Evaluating post-harvest practices on the quality and safety of Kona coffee

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Dissertation submitted to the Faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

In

Food Science and Technology

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Mar 19, 2019

Blacksburg, Virginia

Keywords: moisture, water activity, post-harvest, coffee, drying, Hawaii, Kona, quality, food safety

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ABSTRACT

Coffee grown in the United States represents less than 1% of the world's supply, and most of it comes from the state of Hawai'i. Kona coffee, grown on the western side of the island of Hawai'i, is the most recognized and the highest value Hawaiian coffee. The majority of this coffee is sun-dried after harvest and washing.

Sun-dried coffee should reach 12-13% moisture within 4 to 6 days. Sun-drying will reduce both the moisture content and the water activity (a_w). Reducing a_w below 0.75, especially in the first week of drying, is important for preventing or limiting mold growth. The purpose of this study was to 1) compare drying rates of Kona coffee bean batches using a_w and moisture content % measurements, 2) evaluate factors affecting the drying time of sun-dried Kona coffee, and 3) provide recommendations for post-harvest processing of sun-dried Kona coffee to optimize quality and safety.

Ten farms in the Kona coffee region of Hawai'i were visited in the fall of 2017 to record data on the drying rate of coffee bean batches and to record observations on the post-harvest handling and storage of coffee beans and the environmental conditions that may affect the quality and microbial contamination of drying coffee. The coffee drying surfaces, physical enclosures, fan use, and elevation varied among farms. Daily measurements of coffee moisture level, water activity, depth of bean layer and temperature were recorded along with air temperature, relative humidity and cloud cover during drying for 30 batches.

Most sun-dried batches reached 13% moisture in 6 to 10 days. Initial moisture content (31.6 ± 4.3%), and drying yard characteristics varied greatly among farms. Coffee batches reached 0.75 a_w within 6 days on average, but some batches required more than 10 days. Moisture content and a_w measurements were weakly correlated and water activity level increased at times during drying for some batches. Allowing airflow around drying beans and maintaining a bean layer depth of less than 5 cm appeared to improve drying rates.

Drying coffee parchments within 7 days post-harvest can inhibit growth of molds that may impact quality or molds that could produce mycotoxin. Controlling the drying conditions, including raking the layered beans, and monitoring moisture content can accelerate, or improve the consistency of, batch drying time.

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GENERAL AUDIENCE ABSTRACT

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Sun-dried coffee should reach 12-13% moisture within 4 to 6 days. Sun-drying will reduce both the moisture content and the water activity (a_w*). *(*Water activity is the measurement of water vapor pressure generated by the free or non-chemically bound water in foods and other products. Water activity (range of 0 to 1) is an important indicator for the shelf life of foods and the occurrence and growth of microorganisms).*

Reducing a_w below 0.75, especially in the first week of drying, is important for preventing or limiting mold growth. The purpose of this study was to 1) compare drying rates of Kona coffee bean batches using a_w and moisture content % measurements, 2) evaluate factors affecting the drying time of sun-dried Kona coffee, and 3) provide recommendations for post-harvest processing of sun-dried Kona coffee to optimize quality and safety.

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Most sun-dried batches reached 13% moisture in 6 to 10 days. Initial moisture content (27 to 36 %), and drying yard characteristics varied greatly among farms. Coffee batches reached 0.75 a_w within 6 days on average, but some batches required more than 10 days. Moisture content and a_w measurements were weakly correlated and water activity level increased at times during drying for some batches. Allowing airflow around drying beans and maintaining a bean layer depth of less than 5 cm appeared to improve drying rates.

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DEDICATION

I dedicate my dissertation work to my family and many friends. A special feeling of gratitude to my late father, Mohamed H Masri and beloved mother, Ameerah Al Mashat, whose words of encouragement and push for tenacity ring in my ears. I dedicate this work and give special thanks to my wife Hawazen Nadrah and my wonderful children’s Ameerah, Malak and Salman Masri for being there for me throughout the entire Ph.D. program.

ACKNOWLEDGEMENTS

I would first like to thank all the graduate students, faculty and staff of the Department of Food Science and Technology at Virginia Tech, especially my committee members Dr. Boyer, Dr. Strawn, and Dr. Easton. I would like to express my gratitude to Dr. Eifert for giving me the opportunity to work with him over the past 4 years and for the useful comments, remarks, and engagement through the learning process of this dissertation degree. I am honored to have you in my life as a mentor and friend.

