheli et al., 1998; Mabbett, 1990).

1.5.1.3 Packaging

A Jute sack, made from natural plant fibers, is the conventional and most frequently used packaging material for green coffee storage and transportation (Abreu et al., 2019). It is preferred for coffee storage as the jute sacks can be re-used, are relatively affordable, and can be easily sampled for lot inspections. However, jute sacks are permeable to ambient environmental conditions and hence, do not prevent the exchange of volatile compounds, and water vapor between the coffee beans and the environment (Broissin-Vargas et al., 2018; Selmar et al., 2008). Additionally, prolonged storage of green coffee in jute sacks causes the coffee to absorb the aroma of the jute sacks, inducing a straw-like or “baggy” off-flavor, which can be accelerated by an increase in the MC_{wb} of the coffee (> 12%) (Daniels, 2009; Scheidig et al., 2007). Numerous studies have reported a reduction in the sensory quality of coffee stored in jute sacks (Borém et al., 2008; Ribeiro et al., 2011). Selmar et al., (2008) stated that prolonged storage of green coffee in jute sacks shows a decrease in quality and taste, mainly caused by changes in coffee beans' chemical composition.

Also, hermetic packages are sometimes used in addition to jute sacks to store and transport green coffee, due to their impermeability (Donovan et al., 2020; Aronson et al., 2005; Emblem, 2012). Hermetic packaging diminishes moisture variations in the coffee, and also reduces biochemical reactions due to Oxygen (O_2) depletion, and increase on Carbon Dioxide (CO_2) (De Bruin, 2010). Alternatively, hermetic package atmospheric conditions can be modified by injecting CO_2 to induce a reduction on O_2 (Emblem, 2012). Several studies, performed by Nobre et al. (2007), Ribeiro et al. (2011), Harris and Miller (2008), De Bruyn et al. (2017), and Kleinwächter et al. (2015) evaluated the feasibility of using hermetic packages, with and without the injection of CO_2, to better preserve the physical, chemical and sensory quality of green coffee during storage. Borém et al. (2013) compared the quality of coffee stored in hermetic packages with and without the injection of CO_2, with the storage in plain jute sacks and concluded that hermetic packaging, with or without the injection of CO_2, better preserves the aroma and flavor of coffee beans, while coffee stores in jute sacks developed an earthy and "baggy" flavors. Similarly, Ribeiro et al. (2011) evaluated the physical, chemical, and sensory qualities of green coffee beans during storage in hermetic packages with and without the injection of up to 60% CO_2, and observed that the coffee packed in hermetic packages maintained a stable MC_{wb} level and preserved the green coloration of the beans during a 12-month storage period.

Commonly used hermetic packages for green coffee storage and transportation include GrainPro bags, which are manufactured from multilayer polyethylene plastic with sufficiently low permeability to reduce the entry of air and moisture (Grain Pro. Inc., Concord, MA, USA). These hermetic packages range from 60kg capacity GrainPro SuperGrainbags™ to 1-tonne capacity TranSafeliners™ that engulf coffee packaged in jute sacks on standard 6 or 12m (20 or 40-foot) container (Productioli, 2004). Desiccants are sometimes used in addition to hermetic packaging to absorb any excess moisture that may permeate the shipping container and hermetic packages.

Desiccants are hygroscopic materials that absorb moisture from the air, thus reducing the RH in a controlled environment until reaching equilibrium with the environment (Singh et al., 2018). At equilibrium capacity or saturation, the active pore sites in a desiccant are occupied with water, and hence, the desiccant can no longer absorb more water vapor. Desiccants may be used repetitively by regeneration (a process of heating at temperature ranges of 250 - 500 ° C for 2-3 hrs., depending on the type of desiccant) to return them to their active state, or may be used only once and discarded (Cohen, 2003). The most commonly used desiccant for green coffee transportation is Calcium Chloride ($CaCl_2$) due to its high-water absorption capacity and availability (Thoruwa et al., 2000). Factors such as the desiccant type, absorption capacity, interaction with the food product, cost, and behavior upon saturation must be considered during the desiccant selection.

1.6 Problem statement

The price of coffee is almost completely dependent on its quality; thus, maintaining green coffee's inherent quality through the postharvest phase is imperative. Maintenance of green coffee MC_{wb} within the ideal range (10-12%) during storage and transportation is crucial as variations in MC_{wb}

will lead to coffee quality degradation (Wintgens, 2004). Prolonged storage and long-distance transportation of green coffee beans exposes them to undesirable fluctuations in T and RH, which leads to condensation within the shipping container and variations in the coffee MC_{wb} (Gheorghe, 2012).

Current industrial solutions include the use of hermetic packages during green coffee shipping and transportation (Nobre et al., 2007; Ribeiro et al., 2011; Harris and Miller, 2008). Although hermetic packages have proven to be effective during storage, they are still compromised due to the rapid and extreme environmental changes that occur in the shipping container during transportation. Therefore, the marine transport industry has proposed using desiccants to reduce moisture changes inside shipping containers (Gheorghe, 2012). The most commonly used desiccant for green coffee storage and transportation is $CaCl_2$, and the amount used is usually based on approximations provided by desiccant retailers. Knowledge of the optimized type and amount of desiccants to be placed within shipping container is essential. However, studies that correlate the current industrial practices of desiccant use during green coffee storage and transportation with the physical and chemical characteristics of the beans are unavailable.

In addition to controlling the MC_{wb} of green coffee, accurate measurement of MC_{wb} at the various postharvest steps is also vital. Current methods of MC_{wb} determination typically rely on a sample size of between 5 and 500 g, which does not accurately represent the MC_{wb} range of the entire coffee batch, and therefore the MC_{wb} determination is influenced by sampling errors (Willimack, 2018). Using the sample MC_{wb} to determine whole batch processing parameters such as additional drying requirements, drying time, T, and RH leads to non-uniform quality and highly variable MC_{wb} distribution. Overall, eliminating moisture damage by minimizing the effect of T and RH fluctuations during green coffee storage and transportation will preserve the quality of green coffee and will reduce economical losses.

1.7 Objectives of this thesis

The objectives of this thesis were to;

i) Evaluate the effect of using varying amounts of two different types of commercially available desiccants (Drying Beads®, and $CaCl_2$) to preserve the moisture and quality of green coffee during storage and transportation, in two types of commercially available hermetic packages (GrainPro SuperGrain™ bag, and GrainPro TranSafeliner™), and jute sacks (Chapter 2).

ii) Design, develop, calibrate and validate a prototype inline moisture estimation system capable of accurately measuring the MCwb of green coffee beans, using a commercially available TDR probe (Chapter 3).

Finally, Chapter 4 includes a brief discussion of final remarks and future studies of importance to the coffee industry.

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CHAPTER 2

THE USE OF DESICCANTS FOR PROPER MOISTURE PRESERVATION IN GREEN COFFEE DURING STORAGE AND TRANSPORTATION

Abstract

Prolonged storage and long-distance transportation of green coffee beans exposes them to undesirable fluctuations in temperature (T) and relative humidity (RH), which can change the physical (wet-basis moisture content (MC_{wb}), water activity (A_w), and color) and sensory characteristics of the coffee. High humidity also supports mold growth, decay, and microbial activities. Thus, the objective of this study was to evaluate the efficacy of commercially available desiccants for preserving the moisture content of green coffee between 10-12% MCwb, when stored in either hermetic packages and/or jute sacks, and to assess the corresponding impact on sensory quality. A conventional coffee storage and transportation period from Brazil to Italy with a duration of 42 days was mimicked in environmental chambers. Treatments in a 3 × 3 factorial design consisting of three packaging materials (GrainPro SuperGrain bag, GrainPro TranSafeliner, and/or jute sacks) and desiccants (Drying Beads®, $CaCl_2$, or no desiccants) at four different mass ratios of green coffee to desiccant ranging from 50 to 300 – g coffee per g desiccant were evaluated. The MC_{wb}, A_w, and color of all samples were measured approximately weekly over 42 days. In comparison to the control (no desiccant, and only jute bag), we observed a statistically significant impact for all tested desiccants and hermetic packages for maintaining the proper MCwb, aw, and color. No significant difference was observed for the different desiccant masses tested when they were placed inside the hermetic packaging, but the desiccants were ineffective without the hermetic packaging. Triangle test and descriptive sensory evaluation yielded no significant differences between the use of hermetic packages with or without desiccants.

Keywords: Green coffee beans, Hermetic packaging, Desiccants, Drying Beads, Environmental chambers

1.0 Introduction

The price of coffee is directly related to its quality, hence producing high-quality coffee and maintaining it through its postharvest and distribution phases is imperative. Green coffee storage and transportation are considered important steps in the postharvest phase, as these define the final product's quality (Selmar et al., 2008; Ribeiro et al., 2011; Donovan et al., 2019). Variations in 3environmental conditions during storage and transportation cause significant changes in green coffee moisture content due to its hygroscopic nature, leading to deterioration in its quality. Vilela et al. (2010) reported that the storage of green coffee in varying temperatures (T) (20-35 °C) and relative humidity (Rh) (52-75%) led to a 4% increase in moisture content and a corresponding loss of color in the coffee beans. Palacios-Cabrera et al. (2007) also studied the effect of T and Rh during green coffee transportation on moisture content and reported that a 5 to 10% increase in Rh leads to a 3% increase in the moisture content of the coffee beans.

The recommended wet-basis moisture content (MC_{wb}) and water activity (A_w) of green coffee during storage ranges from 10 to 12% and 0.4 to 0.6, respectively (Harris and Miller, 2008). MC_{wb} above 12% leads to the formation of fungi and mycotoxins, as well as the development of fermented flavors in the end product. Various studies have reported the effects of a high MC_{wb} in green coffee beans. Broissin-Vargas et al. (2018) stated that a high MC_{wb} (12.5%) enables the production of Ochratoxin A (OTA) mycotoxin at a concentration of around 5.1 μg/kg. Furthermore, an increase in MC_{wb} leads to the loss of color in green coffee beans in a process known as whitening, which depreciates the beans appearance and leads to an inferior cup quality (Ribeiro, Borém, Giomo, de Lima, et al., 2011). MC_{wb} below 10% leads to shrunken coffee beans that tend to break up during handling (Vilela et al., 2010; Jones, E.C. and Faas, 2020).

Conventionally, green coffee is stored and transported in jute sacks, which do not prevent the exchange of gases and water vapor between the coffee and the environment (Abreu et al., 2019). Selmar et al. (2008) reported that prolonged green coffee storage in jute sacks shows a decrease in quality and taste as well as the development of straw-like or ‘baggy’ flavors. Prolonged shipping through different weather conditions, loading, and unloading of the shipping containers, and warehouse storage exposes the coffee to significant variations in T and RH which result in moisture transfer into or out of the coffee, leading to a deterioration in the green coffee final quality (Gheorghe, 2012; Jones, E.C. and Faas, 2020).

Hermetic packages are currently used to store and transport green coffee in addition to jute sacks, due to their impermeability (Donovan et al., 2020). Experimental work with hermetic storage packages, such as GrainPro SuperGrain and the Purdue Improved Crop Storage bags, indicates that they are highly effective in preserving the quality of green coffee during storage (Ribeiro et al., 2011; Borém et al., 2013; Donovan et al., 2019a). Despite the effectiveness of hermetic packages during storage, some amount of moisture penetrates these packages due to small leaks in the packages and the rapid and extreme environmental changes that occur in the shipping container during transportation. Borém et al. (2013) reported an increase in carbon dioxide (CO_2) concentration in green coffee stored in hermetic packaging and attributed the CO_2 increase to small leaks in the package. Thus, green coffee is still susceptible to significant moisture content variations during transportation. In view of this, some exporters in the marine transport industry use desiccants to reduce moisture changes inside shipping containers, to consequently reduce the risk of damage to dry produce (Gheorghe, 2012).

Desiccants are hygroscopic materials that absorb moisture from the air in an enclosed environment by physical adsorption or chemical reaction until reaching equilibrium with the environment (Singh et al., 2018; Cohen, 2003). Different types of desiccants in the form of powder, granules, or beads, are commonly used to keep low levels of moisture in dried food packages (Yam, 2010; Nethra et al., 2002), pharmaceutical products (Allinson et al., 2001; Naveršnik and Bohanec, 2008; Waterman and MacDonald, 2010) and electronics (Fenwick et al., 2012; Wong and Rajoo, 2003; Conseil-Gudla et al., 2021) during storage and transportation. The most commonly used desiccants for food packaging applications include silica gel, calcium chloride ($CaCl_2$), calcium oxide (CaO), clay, and molecular sieves (Janjarasskul and Suppakul, 2017; Yildirim et al., 2018). The desiccant is typically packaged in a high-permeable material (sachet material) made of semipermeable polymer films or porous nonwoven fibers to form a desiccant pack (Ozdemir and Floros, 2004; Schuettler et al., 2011).

The quantity of desiccant used during storage and transportation is important because an insufficient quantity will reach its absorption capacity quickly and not provide the required protection against moisture, while excessive use of desiccants may lead to over-drying and an unnecessary increase in product cost (Chen, 2017; Cohen, 2003). Work by Gheorghe (2012) investigating modern techniques for reducing the risk of cargo damage by moisture and condensation concluded that moisture damage in shipping containers can be effectively reduced with the proper amount of desiccants. In addition to using the right amount of desiccants, other factors including the desiccant type, absorption capacity, reaction to the food product as well as behavior upon saturation must be considered. For example, $CaCl_2$ upon saturation liquifies into brine solution which may leak within the packaged food product during storage and transportation

(N'Tsoukpoe et al., 2015). Also, zeolite beads such as Drying Beads® can be regenerated (heated to a T of approximately 500°C to release its absorbed moisture) and reused.

$CaCl_2$ is the most used desiccant in green coffee transportation, due to its high water absorption capacity, non-toxic nature, and availability. Currently, the amount of desiccant per shipping container is usually based on approximations provided by retailers. According to the GrainPro Division Manager for US, Canada, and Europe Diego Lara Lavarreda, the industry standard for the amount of $CaCl_2$ used in green coffee transportation is 1.2 kg $CaCl_2$ per a 20 ft shipping container, containing 320 bags (60 kg each) of green coffee (personal communication, January 7, 2021). Before shipment, desiccant packs are placed within the hermetically packaged green coffee or hung on the shipping container interior walls. By absorbing moisture from the ambient air, the desiccants lower the dew point temperature, keeping the shipping container dry (Gheorghe, 2012).