I would like to thank the Hawaiian Coffee Association and the Kona Coffee Farmers Association for giving me the opportunity to visit you and be a part of my research project. I really enjoyed the time I spent during the data collection in Kona Hawai'i and getting to know you in person.

I would like to thank the Kingdom of Saudi Arabia through the Ministry of Education for the scholarship and financial support granted to me and my family, and the Saudi Arabia Cultural Mission for facilitating my queries during my graduate life.

I would like to thank my family my mother Ameerah Al- Mashat, bother Osama, sisters Dana and Aseel Masri, my wife Hawazen Nadrah and beloved children's Ameerah, Malak and Salman Masri for supporting me during my years of study.

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Chapter I

Introduction

Coffee is an important part of the agriculture industry on the Hawaiian Islands. Due to the natural resources of the islands' tropical environment, and rich volcanic soil, Hawai'i is an ideal location to grow coffee. Coffee grown in the United States represents less than 1% of the world's supply and most of it comes from the state of Hawai'i (Woodill et al, 2014). On the Hawaiian Islands coffee is not only grown on the Big Island of Hawai'i, primarily in the Kona region, but also on Oahu, Molokai, Maui, and Kauai. However, Kona coffee is the most recognized and the highest value per acre coffee on the islands (Bittenbender and Smith, 2008). Kona coffee is internationally known and commands some of the highest prices in the world. The Arabica variety "Kona Typica" is grown almost exclusively in Kona (Bittenbender and Smith, 2008).

Coffee fruits and beans can be contaminated by toxigenic fungi, including those that produce Ochratoxin A (OTA). This toxin is a secondary metabolite produced primarily by *Penicillium verrucosum* and *Penicillium nordicum* and by several species of the genus *Aspergillus*. Ochratoxin A (OTA) is considered to be nephrotoxic, carcinogenic, embryotoxic and teratogenic (Batista et al., 2009; Urbano et al, 2001; Velmourougane et al, 2011; Vecchio et al, 2012: Suárez-Quiroz et al., 2004). Preventive measures to control mold growth in coffee can be achieved through appropriate processing, storage and handling of products and their process environment (Olagunju et al, 2018). Water activity (a_w) and moisture content of the beans, along with storage time, temperature and relative humidity can greatly influence fungal growth and mycotoxin development, and therefore should be controlled or monitored, if possible. Reducing the water activity of coffee beans below 0.75, especially in the first week of drying, is important for preventing or reducing mycotoxigenic fungi from forming toxins (Paterson et al., 2014).

Inappropriate drying of the green coffee beans and the rewetting of the green coffee beans are causes of mold growth. The presence of OTA and ochratoxigenic fungal species in coffee beans has been studied extensively. Ochratoxin A (OTA) on partially dried, rewetted green coffee is primarily produced by *Aspergillus ochraceus* (Batista at el., 2009). Critical factors for fungal OTA production in coffee are environmental conditions, such as temperature, water activity (a_w), pH, nutrients, incubation time, and light (Suárez-Quiroz et al., 2004). If poor control procedures are employed, such as slow drying, the opportunities for OTA accumulation can increase postharvest. Similarly, if inadequate storage conditions are employed, OTA will increase, although it will be reduced during processing from sorting, analysis for OTA and segregation, and roasting. OTA-producing fungi require favorable conditions for a period of time to grow and produce the toxin. The sources for fungal contamination, during postharvest cross contamination include soil, equipment and drying-yard surfaces (Paterson et al., 2014). However, this contamination can be related to post-harvest problems including unfavorable (a) climates for drying, (b) drying practices, (c) quality control, and/or (d) storage conditions.

The coffee berry borer (*Hypothenemus hampei*, (Ferrari)) is a common insect pest for coffee grown in many parts of the world. This insect is also a suspected vector of various mycotoxin producing molds (Velmourougane et al., 2010). In August 2010, the coffee berry borer (CBB) was found in the district of Kona on the island of Hawai'i and appears to be restricted to that area (Burbano et al., 2011). On the island, CBB was first discovered in coffee farms, after over 200 years of borer-free coffee production (Chapman et al., 2015). Vega, et al. (1999) reported that several fungi, including *A. ochraceus,* could be isolated from the coffee berry borer. The isolation of *A. ochraceus* suggested that CBB might serve as a vector for this toxigenic fungus. In a study summary by Velmourougane et al. (2010), higher microbial contamination in CBB infested beans was reported in both the varieties of arabica and robusta coffee with the presence of toxigenic molds (including *A. niger* and *A. ochraceus*).