To date, no information exists in the scientific literature regarding the effectiveness and optimal concentrations of different types of desiccants for green coffee storage and transportation. Thus, the main goal of this study is to assess the efficacy of different types of commercially available hermetic packages and desiccants for preserving the quality of green coffee. To achieve this goal, green coffee was packed in three packaging materials (GrainPro SuperGrain bag, GrainPro TranSafeliner, and/or jute sacks), with and without desiccants (Drying Beads®, and $CaCl_2$) and stored for 42 days in environmental chambers under conditions of fluctuating temperature and humidity that mimic typical storage and transportation conditions for green coffee. MC_{wb}, A_w, and color of the green coffee were measured dynamically over 42 days. At the end of the experiment, two-way mixed design ANOVA, a descriptive and discrimination sensory tests were performed to determine if there were significant differences between the coffee samples.

2.0 Materials and methods

2.1 Packaging materials and desiccant packs

Three packaging materials were used in this study: a) jute sacks measuring 0.3m x 0.5m (Model No. S-8423, Uline, Pleasant Prairie, WI, USA) and b) two types of commercially available hermetic packages (GrainPro SuperGrain bag, and GrainPro TranSafeliner) (GrainPro, Concord, Massachusetts, USA). As recommended by the manufacturer, the GrainPro SuperGrain bags (GP Bags) were used as inner liners for individual jute sacks, while the GrainPro TranSafeliners (GP Liners), which is typically used to line a standard 20 or 40-foot container, were used as an external packaging material for multiple jute sacks. Reduced size hermetic packages were created by cutting and heat-sealing the original GP Bags and GP Liners at three edges each, using a tabletop impulse heat-sealer (Model No. H-163, Uline, Pleasant Prairie, WI, USA). Forty-five GP Bags were resized into 180 individual units each 0.3 m × 0.2 m in length and width. One GP Liner was resized into 15 segments of 0.6 m x 0.4 m.

In addition to the packaging materials, two commercially available desiccants, including Drying Beads: a zeolite-based desiccant (Beads) (Rhino Research, Phichit, Thailand), and $CaCl_2$ (Spectrum Chemical mfg. Corp, CMP, CA, USA) were used in this experiment. Individual Tyvek sheets (1059B Tyvek, DuPont E.I. du Pont de Nemours & Co., Wilmington, Del., U.S.A.) were properly sized and sealed at three edges to form a desiccant pack, and the corresponding amount of desiccant, based on each treatment was placed inside each. The fourth edge in each desiccant pack was then sealed and labeled.

2.2 Treatments and experimental design

The study consisted of two experiments. In experiment 1, a 3 × 3 factorial design was applied, where the three types of packaging materials (jute sacks, GP Bag, and GP Liner) and desiccants (Beads, CaCl2, and no desiccants) were considered as factors. The factors were combined to produce the following treatments: (a) hermetic packages with desiccants (Beads-GP Bag, $CaCl_2$-GP Bag, Beads-GP Liner, $CaCl_2$-GP Liner); (b) hermetic packages without desiccants (GP Bag, and GP Liner); and c) jute sacks with and without desiccants (Beads, $CaCl_2$, only jute sack (Control)). For this study, a 6.1 m (20 ft) industry-standard shipping container that typically transports 320 bags (60 kg each) of green coffee, was simulated by scaling down by a factor of 54 to fit the sizes of the packaging materials used. Thus, each treatment, representing a standard shipping container, included 6 green coffee packages of 1.125 kg each. Similarly, the amount of desiccant per container (1.2 kg) was scaled down to include a ratio of 303 g of coffee per g of desiccant.

In experiment 2, we performed a complementary series of experiments to probe the impact of desiccant quantity. Three different coffee to desiccant ratios (g/g) equal to 151, 76, and 50 were tested for the Beads-GP Bag and $CaCl_2$-GP Bag treatments to evaluate the effect of increasing the amount of desiccant used in the industry by a factor of 2, 4, and 6, respectively. Increasing the amount of desiccants by three levels each for the Beads-GP Bag and $CaCl_2$-GP Bag treatments yielded six additional treatments, bringing the total number of treatments to 15 (9 from the 3x3 factorial design and 6 from increasing the levels of desiccants in the Beads-GP Bag and $CaCl_2$-GP Bag).

2.3 Treatment preparation

Figure 2.1 shows a schematic representation of the treatments and their preparation procedures. The procedures below, mimicking typical industry practice, were followed to prepare the coffee beans for storage:

GP Bag treatments: 1) an individual GP Bag was filled with 1.125 kg of green coffee beans; 2) a desiccant pack was then submerged in the approximate centroid of the coffee beans, or no desiccant was added for the no-desiccant treatments; 3) The GP Bag was sealed with a zip tie and placed inside a jute sack that was also zip tied.

GP Liner treatments: 1) 1.125 kg of green coffee beans were placed inside a jute sack and sealed with a zip tie; 2) six individual jute sacks were prepared and placed into a GP Liner; 3) six desiccant packs were then placed around the jute sacks within the GP liner, or no desiccant was added for the no-desiccant treatments; and 4) the GP Liner was sealed with a zip tie.

Jute bag only treatments: 1) a jute sack was filled with 1.125 kg of green coffee beans; 2) the corresponding desiccant pack was submerged in the approximate centroid of the coffee beans, or no desiccant was added for the no-desiccant treatments; 3) The jute sack was sealed with a zip tie.

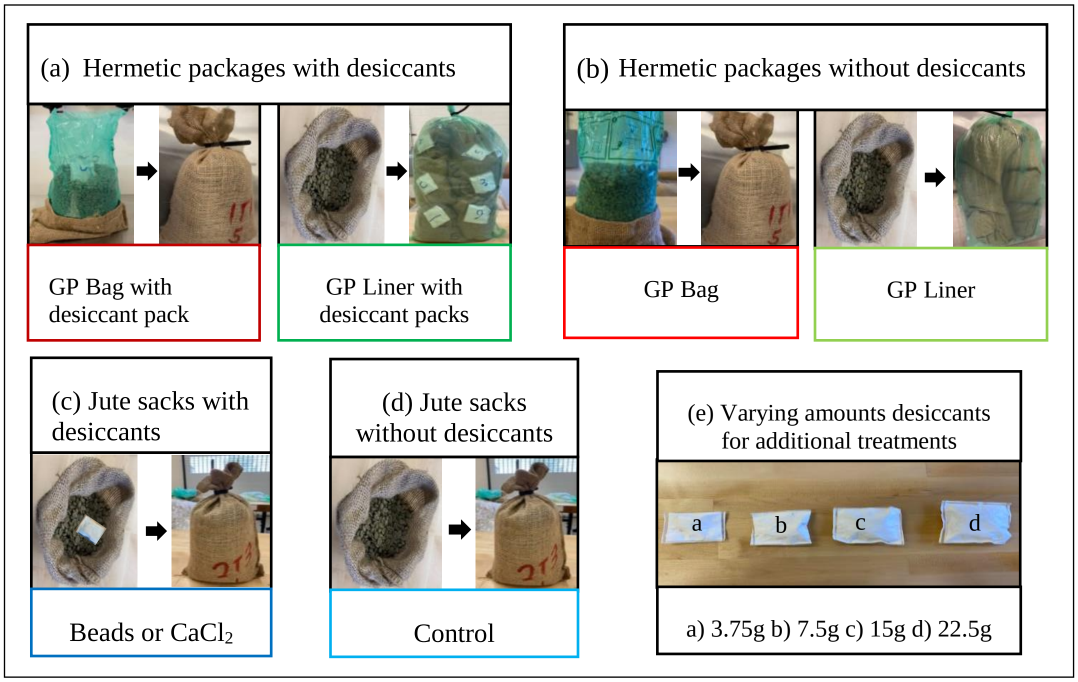

Figure 2.1. Schematic representation of treatments and their preparation procedures.

2.4 Storage and transportation environmental conditions

The experiment was conducted at the Coffee Center at the University of California, Davis from March to April 2021 using green coffee (*Coffea Arabica* 'Bourbon') from Uganda. After treatment preparation, the bagged coffees were randomly assigned to one of two identical environmental chambers (Caron Inc., model 7000-25, Marietta, OH, USA) where T and RH conditions were controlled and recorded. Typical green coffee storage and transportation conditions were based on a previous study that recorded the T, RH, and MC_{wb} of green coffee beans shipped from Brazil to Italy (Palacios-Cabrera et al., 2007). Thus, this experiment consisted of three transportation phases (Fig. 2.2), including storage (12 days at an average T, and RH of 26 °C and 75%, respectively), maritime (18 days, average T: 20 °C, and RH: 80%), and road/railway (18 days, average T: 10 °C, and RH: 85%). Approximately 100g of coffee from each of the six 1250g-bags in a treatment was randomly selected and the MC_{wb}, A_w, and color parameters were measured in triplicate at the beginning of the study and again at 4, 12, 17, 27, 31, and 42 days. The tests were non-destructive and thus the 100g samples were placed back in the bags after each measurement. Both T and RH were recorded every five minutes using the internal data logger for each environmental chamber. Six wireless data loggers (El-USB-2, Lascar electronics Co, Erie, Pennsylvania, USA) were placed in the chambers to assess for spatial gradients in the environmental conditions; one data logger was placed in the center of the top, middle, and bottom shelf respectively of each environmental chamber.

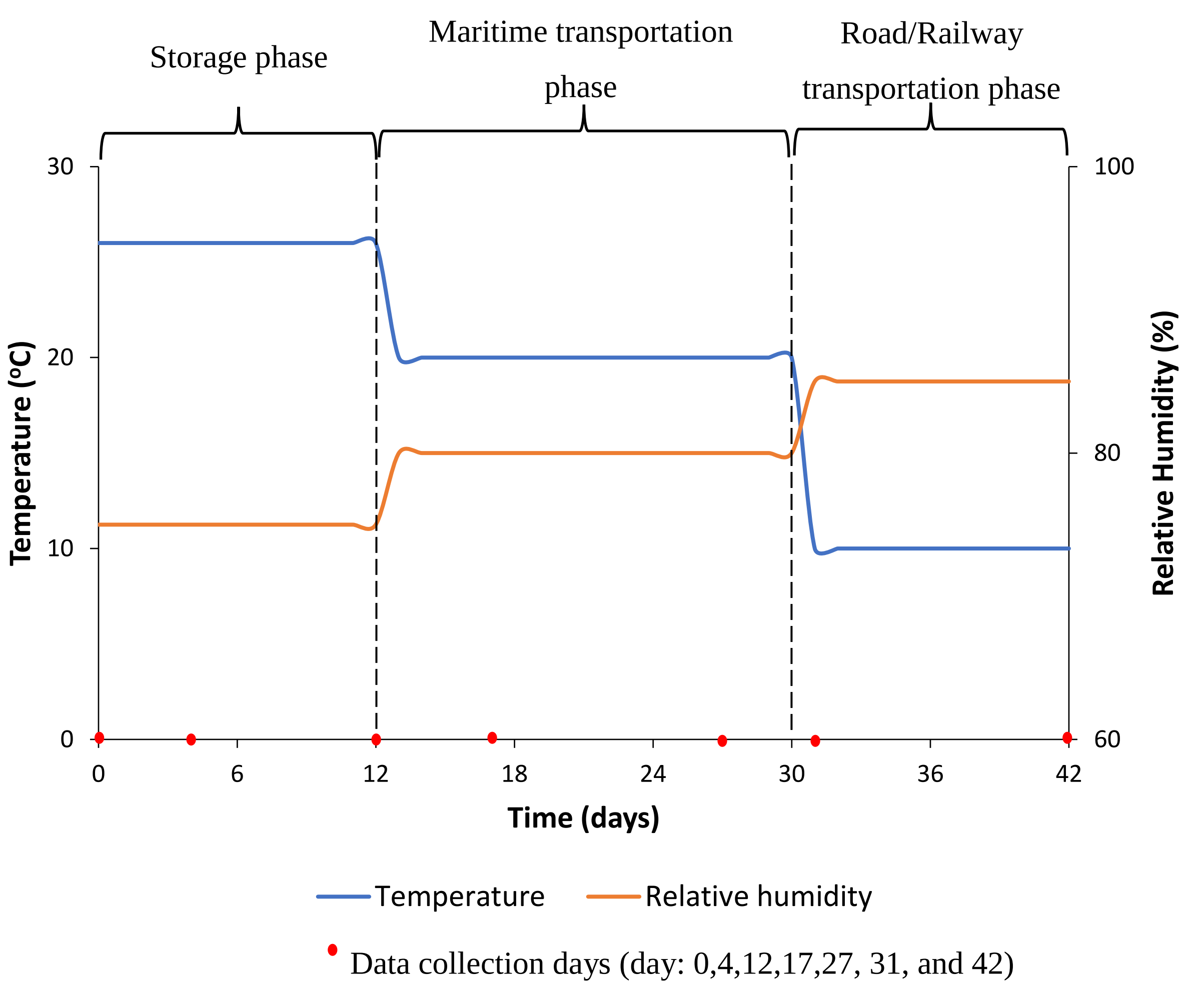

Figure 2.2. Environmental conditions used during the 42-Day storage and transportation experiment. (Storage: 12 days T: 26 °C, RH: 75%; Maritime Transportation: 18 days T: 20 °C, RH: 80%; Road/Railway Transportation: 12 days T: 10 °C, RH: 85%)

2.5 Quality parameters determination

2.5.1 Wet basis moisture content (MC_{wb}) and Water activity (a_w)

The initial (day 0) and final (day 42) MC_{wb} of the green coffee samples were determined using the laboratory oven method according to the standard ISO method 6673 (ISO, 2003). A sub-sample of each treatment sample (100 g) was weighed and dried in an oven (Thermo Fisher Scientific, Waltham, MA, USA) at 105 °C for 16 hours. Intermediate MC_{wb} measurements (on days 4, 12, 17, 27, and 31) were non-destructively performed (using the whole bag of each treatment sample) with a laboratory-scale moisture analyzer (DICKEY-John GAC 2500-INTL, Auburn, IL 62615, USA). Green coffee sub-samples weighing 100g were obtained from each sample within a treatment in triplicate to estimate their water activity (A_w) using a water activity meter (Aqua Lab Model 4TE, Decagon Devices, Inc., Pullman, WA, USA).

2.5.2 Color analysis

The color of the green coffee samples was measured with a spectrophotometer (Colorflex EZ, Hunter Associates Laboratory Inc, Reston, VA, USA) by direct reading of the coordinates L* (lightness), a*(red-green component), and b* (yellow-blue component) on the CIEL*a*b* color scale. Measurements were performed in a spectrophotometer Opti-glass cylinder containing a randomly selected sub-sample (20 g) from each sample within each treatment. Three measurement replicates were carried out for each sample and the sample was placed back in the bag. The instrument was calibrated against a black and white tile before each measurement.

2.6 Sensory Analysis

Two separate sensory tests were conducted after the 42-day storage and transportation experiment: discrimination testing (also known as triangle tests) with untrained panelists, and descriptive analysis tests using trained cuppers. The descriptive analysis was performed two weeks after the experiment while the triangle test was performed eight weeks after the experiment. The green coffee samples were kept in the environmental chambers at room temperature prior to the sensory tests.

The triangle test was approved by the UC Davis Institutional Review Board (Protocol: 1797623-1) and was conducted using a methodology similar to Frost et al. (2019). According to Sinkinson, (2017), a triangle test is a discrimination analysis used to establish if a perceivable difference between two products exists. In a triangle test, a panelist is presented with three samples, two of which are identical and one of which is different and asked to identify which of the three is the odd sample. In this study, the Beads-GP Bag, $CaCl_2$-GP Bag, GP Bag, and Control treatments were compared using four triangle tests (1: Control vs Beads-GP Bag; 2: Control vs $CaCl_2$-GP Bag; 3: GP Bag vs Beads-GP Bag; and 4: GP Bag vs Beads-GP Bag). These four treatments were selected to determine if there were perceived differences between the use of hermetic packages with and without desiccants, and the use of jute sacks only. Data was collected over a 7-day period, during 16 sessions, with a maximum of five panelists per session. A total of seventy-eight untrained panelists were recruited from students, faculty, and staff at UC Davis and each panelist was asked to attend the four successive triangle tests, lasting approximately 30 minutes.

Prior to the triangle test, 2000g sample of each treatment was roasted on a Probat roaster (Probatino model, Probat Inc, IL, USA) to a medium roast degree (Agtron score of 54).

Representative roast profiles and detailed roast metrics are provided in Appendix I. After roasting, the beans were degassed for two days before being packed into vacuum-sealed bags of 100 g each. The sealed bags were stored in a freezer at -20 °C and thawed for 24 hours at room temperature in advance to brewing. On the day of evaluation, the thawed coffee beans were ground (at setting 4) on a Mahlkönig Guatemala Lab grinder to a fine drip brewing size (1200 ± 44 μm) as per the manufacturer specifications. The coffee beverage was then brewed using a commercial drip brewer (Breville precision brewer Model: BDC450BSS1BUS1, Breville Group Ltd, Alexandria, Australia) at a flow rate and temperature equal to 4 mL/s, and 95 °C, respectively with 80 g of ground coffee per 1.18 L of water (brew ratio: 1:15). To maintain a hot serving temperature at 80 °C, the brewed coffee was kept in thermal carafes throughout the duration of the triangle test.

Brewed coffee (50 mL) was served in 200 mL white ceramic mugs, labeled with a three-digit randomly generated code. During each triangle test, a panelist received a set of 3 samples, two identical and one different, and was instructed to taste each from left to right and then select the odd sample (Appendix II shows the answer sheet given to each panelist during the triangle test). Panelists were provided with a cup of water and crackers for palate cleansing between samples, and an empty cup to expectorate. The tasting room, having five isolated tasting stations, was free from any foreign odor and noise and lit with red lamps to mask visual differences between the coffee samples.

For the descriptive sensory analysis, a panel of eight Q-certified judges/trained cuppers from Crown Royal Coffee company (The Crown Royal Coffee, Oakland, Ca, USA) evaluated the sensory profile of the four treatments according to the methodology described by Madison (2020), using the same roasting and brewing procedure as the triangle test/incorrect-they most likely used spoons and a traditional cupping format. According to this methodology, coffee beans are scored from -3 to 3 points in the evaluation of the primary attributes that comprise the sensory profile of coffee; sweetness, acidity, body, flavor, and aftertaste. The sum of the individual scores of all the attributes constitutes the final score, which represents the overall quality of the coffee. Coffees with a final score of 0-3 are considered to be of higher quality.

2.7 Data analysis and visualization

Data analysis and visualization were conducted using R studio (R Development Core Team, 2020) and SAS Enterprise 7.1 (SAS Inst. Inc., Cary, NC, USA). Two types of statistical tests were performed: 1) two-way mixed-design analysis of variance (ANOVA), with treatments as the between-subjects factor and the measured response variable (MC_{wb}, $A_{w,}$ and color) as the repeated measure, were conducted to ascertain if there were significant interaction between treatments and time on response variables and if there was a significant simple main effect of treatments ($P < 0.05$) (Meyers et al., 2012). When a significant main effect was found, a post hoc Tukey Honest Significant Difference (HSD) test was applied to determine the treatments that were significantly different from each other at a 95% confidence level. The measured response variables were reported as mean ± one standard deviation, with n = 3 measurement replicates from one trial replicate; 2) triangle test data analysis was performed in accordance to the ISO 4120 (ISO 4120:2021, 2021) regulation (Table 2); where the number of correct answers per total number of panelists was compared to a critical value ($\alpha = 0.05$) to evaluate the significance of each triangle (Sinkinson, 2017; Benedetti et al., 2004).

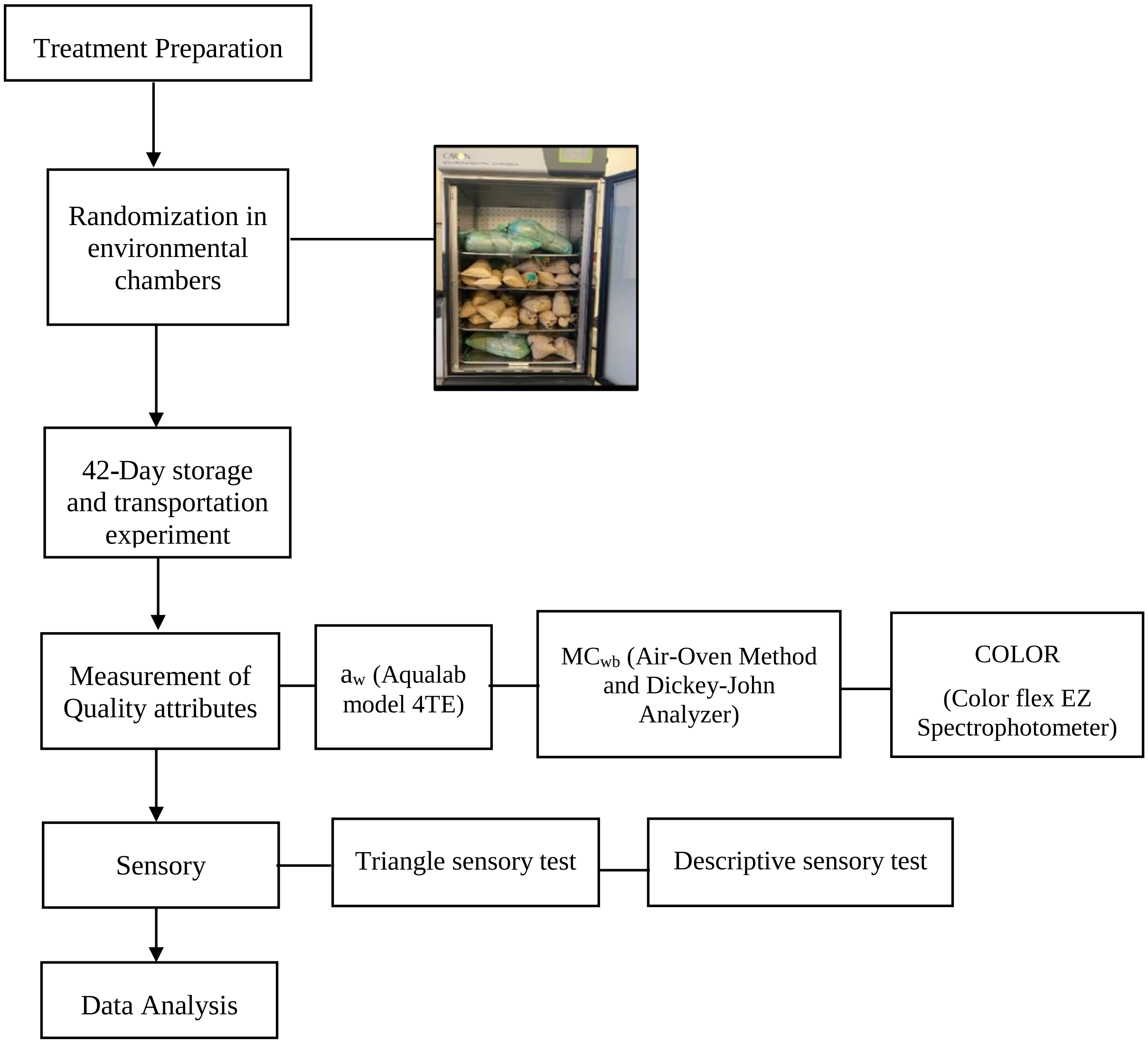

Figure 2.3. Summary of experimental procedures for green coffee storage and transportation experiment

3.0 Results

3.1 Green coffee wet-basis moisture content (MC_{wb}) and water activity (A_w) analysis

The MC_{wb} versus storage time is shown in Figure 2.4. The mean initial MC_{wb} was 10.76 ± 0.2% (A_w = 0.57). The MC_{wb} of green coffee packed exclusively in jute sacks (control treatment) increased to a final, high, and undesirable MC_{wb} of 17.34 ± 0.6% as compared to the MC_{wb} of green coffee packed in hermetic packages (Fig. 2.4a). Although the hermetic packages in general kept the MC_{wb} much lower than in the control treatment, notably the MC_{wb} of coffee packed in hermetic packages without desiccants (GP Bag and GP Liner treatments) still exceeded the critical level of 12% during the maritime and road/railway transportation phases. The MC_{wb} of coffee packed in hermetic packages with desiccants (Beads-GP Bag, Beads-GP Liner, $CaCl_2$-GP Bag, and $CaCl_2$-GP Liner treatments) on the other hand, remained below 12% with an average MC_{wb} of 10.68 ± 0.4% at the end of the experiment (Fig. 2.4b). The MC_{wb} of green coffee packed in jute sacks with desiccants (Beads and $CaCl_2$ treatments) also increased to a final undesirable MC_{wb} of 16.24 ± 0.6% and 18.29 ± 0.4% respectively, similar to the Control treatment (Fig. 2.4b).

A two-way mixed-design ANOVA, with MC_{wb} as the repeated measure and the treatments as the between-subjects factor, showed a significant interaction between treatments and time on MC_{wb} (F (48, 732.28) = 34.33, $p < 0.0001$), indicating that the MC_{wb} was affected by both the treatments and the time of measurements. Post hoc analyses using Tukey's HSD test showed that the average MC_{wb} was significantly different between hermetic packages with desiccants, and hermetic packages without desiccants from day 12 to 42. There was also a significant difference between hermetic packages with and without desiccants treatments versus the control treatment from day 4 to 42 (Fig. 2.4b). There was no significant difference between the control and jute sacks with desiccants treatments (Beads and $CaCl_2$ treatments).

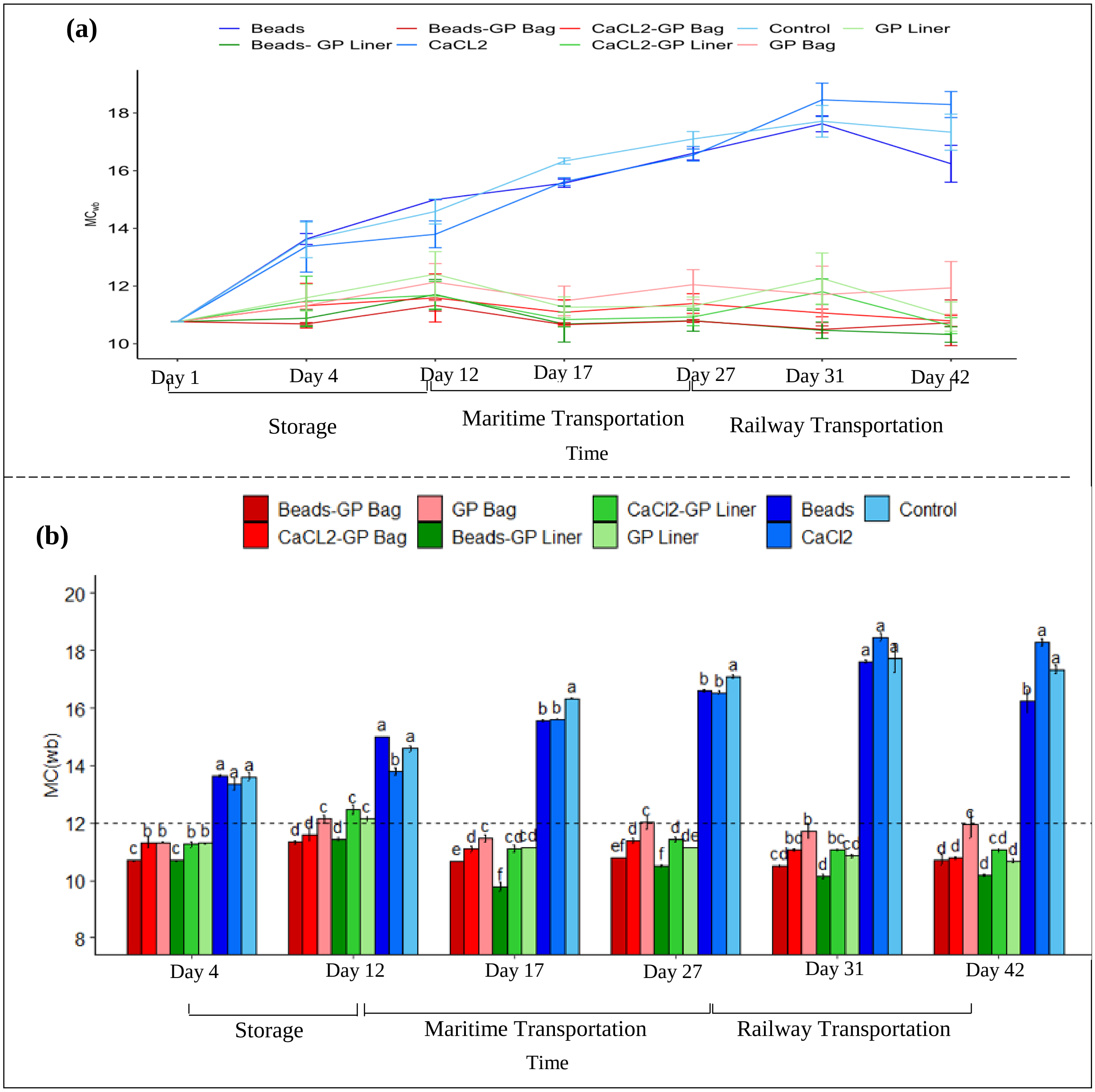

Figure 2.4. (a) Line graph showing the variation in moisture content (MC_{wb}) for each treatment during green coffee storage and transportation. Error bars represent the standard deviation from the mean of three replicates (b) Effect of treatments on MC_{wb} during green coffee storage and transportation. Bars with different small letter(s), within the same day, indicate significant differences in treatments at $P<0.05$; analyzed by Tukey post-hoc test. The dotted black line shows the optimum MC_{wb} of green coffee. For interpretation of the references to color in this figure, the reader is referred to the web version of the thesis.

An important observation during the testing was that the desiccants liquified under some conditions. The $CaCl_2$ desiccants in $CaCl_2$-GP Bag, $CaCl_2$-GP Liner and $CaCl_2$ treatments liquified into brine solution by day 12 (Fig. 2.5). According to N'Tsoukpoe et al. (2015), $CaCl_2$ continues to absorb moisture even after turning into liquid form due to its high affinity to water. Thus, the results of the $CaCl_2$ treatments were still used in the statistical analysis.

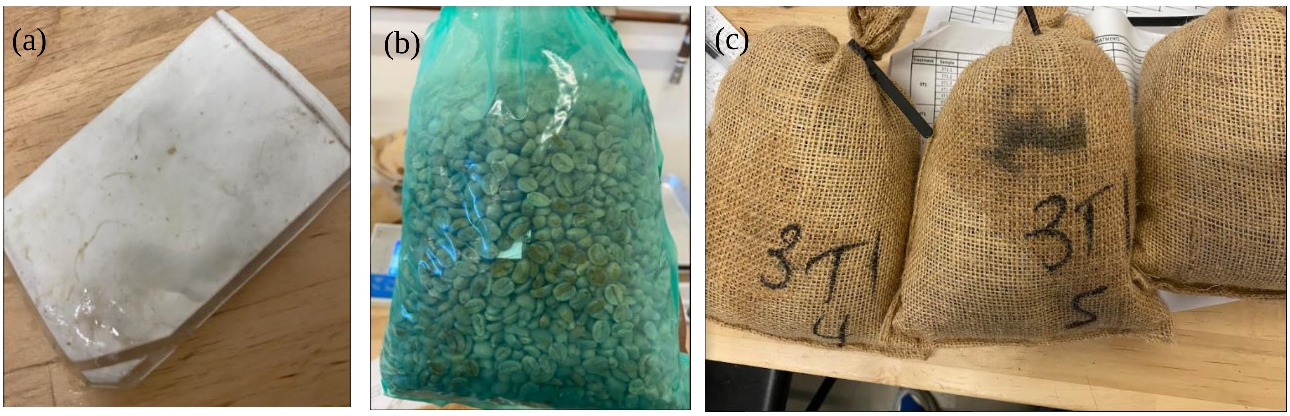

Figure 2.5. Liquified $CaCl_2$ in $CaCl_2$ treatments. a) $CaCl_2$ leakage from desiccant pack. b) $CaCl_2$ leakage into a coffee sample in a GP-Bag. c) $CaCl_2$ leakage through the jute sack of a jute sack with desiccant ($CaCl_2$) treatment.

Figure 2.6 presents the variation in A_w of the coffee samples with time. Similar to the observed MC_{wb} trends, the A_w of the coffee packed in jute sacks only treatments (Control, Beads and $CaCl_2$ treatments) increased to high, undesired levels of 0.76 ± 0.1, 0.78, and 0.76 ± 0.1 respectively (Fig. 2.6a and b). The A_w of coffee packed in hermetic packages without desiccants (GP Bag and GP Liner treatments) increased to above the critical levels of 0.6 while the A_w of coffee packed in hermetic packages with desiccants remained below 0.6 with an average of 0.58 ± 0.1 during the transportation phase (Fig. 2.6b). The ANOVA showed a significant interaction between treatments and time on a_w (F (48, 200.8) = 11.24, $p < 0.0001$), and the post hoc analyses using Tukey's HSD test showed significant differences between coffee packed in hermetic packages with and without desiccants and coffee packed in jute sacks only (Fig. 2.6b).

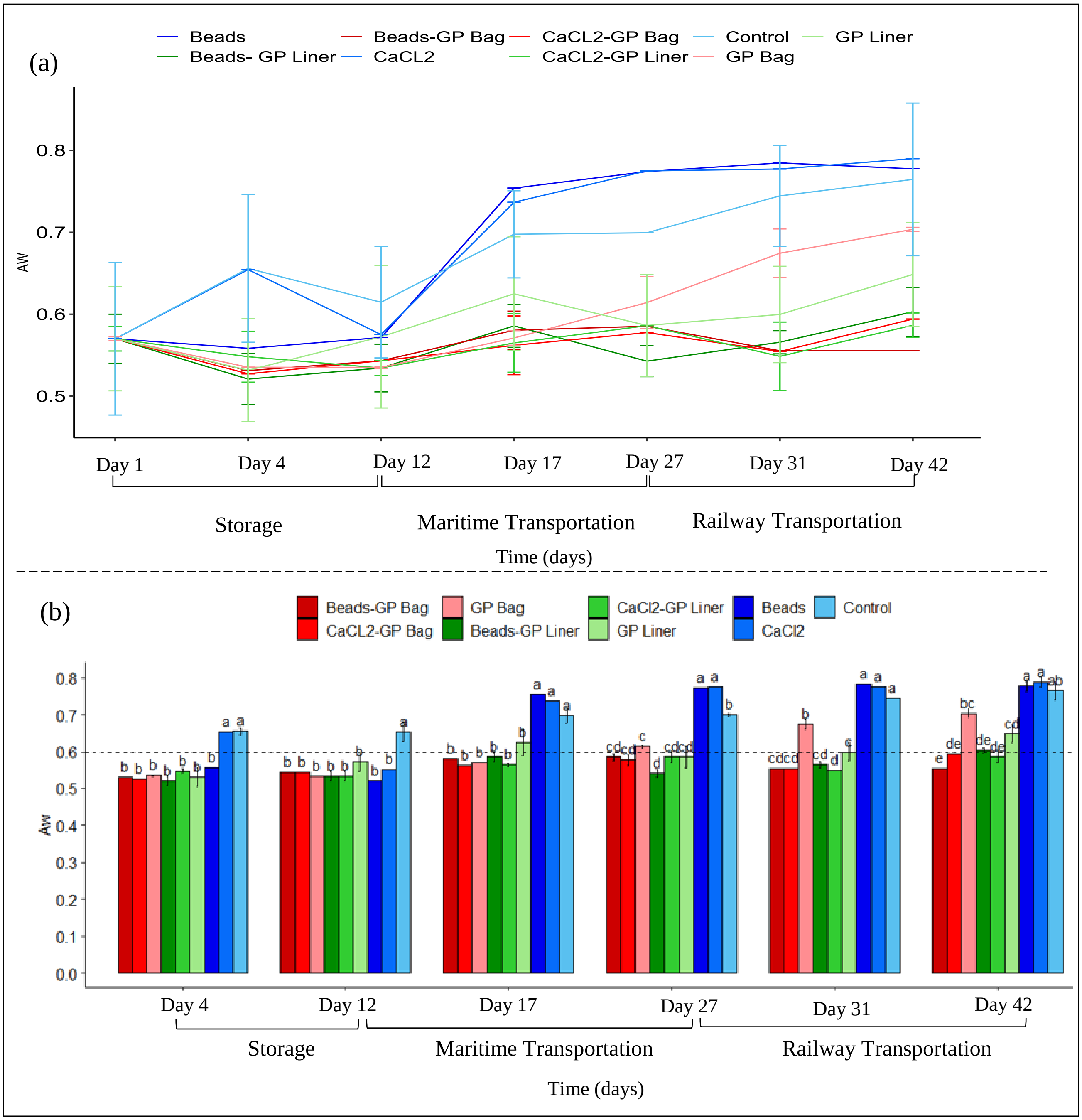

Figure 2.6. (a) Line graph showing the variation in water activity (A_w) for each treatment during green coffee storage and transportation. Error bars represent the standard deviation from the mean of three replicates. (b) Effect of treatments on A_w during green coffee storage and transportation. Bars with different small letter(s), within the same day, indicate significant differences in treatments at P<0.05; analyzed by Tukey post-hoc test. Dotted black line shows the optimum A_w of green coffee. For interpretation of the references to color in this figure, the reader is referred to the web version of the thesis.

3.2 Color analysis

The results of the green coffee color analysis was expressed in terms of coordinates L*, a*, and b*. The ANOVA showed significant differences among treatments for coordinate L* ($F(11.94, 201.5) = 2.803$, $p < 0.0001$), but no significant differences among treatments for coordinates a*, and b*. Green coffee packed in hermetic packages, with and without desiccants, yielded lower L* values with less variability (between 46 and 48) as compared to green coffee packed exclusively in jute sacks (L* values between 48 and 52) (Fig. 2.7a). In other words, the coffee packed in jute sacks only was considerably whitened compared to those packed in hermetic packaging (Fig. 7b). The lower variations in L* values observed in coffee packed in hermetic packages with and without desiccants indicate that these treatments better maintained the color of green coffee throughout the experiment. Coffee packed in jute sacks with desiccants (Beads and $CaCl_2$ treatments) also whitened considerably with increased L* values of 51 and 52 respectively, by the end of the experiment (Fig. 2.7b).

3.3 Varying amounts desiccants for additional treatments

Increasing the amount of desiccant in the Beads-GP Bag and CaCl2-GP Bag by multiples of 2, 4, and 6 had no significant effect on the response variables measured ($p>0.05$) (Appendix III). In other words, there was no significant difference between using 3.75g, 7.5g, 15g, or 22.5g of desiccants.

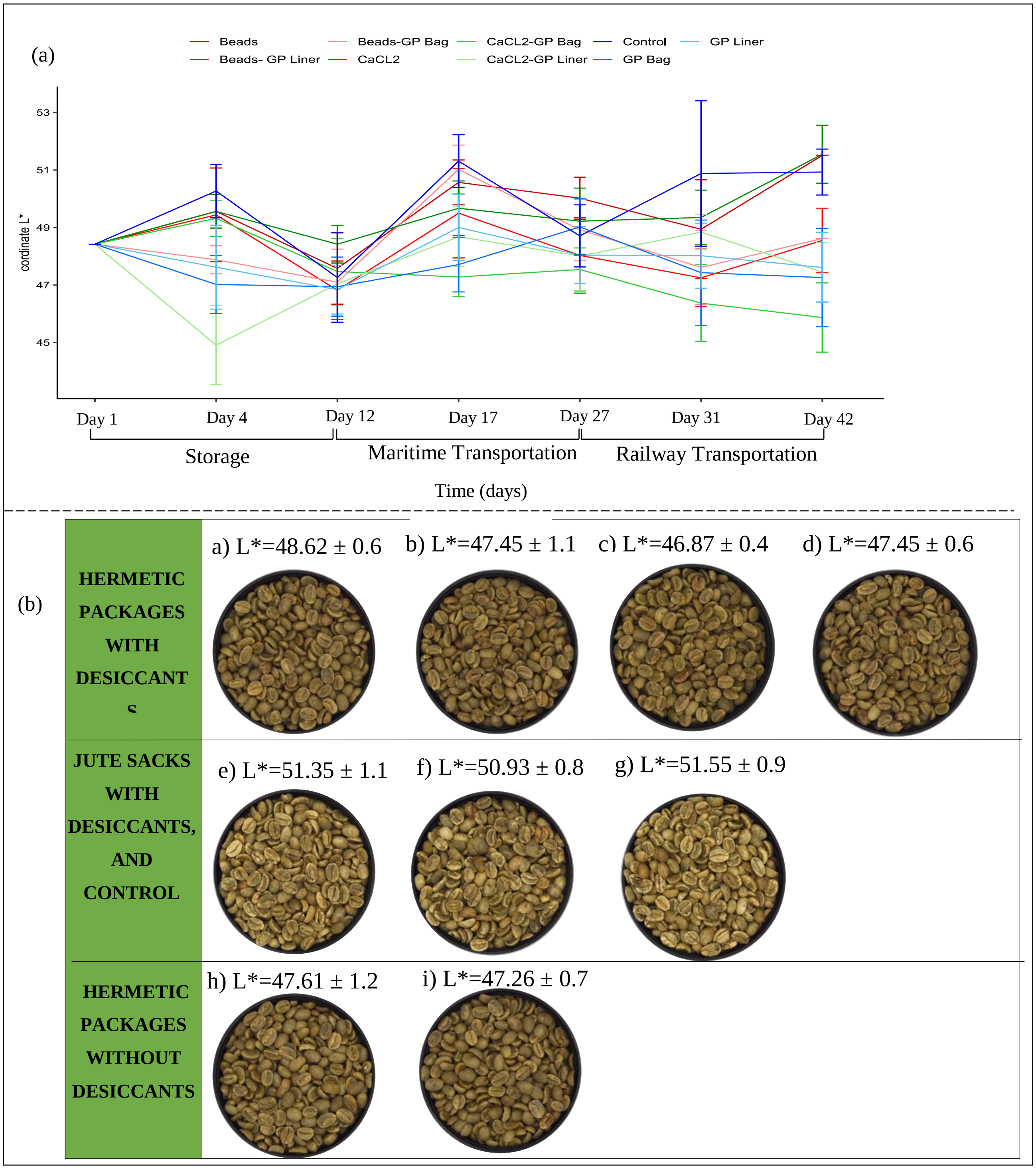

Figure 2.7. (a) Line graph showing variation in Luminosity (L*) color parameter for each treatment during green coffee storage and transportation. Error bars represent the standard deviation from the mean of three replicates (b) Picture showing the color of a) Beads-GP Bag, b) $CacL_2$-GP-Liner, c) $CacL_2$-GP-Bag, d) Beads-GP-Liner, e) Beads, f) Control g) $CacL_2$, h) GP bag, and i) GP Liner treatments at the end of the experiment. Whitening (loss of color) can be observed in coffee packed in jute sacks and control treatment, due to an increase in L* values. For interpretation of the references to color in this figure, the reader is referred to the web version of the thesis.

3.4 Sensory analysis

Table 2.1 shows the results obtained from the triangle sensory test. According to the statistical tables (ISO 4120:2021, 2021), for 78 panelists, a minimum number of 34 correct responses are required to detect a significant difference between samples at $\alpha = 0.05$ (Sinkinson, 2017; Benedetti et al., 2004). Among the four triangles, a significant difference was observed between GP Bag vs Beads-GP Bag treatments (38 correct responses) with a p value of 0.003. No significant differences were found between the Control and Beads-GP Bag (28 correct responses), Control vs $CaCl_2$-GP Bag (32 correct responses), and GP Bag vs $CaCl_2$-GP Bag (32 correct responses) treatments as illustrated in Table 1. From the results, the panelists were able to differentiate between the GP Bag (coffee stored in hermetic packages without desiccants) and the Beads-GP Bag treatment (coffee stored in hermetic packages with Beads desiccants) but were unable to differentiate the GP Bag and the $CaCl_2$-GP Bag (coffee stored in hermetic packages with $CaCl_2$ desiccants).

The results of the quantitative descriptive analysis showed that the Beads-GP Bag treatment had the highest final score of 0.8, followed by the $CaCl_2$-GP Bag (-0.1), GP Bag (-0.1), and control treatment with the lowest final score of -0.4 (not pictured). However, the differences in final scores between these treatments were not statistically significant ($p>0.05$). Overall, the samples were difficult to differentiate – there were no obvious sensory differences.

Treatment	Correct Answers	Perceivable difference in treatments
GP Bag vs Beads-GP Bag	38/78	Significant difference
Control vs Beads-GP Bag	28/78	No significant difference
Control vs $CaCl_2$-GP Bag	32/78	No significant difference
GP Bag vs $CaCl_2$-GP Bag	32/78	No significant difference

Table 1.1. Results of the triangle test sensory evaluation (panel of 78 tasters)

4.0 Discussion And Conclusion

The maintenance of green coffee MC_{wb} at or below 12% during storage and transportation is essential to defeating microbial growth and preserving the sensory quality of the coffee (Aronson et al., 2005; Bucheli et al., 1998; Abreu et al., 2017). This study demonstrates that a stable MC_{wb} (<12%) can be maintained by using desiccants with hermetic packaging during green coffee storage and transportation. Recent studies (Donovan et al., 2019; Ribeiro, Borém, Giomo, de Lima, et al., 2011) concluded that hermetic packages maintain the quality of green coffee for up to 12 months of storage. However, these studies are limited to analyzing green coffee quality only during the storage period in the country of origin, and therefore does not cover the changes that may occur during transportation. Our study indicates that in the extreme environmental conditions during maritime and railway transportation some moisture leaks into the hermetic packages. The integration of desiccants with hermetic packaging reduces the moisture within the hermetic packages by absorbing any moisture that may leak through the packages and hence, prevents the coffee from absorbing excess moisture.

The high levels of MC_{wb} and a_w observed in coffee packed only in jute sacks accords with previous studies that have reported an increase in MC_{wb} of green coffee stored in jute, leading to a reduction in coffee quality (Carmanini et al., 2011; Borém et al., 2013; Tripetch and Borompichaichartkul, 2019).

The jute sack with desiccants treatments (Beads and $CaCl_2$ treatments) in this study behaved similar to the jute only treatment. In other words, there were no significant differences between using jute sacks only and using jute sacks with desiccants. Desiccants must be placed in an enclosed space or container to maintain their effectiveness. When exposed to open air, desiccants constantly absorb moisture and rapidly become saturated (Thoruwa et al., 2000; Cohen, 2003). For example, activated clay, silica gel, and molecular sieves can all absorb approximately 10% of moisture when exposed to 25°C T and 75% RH for 1 hour (Dobson, 1987). In the Beads and $CaCl_2$ treatments (jute with desiccants treatments), there were no hermetic packages to serve as enclosed containers, thus, the desiccants were directly exposed to variable temperature and moist environment through the porous jute sacks. With the small amounts (3.75 g) and an absorption capacity of 20% of their initial weight for Beads (Hay et al., 2012) and up to 150% for $CaCl_2$ (García-Morales et al., 2015), the desiccants in these treatments were saturated within the first few days of the experiment, indicating that the use of desiccants alone cannot replace hermetic packaging.

Maintenance of the green color of coffee beans during storage and transportation is very important as visual characteristics often determine the commercial acceptance of the coffee. The variations observed in coordinate L* during the experiment indicate that the coffee packed in hermetic packages with and without desiccants better maintained the green coffee color throughout the experiment. On the other hand, the observed increase in the values of coordinate L* in Control, Beads and $CaCl_2$ treatments indicates whitening which is undesirable in terms of the quality of the coffee (Afonso Júnior and Corrêa, 2003). Similar results were observed by Ribeiro et al. (2011), where small variations in L* were observed in coffee packed in hermetic big bags (43-45) in comparison to coffee stored in jute sacks, during a 12-month storage.

In this study, there were no significant differences between the two evaluated desiccants ($p>0.05$). As observed in the study, the dissolution of $CaCl_2$ into brine solution poses a threat of contamination to the green coffee. To prevent leakage, $CaCl_2$ desiccants should be placed in a watertight container instead of the Tyvek sheets used in this study. Furthermore, increasing the conventional industry amount of desiccants by factors of 2, 4, and 6 had no significant effect on the behavior of the desiccants. An alternative approach would be to explore different amount of desiccants than the ones tested in this study.

After roasting and brewing, panelists in both sensory tests were unable to differentiate coffee beans that had been stored under different conditions. The only significant difference observed was between GP Bag vs Beads-GP Bag treatments in the triangle test and the number of correct responses (38/78) was barely over the threshold of minimum number of correct responses (34) with a p value of 0.003. This indicates that this difference could be due to a type I error. Panelists were not able to differentiate even the most extreme storage conditions. In other words, treatments with the largest difference in MC_{wb} (Control (17.34%), and Beads-GP Bag (10.68%)) did not appreciably taste different to the panelists. The lack of perceivable difference between treatments in the sensory test can potentially be attributed to the long storage at room temperature for eight weeks after the experiment. During this period, the treatments equilibrated with the ambient RH, lowering the MC_{wb} of treatments such as the Control, to the MC_{wb} level of the other treatments (lowered from 18% to <12%). Thus, these treatments roasted similarly as observed in the roast profiles in appendix I. Unfortunately, logistical challenges during the COVID-19 pandemic prevented us from performing sensory evaluations immediately after the end of the experiment. Future work would benefit from an accelerated testing schedule.

Nonetheless, our results indicate that hermetic packages, even without desiccants, provide a stable MCwb for green coffee compared to jute sacks only, but under some conditions such as green coffee transportation, desiccants should be added to prevent MCwb in excess of 12%. Given that green coffee with MC_{wb} at or above 12% is prone to degradation, the use of desiccants with hermetic packages can play an important role in eliminating moisture damage and preserving the quality of green coffee, therefore preventing quantitative and economic losses. Future work will evaluate the use of desiccants to further dry coffee samples that are not properly dried and validate the effect of desiccant use during a large-scale commercial-scale application.

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Appendix

Appendix I:

Table showing roast profiles of treatments in triangle sensory test.

Treatment	Initial mass (kg)	Final mass (kg)	Initial temperature (°C)	Final temperature (°C)	First crack (s)	Development (s)	Overall (s)
Beads-GP Bag	1.043	1.043	349	401.9	09.49	01.42	11.31
$CaCl_2$-GP Bag	1.043	1.043	352	403.3	09.28	01.42	11.10
GP Bag	1.043	1.043	355.5	400.5	09.16	01.41	10.57
Control	1.043	1.043	351.5	401	08.29	01.42	10.11

Appendix II:

Answer sheet used for triangle sensory test.

TRIANGLE TEST SENSORY EVALUATION

INSTRUCTIONS

You are presented with three coded coffee samples (for each triangle test). Two of these samples are the same and one is different.

Taste the samples in order from left to right and circle the code of the one sample that is DIFFERENT from the other two.

Rinse your mouth using water and plain crackers between samples.

If no difference is apparent, you must guess!

(There will be 4 triangle tests)

Triangle 1: ____________ ____________ ____________

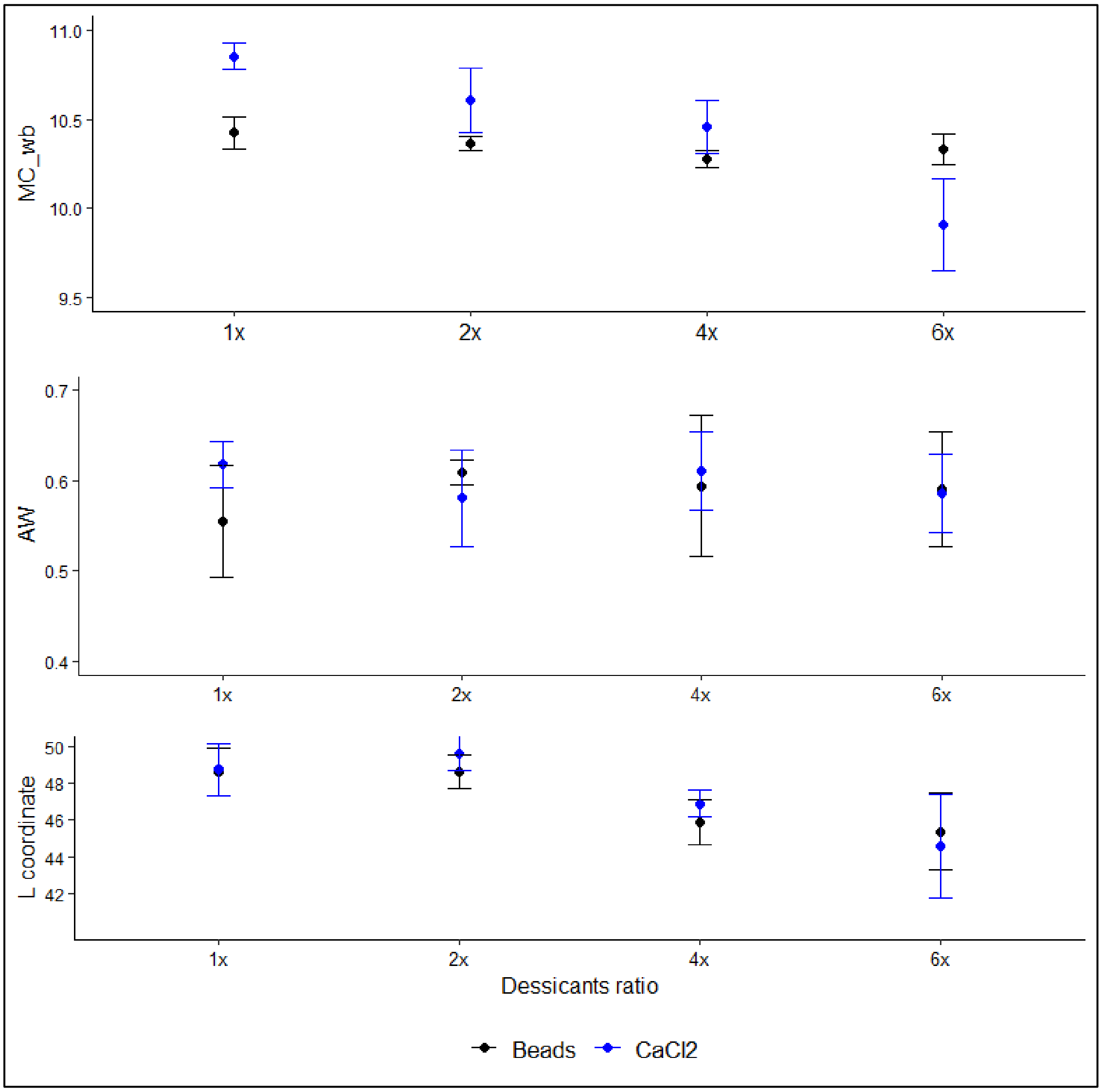
Triangle 2: ____________ ____________ ____________

Triangle 3: ____________ ____________ ____________

Triangle 4: ____________ ____________ ____________

Appendix III:

Figure showing the different desiccant ratios on day 42 (end of the experiment).



CHAPTER 3

DESIGN, CALIBRATION, AND VALIDATION OF A GREEN COFFEE INLINE MOISTURE CONTENT ESTIMATION SYSTEM USING TIME-DOMAIN REFLECTOMETRY

Abstract

Wet basis moisture content (MC_{wb}) is an important quality parameter of green coffee as it affects its physical, chemical, and sensory characteristics. Accurate estimation of green coffee MC_{wb} after dry hulling, long-term storage, and transportation is imperative to prevent quantitative and qualitative losses. Current methods to determine green coffee MC_{wb}, rely on samples to predict the MC_{wb} range of an entire coffee batch, which lacks accuracy. Therefore, there is a need for an accurate, inexpensive, robust, and commercially available inline moisture estimation technique that allows coffee processors to sort green coffee by MC_{wb} to properly optimize post-harvest processes, roasting, and improve quality. Thus, this study aimed to design, develop, calibrate and validate a prototype inline system capable of accurately measuring the MC_{wb} of green coffee beans, using a commercially available time-domain reflectometry (TDR) probe. TDR was applied due to its high accuracy, flexibility, robustness, and capability of providing real-time measurements. The TDR probe was calibrated and validated with green coffee within a MC_{wb} range of 9 to 21 %. A calibration linear regression model correlating the TDR probe output (dielectric constant) to reference MC_{wb} measurements obtained by a halogen moisture analyzer, yielded a high coefficient of correlation (R^2 =0.99). Model validation yielded a high R^2, and a low Root Mean Squared Error equal to 0.93, and 0.9% MC_{wb}, subsequently. Results indicate that the TDR inline green coffee moisture estimation system has the potential to be applied in real-time, industrial-scale operations.

Keywords: Moisture estimation, Calibration, Validation

1.0 Introduction

Wet basis moisture content (MC_{wb}) is an important parameter that affects the quality and storage ability of dry food products (Isengard, 2001; Bell, 2020). In coffee, the estimation of MC_{wb} during post-harvest operations such as drying, storage, and roasting, is crucial as it affects the physical, chemical, and sensory characteristics of the final product or beverage (Reh et al., 2006; Adnan et al., 2017). Coffee cherries at harvest, typically contain a MC_{wb} of 45 to 70 % (Berbert et al., 2001; Finzer et al., 2003; Paulo Cesar Corrêa et al., 2013). After harvest, coffee cherries are processed and dried through several processing methods (natural, washed, semi-dry and wet-hulled), and dry-hulled to produce green coffee beans with an ideal MC_{wb} range of 8.0 to 12.0% (Rotta et al., 2021). Controlling and maintaining the ideal MC_{wb} is important because over-drying can produce brittleness, and under-drying leads to the development of off-flavors, mold growth, and accumulation of mycotoxins (Palacios-Cabrera et al., 2004; Caporaso et al., 2018). Accurate estimation of green coffee MC_{wb} after dry-hulling is imperative to prevent quantitative and qualitative losses (Haile et al., 2019). Green coffee beans are typically stored in jute sacks inside a warehouse for weeks to months or transported to consuming countries (Palacios-Cabrera et al., 2007). Maintaining the ideal MC_{wb} range during storage and transportation is essential to preserve the inherent green coffee quality (Ribeiro et al., 2011; Ivanova et al., 2016). Furthermore, green coffee MC_{wb} is a determinant factor on the roasting time and temperature; thus, a homogeneous MC_{wb} is required to produce uniform and high-quality roasted beans (Baggenstoss et al., 2008).

Several methods are available to determine the MC_{wb} of green coffee, including direct methods such as oven-drying, moisture analyzer balances, distillation, and desiccant-drying methods (Mendonça et al., 2007). Direct methods involve removing moisture from a sample of coffee beans, measuring their weight loss, and calculating MC_{wb} on either a wet basis (wb) or dry basis (db). Although direct methods are highly accurate, they are destructive and time-consuming (Nath and Ramanathan, 2017; Vera Zambrano et al., 2019). In contrast, real-time non-destructive indirect methods such as near-infrared spectroscopy (NIRS) (Adnan et al., 2017), hyperspectral imaging (Caporaso et al., 2018), microwave-based (Wiseman, 1999), resistance or conductance (Joaquin et al., 2019), capacitance methods (Alibayan et al., 2019), and time-domain reflectometry (TDR) methods (Toledo et al., 2008), have been used to estimate green coffee MC_{wb}. Indirect methods typically measure changes in electrical or structural properties of the coffee beans to predict MC_{wb}. NIRS, hyperspectral imaging, and microwave-based methods are considered the most accurate indirect methods. However, the high costs of their implementation limit their practical application (Reh et al., 2006; Caporaso et al., 2018). Conversely, resistance, conductance, and capacitance methods are convenient and inexpensive, but of limited accuracy (Gautz et al., 2008). Among the indirect methods, TDR is one of the most accurate, well-established, inexpensive methods to measure the MC_{wb} in porous media, based on changes in the media dielectric properties (Cataldo et al., 2009; Iaccheri et al., 2020).

TDR determines the dielectric constant (k) of a porous media, by measuring the propagation time of an electromagnetic wave as it travels along a waveguide or a TDR probe in contact with the porous media (Topp et al., 1980). The k is then converted to MC_{wb} through the use of empirical calibration equations obtained with experimental measurements (Cataldo et al., 2009; Jones et al., 2002), or by the application of dielectric mixing models (González-Teruel et al., 2020). TDR has been used to estimate the MC_{wb} of various porous media, mainly soil (Dalton et al., 1986; Herkelrath et al., 1991; Fujiyasu et al., 2004; Zhu et al., 2019; Bhuyan et al., 2020). Water has a high k (~80), while other soil components, such as air and mineral particles, have low k of around 1 and 3, respectively (Booth, 1951). Therefore, changes in the soil k are attributed to its MC_{wb} changes and generalized empirical calibration equations can be used to determine soil MC_{wb} (Jones et al., 2002). For porous, heterogeneous agro-food materials like coffee however, other factors such as bulk density, grain size, temperature, and ionic conductivity also affect the k. Hence, general calibration equations cannot be used to determine MC_{wb}, and specific calibration models must be developed for each material (Cataldo et al., 2009; Tomer et al., 1999). TDR allows MC_{wb} measurement over a wide frequency range (100 kHz to 20 GHz), therefore reducing the effect of external factors such as temperature and hence, can produce accurate results (Cole, 2003). The feasibility of using TDR for MC_{wb} monitoring of porous food materials has been investigated. Cataldo et al. (2009) demonstrated that the TDR method is a valid alternative to other indirect methods in determining the MC_{wb} of porous food materials including coffee, corn, and bran. Results from a study by Toledo et al. (2008) also indicated that properly calibrated TDR probes can be effectively used for real-time MC_{wb} measurement of green coffee.

Regardless of the method, the commercially available equipment to measure green coffee MC_{wb} (both direct and indirect), typically rely on a sample size of between 5 and 500 g, which does not accurately represent the MC_{wb} range of the entire coffee batch, and therefore the MC_{wb} determination is influenced by sampling errors (Willimack, 2018). Farmers and coffee processors use the sample MC_{wb} to determine whole batch processing parameters such as additional drying requirements, drying time, and temperature, which leads to non-uniform quality and highly variable MC_{wb} distribution. For instance, applying the same drying or roasting time to a coffee batch with a MC_{wb} range of 9 to 15 % results in unevenly dried or roasted coffee, and may lead to the product being rejected, as well as affecting energy usage due to over-drying (Vincent, 1987). There is a need for an accurate, inexpensive, commercially available inline moisture sensing equipment that allows processors to sort green coffee beans by MC_{wb} levels during various unit operations, to properly optimize post-harvest processes, reduce energy consumption if additional drying is required, and achieve uniform quality. Therefore, the aim of this study was to design, develop, calibrate and validate a prototype inline moisture estimation system capable of accurately measuring the MC_{wb} of green coffee beans, using a commercially available TDR probe.

2.0 Materials and methods

2.1 Design and development of a TDR inline moisture estimation system

A prototype inline moisture estimation system using a commercially available TDR probe (SONO-VARIO LD, IMKO Micromodultechnik GmbH, Ettlingen, Germany) was designed and developed at the Postharvest Engineering Laboratory in the Department of Biological and Agricultural Engineering at UC Davis to determine green coffee MC_{wb} at a throughput equal to 87 kg/hr. Figure 1(a) shows a schematic view of the inline moisture estimation system, which consists of four main components including 1) a structural frame built from 80/20 T-slot aluminum profiles; 2) a 0.6 m x 0.3 m x 0.2 m (length x width x height) conveying steel vibrational feed table that automates and controls the feed rate of coffee beans; 3) the TDR probe to measure the MC_{wb} of the coffee (Figure 1 b); 4) a system control box (Figure 1 c and d). Attached to the feed table is a 100W single-phase Pulse-Width Modulation speed controlled vibratory motor (Part number: XP-0.28, Concrete Vibrator Motor, Shenzhen Fast to Buy Co., Ltd, China), with an unbalanced load on its shaft, that causes the feed table, held by two fiberglass leaf vibration isolators, to vibrate at variable speeds. As the feed table is loaded with green coffee, the vibration of the feed table conveys the coffee beans through a tapered (0. 3 m x 0.2 m x 0. 3 m) acrylic chute into the housing (0.1 m x 0.03 m x 0.1 m) that serves as a temporary green coffee repository as it is conveyed through the system. A coffee sample (0.1 kg) is then deposited into an open-ended bin (0.1 m x 0.03 m x 0.06 m). The bin is meant to collect coffee samples from the feed table, it then moves forward over the TDR probe that measures the MC_{wb} of the coffee sample, and ultimately moves forward to drop the samples into a secondary container. The back and forth movement of the bin is repeated to measure consecutive samples. The bin's movement, which is guided by linear slides in the central rail, is controlled by a rack and pinion gear (PRO Rack and Pinion Drive-NEMA 34, AVIDCNC Co, Washington USA) attached to a single high torque stepper motor (Model: 57BYGH1004204A, NEMA 23 Stepper Motor, AVIDCNC Co, Washington USA). Two limit switches detect the position of the bin and define its location. The system control box (Appendix I) consists of an emergency stop button, dual fans to prevent overheating, a rail mounting block that holds electronic components and the system power supply, and a SONO-VIEW LCD display configuration module (SONO-VIEW, IMKO Micromodultechnik GmbH, Ettlingen, Germany) connected to the TDR probe. The SONO-VIEW LCD module is connected to the USB port of a Windows 10 operating system computer (MODEL G3 15, Dell Computer Co., Austin, Texas) which allows the user to control the TDR probe, adjust measuring parameters, conduct calibrations, display MC_{wb} readings, and save measurements through the TDR probe software (SONO-CONFIG, IMKO Micromodultechnik GmbH, Ettlingen, Germany).

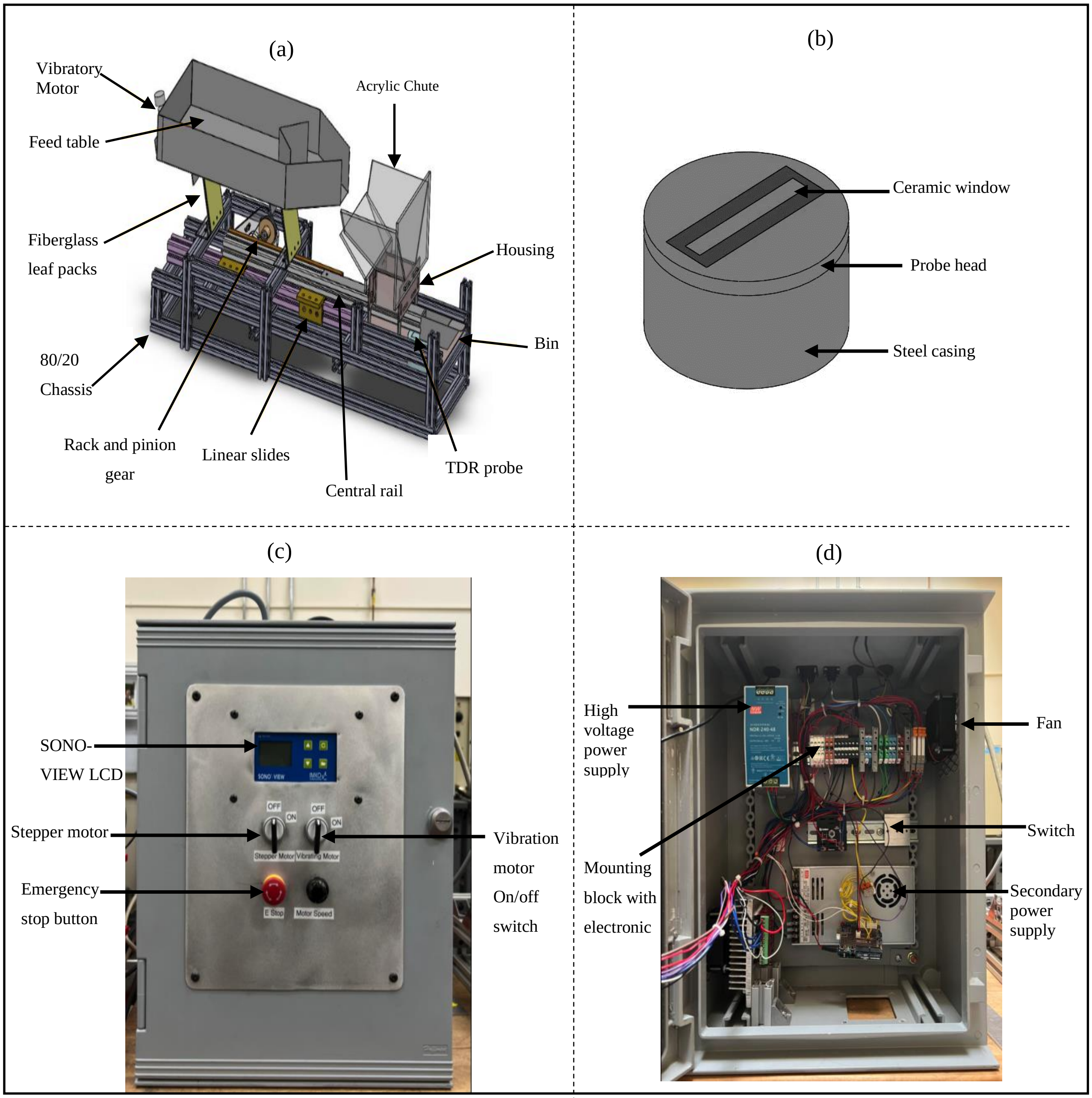


Figure 3.1. (a) Schematic representation of inline moisture estimation system showing main components (b) Schematic representation of the TDR probe with overall dimensions of 108 mm (diameter) and 71 mm (height) (c) Picture showing the exterior of the system control box (d) Picture showing the interior of the system control box. For interpretation of the references to color in this figure, the reader is referred to the web version of the thesis.

2.2 Time Domain Reflectometry (TDR) probe

The TDR probe is composed of a V2A high-grade stainless steel (material number: 1.4301) casing and a probe head with a ceramic window used as a waveguide for the transmission of electromagnetic waves. The TDR probe operates on the principle of guided radar technology (Lewis, 2006). A high-frequency (1GHz) electromagnetic wave is generated within the TDR probe and propagates at the speed of light along the waveguide, generating an electromagnetic field around the waveguide and in the porous material or green coffee. At the end of the waveguide, the electromagnetic wave is reflected back to its source. The travel time (tpAve) of the wave along the waveguide depends on *k*, which is a function of green coffee MC_{wb} (Preko and Wilhelm, 2012; Cole, 2003). Thus The TDR probe measures tpAve and converts it to *k* as shown in equation (1) (Jones et al., 2002)

$$k = (\frac{ct_{pAve}}{2L})^2 \qquad (1)$$

Where tpAve is the time (ps) it takes the electromagnetic wave to travel back and forth along the waveguide, L is the length (m) of the waveguide, and c is the speed of light (3×10^8 ms^{-1}) in a vacuum.

After calibration, the TDR probe establishes a linear relationship between *k* and MC_{wb}. The TDR probe has integrated signal processing and conversion functions to ultimately display the MC_{wb} of a coffee sample after performing a measurement.

2.3 Calibration and validation of the TDR probe

2.3.1 Sample Preparation

Figure 3.2 shows a schematic representation of the experimental procedure. Experiments were conducted using commercially dried green coffee (*Coffea Arabica* 'Bourbon') beans at 9% MC_{wb}. Green coffee samples with varying MC_{wb} (9-21%) were prepared following these steps: 1) A 10 kg batch of green coffee was thoroughly mixed with two liters of water, and placed in an airtight container at room temperature (~25 °C) for 24 hours, to ensure uniform moisture absorption; 2) subsequently, 10 samples of 1000 g each, were placed in 2.5 m x 1.5 m aluminum trays, and spread to a uniform thickness of approximately 0.02 m; 3) the trays were then placed in a gravity convection oven (model OGS100, Thermo Scientific Heratherm, Waltham, MA, USA) at 60 °C; 4) after one hour of drying, one sample (tray) was removed from the oven and placed in a desiccator for 15 minutes to cool to 25 °C; 5) a subsample (50 g) was randomly selected and milled using a sample mill (model KN 295 Knifetec™, Thermo Scientific Heratherm, Waltham, MA, USA); 6) the MC_{wb} of the subsample was determined with a halogen moisture analyzer (Mettler Toledo, Columbus, OH, USA), using 3 g of ground sample as described in Ileleji et al. (2010); 7) If the MC_{wb} was in the desired MC_{wb} range, the remaining sample was stored in an airtight container, otherwise, the sample was returned to the oven for further drying; 8) This procedure was repeated until target calibration and validation samples from a range of MC_{wb} were obtained, as described in the calibration and validation procedure sections.

2.3.2 Calibration procedure

The calibration procedure was performed with coffee samples with MC_{wb}'s equal to 9%, 11%, 13%, 15%, 17%, 19%, and 21% by using the halogen moisture analyzer data as the reference standard. Calibration procedure is outlined in the probe's user manual (IMKO GmbH, 2015, SONO-VARIO LD User Manual, p.18) which consisted of the following steps: 1) the bin was filled with the coffee sample with the lowest MC_{wb} (9%), and placed on top of the TDR probe; 2) the Sono-config software was used to record the tpAve value (ps) for 60 s at a rate of one reading per second; 3) approximately 20 g of the sample was extracted from as close as possible to the surface of the TDR probe, and the MC_{wb} was measured by the halogen moisture analyzer in triplicate and used as the reference MC_{wb}; 4) the bin was emptied, and the process was repeated with the samples of varying MC_{wb}, in ascending and then in descending order; 5) using equation (1), the corresponding k values of the different samples were calculated from the measured tpAve values; 6) A TDR probe calibration model using linear regression correlating the k values with the reference MC_{wb} values was generated in R software (R Development Core Team, 2020), and the calibration coefficients were manually entered into the Sono-config software.

2.2.3 Validation procedure

To validate the TDR probe and prototype inline moisture estimation system performance, sets of completely independent samples from those used in the calibration procedure with MC_{wb}'s of 9%, 11%, 12%, 13%, 14%, 15% 16% 17%, 18%, 19%, 20% and 21% were prepared and used as reference. During the validation of the prototype inline moisture estimation system, the feed table was manually filled with coffee at the desired MC_{wb} and continuously fed to the bin until it was full. MC_{wb} values per bin were then continuously measured, as described in the calibration procedure and recorded by the Sono View software.

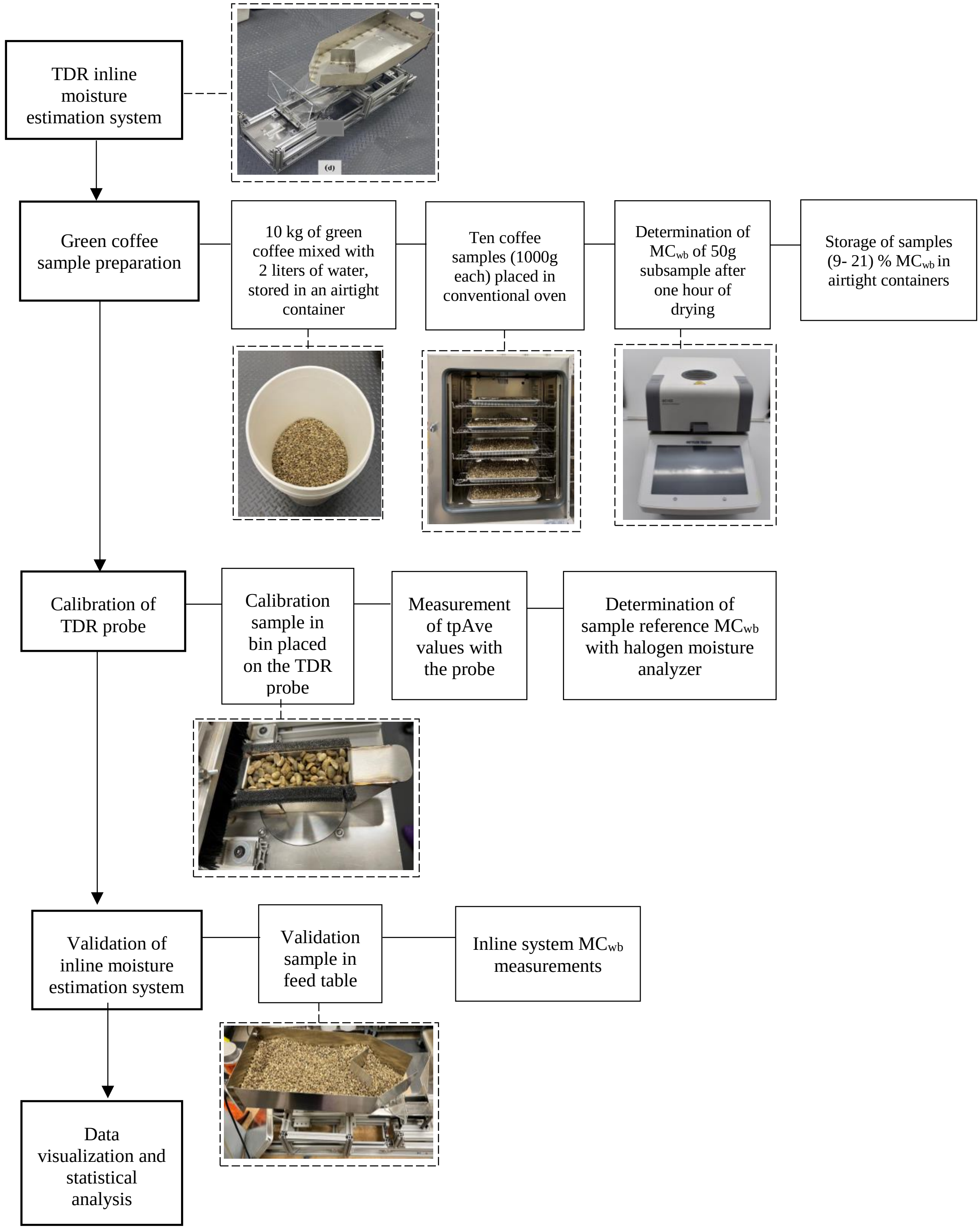


Figure 3.1. Schematic representation of experimental procedure used to calibrate and validate the inline moisture estimation system

The inline system MC_{wb} measurements were done in triplicates, by recording the measured values from three consecutive bin readings, in a completely randomized design to validate the system's accuracy. MC_{wb} values obtained during validation and the reference standards were compared using a linear regression model. The accuracy of the inline system was assessed by analyzing the model coefficient of determination (R^2) and the Root Mean Square Error (RMSE), as described in (Ivanova et al., 2016).

3.0 Results and Discussion

3.1 Calibration results

The prototype inline moisture estimation system, using a TDR probe, was calibrated within the range of 9 to 21% MC_{wb}, as this range of moisture is typically observed in green coffee that has been recently dry-hulled (processed), stored, and transported to importing countries (Selmar et al., 2008; Clarke, 1987). Green coffee MC_{wb} of 10 to 12% is optimum to avoid microbial growth and changes in quality (Vincent, 1987). Calibration data is shown in Table 3.1 and Figure 3.3, where results show that the *k* values increased from 0.018 to 0.028 with increasing MC_{wb} of the coffee samples. The values of k obtained are within the range of k values reported for green coffee (0.02-0.03) (Velasquez et al., 2018). Regression analysis of the results indicated that the calibration model was statistically significant ($R^2 = 0.99$, $F (1, 6) = 1531.68$, $p < 0.05$), yielding a strong positive linear relationship between the *k* and MC_{wb}. The calibration model slope (sensitivity error) and intercept (zero-shift error) are equal to 1313 and -15.28, respectively, with a low standard error of estimate (SEE) equal to 0.27% MC_{wb}, which reflects a highly accurate model (Zagayevskiy and Deutsch, 2010).

Table 2.1. Average tpAve (ps) values measured by the TDR probe and corresponding dielectric constant (k) values for green coffee samples in the calibration set.

Reference mc	tpAve (ps)	*k*
9	97.22	0.018
11	101.85	0.020
13	106.48	0.022
15	109.67	0.023
17	112.85	0.025
19	116.17	0.026
21	119.48	0.028

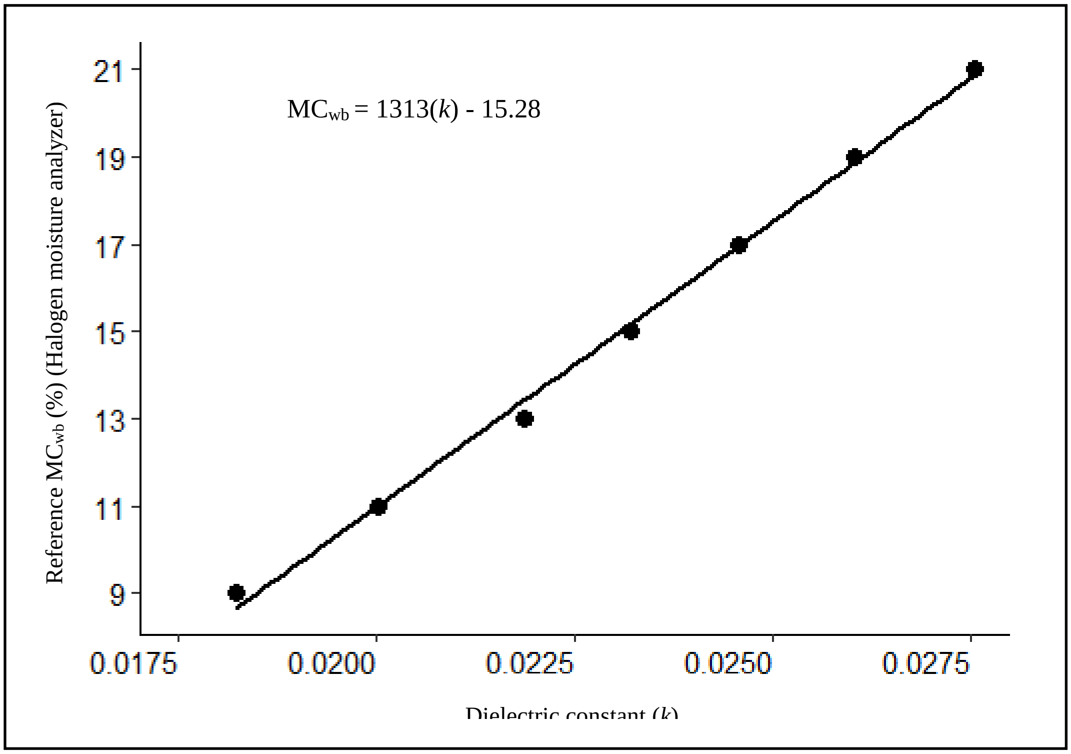


Figure 3.3. Plot of calibration results of the TDR probe

3.2 Validation results

Regression analysis from the validation data showed a high correlation with an R^2 of 0.93, and a low RMSE value of 0.9% MC_{wb}, indicating a high prediction accuracy of the system (figure 3.4). The observed error, equal to ±1% MC_{wb}, is within the TDR probe specification as reported by the manufacturer (SONO-VARIO LD, 2015, p.19). Validation results, which were obtained from completely randomized and independent samples, reflect that the inline moisture estimation system is highly repeatable and accurate.

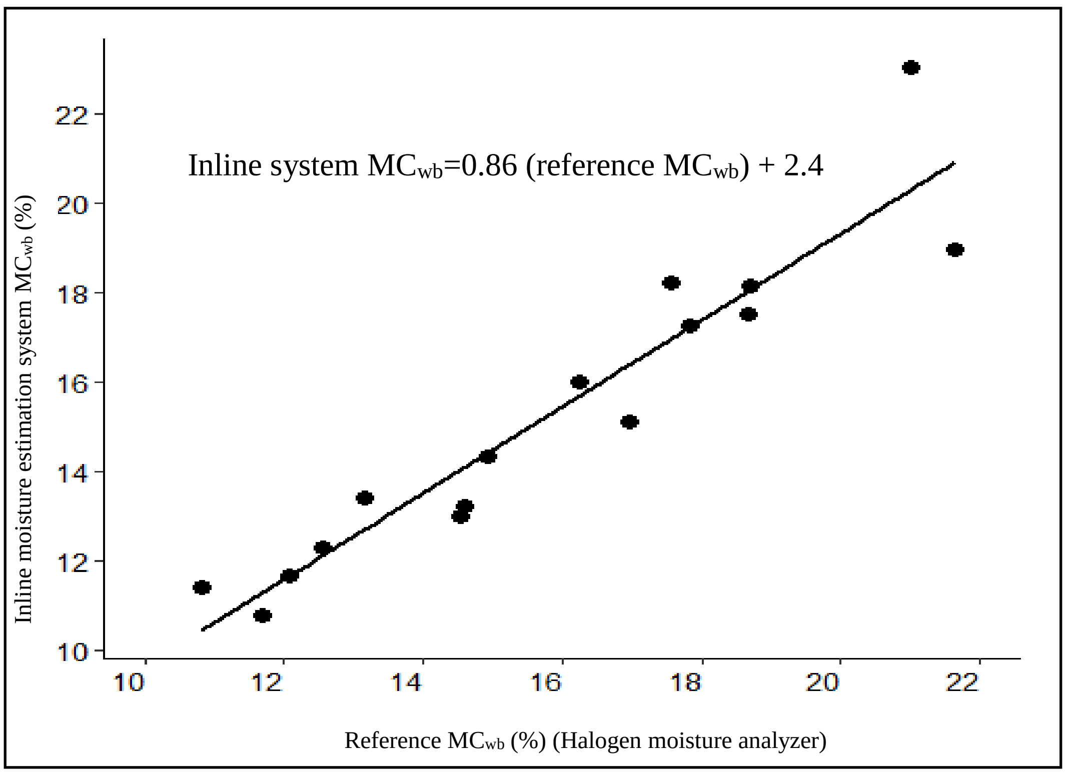


Figure 3.4. Comparison of Inline system MC_{wb} (%) and Reference MC_{wb} (%) values for green coffee samples (validation set)

The validation results of this study are consistent with the results of other studies where TDR probes have been used to estimate the MC_{wb} of several foods. Toledo et al. (2008) predicted the MC_{wb} of coffee beans using a handheld TDR probe, yielding an R^2 of 0.97. Similarly, Cataldo et al. (2009) investigated the feasibility of the adoption of the TDR technique for MC_{wb} determination in granular materials such as corn, coffee, and bran, by yielding calibration models with R^2 values ranging from 0.94 to 0.97. In addition, the performance of the inline moisture estimation system developed in this study is comparable to indirect methods that have been generated to estimate green coffee MC_{wb}. For example, Adnan et al. (2017) used NIR spectroscopy to predict green coffee MC_{wb} with a low RMSE value of 0.8% MC_{wb}, Joaquin et al. (2019) used a capacitance type moisture meter yielding a low RMSE value of 0.85% MC_{wb}, and Caporaso et al. (2018) investigated the use of hyperspectral imaging to estimate green coffee MC_{wb} and lipid content, reporting an observed error equal to ±0.28% MC_{wb}. The system in this study has the advantage that it can continuously measure green coffee MC_{wb} inline, unlike other TDR handheld probe systems and conventional indirect methods. This study provides a system to rapidly, nondestructively, and accurately estimate the MC_{wb} of green coffee inline and in real-time, which has the potential to be installed during industrial-scale coffee conveying.

The commercially available TDR probe, which was used in this study, has been applied in several processing stages within the concrete, food, and wood industries. During cement production, the TDR probe is used to estimate the MC_{wb} of raw materials including sand, gravel, powders, and water, as well as to monitor the MC_{wb} of the final concrete mix (Ferraris, 2001). In wood and grain processing, the TDR probe has been used during pressing and drying, respectively. The probe is typically installed on hopper walls, concrete mixer floors, dryer walls, and above conveyor belts with throughputs ranging from 1,361 kg/hr to 36,282 kg/hr depending on the size of the equipment (Rahmanulloh, 2020; McGuire, 2009). The electromagnetic measuring field generated by the TDR probe penetrates up to 2 liters (2000g) of the volume of the material being measured, resulting in accurate MC_{wb} determination under large throughput applications (Sono-Vario LD-IMKO Micromodultechnik GmbH, 2015). The high-frequency (1GHz) measurements of the TDR probe reduce interferences caused by changes in temperature and mineral contents of the measured material. Additionally, signal analysis and filter algorithms within the TDR probe compensates for the electrical conductivity of the material being measured, which otherwise affects the MC_{wb} measurements (Stacheder et al., 1997; Laurent et al., 2005).

The inline moisture estimation system designed in this study can be potentially applied during several coffee postharvest processes, such as after dry milling, sorting, and bagging per importing countries' specifications (Clarke, 1985). For example, the developed system in this study has the potential to be used in parallel with electronic sorters to additionally sort the green coffee beans, based on their MC_{wb}. Alternatively, it can be used to determine the MC_{wb} of green coffee before it is shipped to importing countries. Green coffee with $MC_{wb} \geq 14\%$ is not allowed to be shipped (Trade and Itc, 2012). Thus, accurate estimation of MC_{wb} will prevent significant economic losses to producing countries. The inline moisture estimation system can also be used to estimate the MC_{wb} of green coffee as soon it arrives at importing countries to determine if significant changes of MC_{wb} occurred during storage and transportation. Previous studies have indicated that due to the hygroscopic nature of coffee, changes in green coffee MC_{wb} can occur during storage and transportation, especially when the coffee hasn't been properly packaged, and it is exposed to fluctuations in environmental conditions (Borém et al., 2013a, 2013b; Selmar et al., 2008, Chapter 2). Lastly, the system can be used immediately before roasting to sort green coffee beans into batches of similar MC_{wb}. A uniform MC_{wb} of coffee is required during roasting to guarantee efficient roasting, and high quality of the roasted coffee (Baggenstoss et al., 2008). The current throughput of the system developed for this study is dependent on the feed table, and bin size. Based on the properties and measuring capabilities of the TDR probe, a larger industrial-scale system that accommodates the typical throughput of coffee processing equipment (22,300 kg/hr) can be developed and applied in industrial-scale operations (Minglani et al., 2020). The affordability, robustness, flexibility, and high accuracy of the inline moisture estimation system offer a potential alternative to other methods of estimating green coffee MC_{wb}.

4.0 Conclusions

A prototype inline moisture estimation system using a TDR probe for measuring green coffee MC_{wb} was designed and constructed. The system was calibrated and independently validated using green coffee with a MC_{wb} range of 9% - 21% and inline validation results indicated a strong correlation between the inline moisture estimation system and the reference method used (R^2 = 0.93; RMSE = 0.9% MC_{wb}). Overall, results demonstrated that TDR is a valid non-destructive alternative to gravimetric and other indirect methods to estimate the MC_{wb} of green coffee due to its high accuracy and speed, real-time inline capability, and density-independent measurements. The system in this study can be used through several coffee postharvest processes phases to ensure efficient processing and high quality of the final product. Future work will focus on calibrating the system for parchment coffee and developing a large-scale inline moisture estimation system with a throughput equivalent to that of current coffee processing units and implementing the equipment in an industrial-scale dry hulling coffee processing line.

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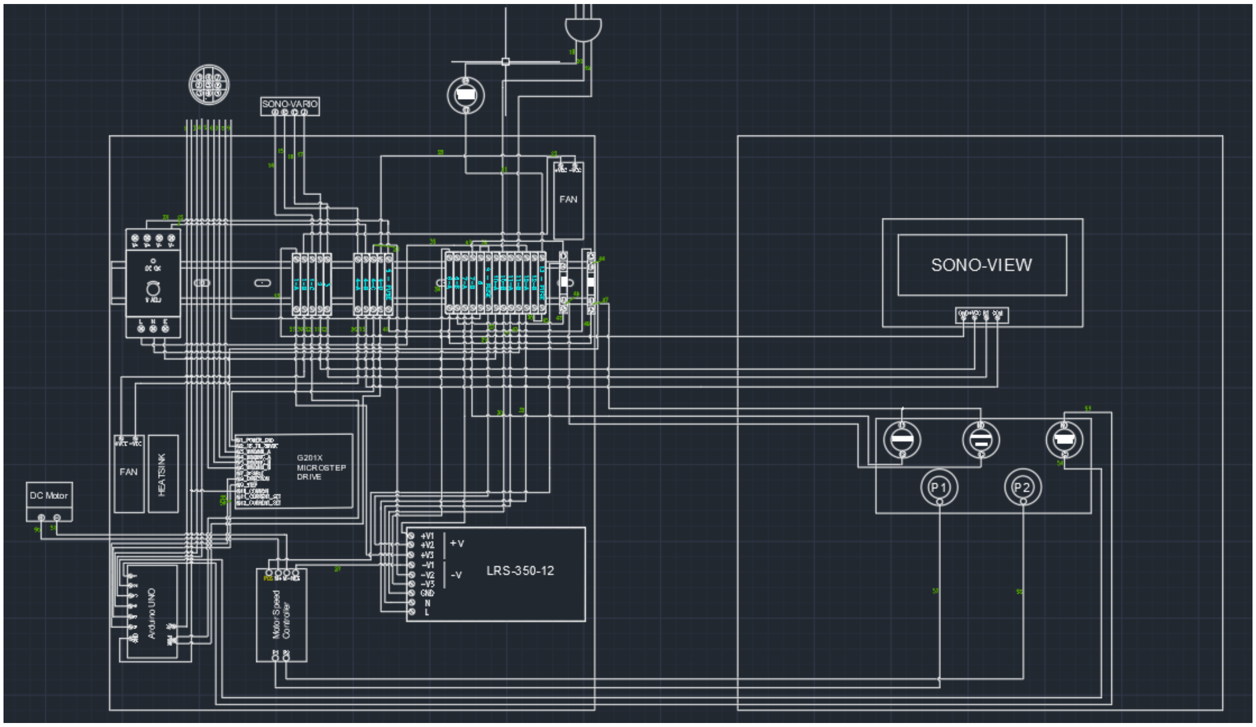
Appendix

Appendix I

Mapping of the electronic components within the control box of the inline moisture estimation system.



CHAPTER 4

FINAL REMARKS AND FUTURE WORK

Coffee is an agricultural commodity with a quality-based price. The value of coffee increases significantly with improvements in its quality, which is determined by the physical and chemical composition of the green coffee bean (Flávio Meira Borém et al., 2013c). Therefore, focusing on green coffee is key to increasing the quality and price of the final product. As described in Chapter 1, the maintenance of green coffee moisture content (MC_{wb}) within the ideal range (10-12%) during storage and transportation is crucial, as variations in MC_{wb} will lead to coffee quality degradation (N. Wintgens, 2004). Factors such as ambient environmental conditions (T and RH), packaging, storage and transportation time are important parameters to preserve the quality of coffee beans (Broissin-Vargas et al., 2018c; Bucheli et al., 1998b). As of today, the most common packaging material to store and transport green coffee is the jute sack, which does not prevent the exchange of gasses and water vapor between the coffee beans and ambient air. The exchange of gasses and vapor rapidly reduces the quality of the coffee through changes in the coffee's chemical composition (Selmar et al., 2008a). Several studies have evaluated strategies for preserving the initial quality of green coffee for longer times during storage. These strategies include the use of hermetic packages with and without modified atmosphere (Harris and Miller, 2008; Nobre et al., 2007; Ribeiro, Borém, Giomo, de Lima, et al., 2011). Despite recent advances in the field, the use of hermetic packages has only been proven to be effective during green coffee storage for up to 3 years (Donovan et al., 2019; Ribeiro, Borém, Giomo, de Lima, et al., 2011). Hermetic packages are still compromised due to the rapid and extreme environmental changes that occur in the shipping container during transportation. Current industrial practices involve the use of desiccants, such as $CaCl_2$, to reduce moisture changes inside shipping containers (Gheorghe, 2012). Knowledge of the optimized type and amount of desiccants to be placed within shipping container is essential. However, studies that correlate the current industrial practices of desiccant use during green coffee storage and transportation with the physical and chemical characteristics of the beans are unavailable. Furthermore, for effective storage and transportation and to avoid quality degradation, green coffee beans must be well dried to a MC_{wb} of 10-12%. Thus, accurate and fast measurement of MC_{wb} at the various postharvest steps is also vital to prevent quantitative and qualitative losses. Current methods to determine green coffee MC_{wb}, rely on samples to predict the MC_{wb} range of an entire coffee batch, which lacks accuracy. Overall, scientific research related to accurate moisture determination and preservation during green coffee storage and transportation is limited. Therefore, the goal of this thesis was to contribute to the sound multi-disciplinary science in coffee, by focusing on eliminating moisture damage by minimizing the effect of T and RH fluctuations during green coffee storage and transportation and investigating accurate inexpensive methods of determining green coffee MC_{wb}.

Chapter 2 investigated the efficacy of commercially available desiccants for preserving the MC_{wb} of green coffee between 10-12%, when stored in either hermetic packages and/or jute sacks and assessed the corresponding impact on sensory quality. Green coffee was packed in three packaging materials (GrainPro SuperGrain bag, GrainPro TranSafeliner, and/or jute sacks), with and without desiccants (Drying Beads®, and $CaCl_2$) and stored for 42 days in environmental chambers under conditions of fluctuating T and RH that mimic typical storage and transportation conditions. The MC_{wb}, a_w, and color of all samples were measured approximately weekly over 42 days. At the end of the experiment, two-way mixed design ANOVA, a descriptive and discrimination sensory tests were done to determine if there were significant differences between the coffee samples. Overall, the results indicated that hermetic packages, even without desiccants, provide a stable MC_{wb} for green coffee compared to jute sacks only, but under extreme conditions such as during green coffee transportation, desiccants should be added to prevent MC_{wb} to increase above12%. In comparison to the control (no desiccant, and only jute sack), we observed a statistically significant impact for all tested desiccants and hermetic packages for maintaining the proper MC_{wb}, aw, and color. No significant difference was observed for the different desiccant masses tested when they were placed inside the hermetic packaging, but the desiccants were ineffective without the hermetic packaging. The triangle test and descriptive sensory evaluation yielded no significant differences between the use of hermetic packages with desiccants, and without desiccants.

In chapter 3, a prototype inline moisture estimation system capable of accurately measuring the MC_{wb} of green coffee beans, using a commercially available time-domain reflectometry (TDR) probe was designed, constructed, calibrated, and validated. The system was calibrated and independently validated using green coffee with a MC_{wb} range of 9% - 21%. A calibration linear regression model correlating the TDR probe output (dielectric constant) to reference MC_{wb} measurements obtained by a halogen moisture analyzer, yielded a high coefficient of correlation (R^2=0.99). Validation results indicated a strong correlation between the inline moisture estimation system and the reference method (R^2 = 0.93; RMSE = 0.9% MC_{wb}). Overall, results demonstrated that TDR is a valid non-destructive alternative to gravimetric and other indirect methods to estimate the MC_{wb} of green coffee due to its high accuracy and speed, real-time inline capability, and density-independent measurements. The designed inline moisture estimation system can be potentially utilized during sorting, after dry milling, before and after shipping, and before roasting to ensure efficient processing and high final product quality.

The findings in this thesis provides relevant information to the coffee industry. By using desiccants with hermetic packages during storage and transportation, coffee importers and exporters will avoid economical losses since moisture damage will be reduced, and the quality of green coffee will be better preserved. Furthermore, by implementing the inline moisture estimation system, coffee processors, importers, exporters, and roasters will be able to sort green coffee beans by MC_{wb} levels during various unit operations, to properly optimize post-harvest processes, reduce energy consumption, and achieve uniform quality.

Although this study produced accurate and meaningful results, there are some shortcomings that were encountered. For example, the $Cacl_2$ desiccants used in Chapter 2 dissolved into brine solution during the experiment. The brine solution leaked into some of the coffee samples and thus, these samples could not be used for the sensory tests. Also, the experiment in Chapter 2 explored the effect of increasing the conventional amount of desiccants by multiples of 2, 4, and 6 and observed no significant effects in the response variables measured. It is possible that the variations in the amount of desiccant were not broad enough to cause a significant difference in treatments. An alternative solution will be to increase the amount of desiccant on a logarithmic scale in a future experiment. The TDR probe used in chapter 3 could only measure MC_{wb} of 9% and above. Thus, the inline moisture estimation system was only calibrated on a 9-21% MC_{wb} range. The robustness of the probe can be improved to measure a wider range of MC_{wb}.

Results of this thesis highlight interesting opportunities for future research. For Chapter 2, future work will evaluate the use of desiccants to further dry coffee samples that are not properly dried and validate the effect of desiccant use during commercial-scale application. Also, future studies will explore the effect of the initial quality of green coffee (color, A_w, MC_{wb}) on the quality of roasted coffee beans (titratable acidity, and color), as well as investigate the possibility of building a roast profile based on the green coffee quality parameters. For Chapter 3, future work will focus on developing a large-scale inline moisture estimation system with a throughput equivalent to that of current coffee processing units and implementing the equipment in an industrial-scale dry hulling coffee processing line. Additionally, future studies will involve the calibration and validation of the inline moisture estimation system for parchment coffee.

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