Climate changes including temperature increase, variation in precipitation, drought, and atmospheric carbon dioxide (CO_2) have been identified as relevant for agriculture and food safety (Miraglia et al., 2009). Furthermore, the importance of climate change to coffee production and the effect of on mycotoxin contamination, require urgent consideration. Due to the hot and humid conditions typical of coffee growing regions, coffee is susceptible to fungal contamination and growth of fungi that may or may not produce mycotoxins (Paterson et al., 2014, Tirado et al., 2010).

The water activity of coffee cherries should be reduced from approximately 0.97 to 0.80 in no more than four days. Drying time to get below a critical water activity (a_w) of 0.80, is crucial to delaying or preventing the development of *A. ochraceus* toxin (Paterson et al., 2014). The purpose of this research was to compare drying rates of Kona coffee bean batches using water activity and moisture content % measurements, and to evaluate factors affecting the drying time of sun-dried Kona coffee.

Chapter II

Literature review

1. Coffee Consumption and Production

1.1. Global coffee consumption

In 2018/19 the world coffee consumption is estimated at 165.19 million bags, an increase of 2.1% compared to 2017/18. Furthermore, in exporting countries consumption is estimated to increase by 1.4% to 50.3 million bags domestically. Moreover, importing countries consumption is estimated at 114.88 million bags (ITC, 2018). Worldwide every day, more than two billion cups of coffee are consumed, and Brazil is the largest consumer of coffee in the world. In the last 40 years the global consumption has almost doubled and is forecast to reach more than nine million tons by 2019 (Taniwaki et al, 2013). Since the early 1980s coffee consumption increased by an average of 1.2% annually. In Japan, coffee consumption increased 3.5% annually over the same period. That makes Japan the third largest importer of coffee in the world (ITC, 2012a).

Coffee production from October 2017 to September 2018 was approximately 165 million bags. Furthermore, a surplus of coffee will be produced during the 2018/2019 season. The estimated 167.47 million bags will exceed the world consumption, estimated at 165.18 million bags. In November 2018, world coffee exports reached 9.88 million bags, an increase of 5.7%, compared with 9.35 million in November 2017. Moreover, exports of arabica increased 13.2% to 13.84 million bags in the first two months of coffee year 2018/19, compared to the same period in 2017/18, with the largest increase in shipments of Brazilian Naturals, which rose by 24.8% to 7.92 million bags. With an output estimated at 58.5 million bags for crop year (April-March) 2019/20, Brazil will remain the world's largest coffee producer. The next largest producing countries are expected to be Vietnam's (29.5 million bags), Colombia (14.2 million bags), Indonesia (10.2 million bags), Ethiopia (7.5 million bags), Honduras (7.45 million bags), and India (5.2 million bags) (ITC, 2018).

From 2000 to 2005 the consumption of decaffeinated coffee was relatively stable in the United States, accounting for 8– 9% of normal coffee sales and about 20% of sales of specialty coffee. According to the latest National Coffee Association =(NCA) Coffee Drinking Study, sales increased significantly in 2009 to reach 16%, but fell back to 13% in 2011. Since 2000, the consumption of decaffeinated coffee has been fairly static elsewhere, and low-caffeine coffee products are now established in many countries. Low caffeine coffee products, also sold as 'light' coffee, are not caffeine free, but are either a mixture of regular coffee and decaffeinated coffee or blends of coffees with a naturally low caffeine content (ITC, 2012b).

1.2. World coffee industry

Coffee plays a vital role in the balance of trade between developed and developing countries, as it is the second biggest internationally traded commodity (after oil) (Taniwaki et al, 2013). Coffee is considered the world's favorite beverage with retail sales worldwide estimated at US $90 billion (Davis et al., 2012). Since 1840, the bulk of the world's coffee is produced in Latin America and, in particular, Brazil which is the world's largest grower and seller of coffee. Growing an average of 2.5 million tons a year from 2007 to 2011 Brazil has long been by far the world's largest coffee producer and exporter (Taniwaki et al, 2013).

Considering its cultivation, processing, transportation and marketing, the international coffee trade involves more than 80 million people worldwide (DaMatta et al., 2006). Many countries and citizens depend on coffee production for income as it is a major commodity in the world market. Worldwide, coffee produced by small farmers contributes to 3/4 of total global production and an estimated 500 million people are dependent on coffee production in these countries (DaMatta et al., 2006).

From 2009 to 2013, worldwide coffee production steadily increased by 17%, with an annual growth of 4%, whereas the exportable product increased by 12%, with an average growth per year of 3%. In 2013, 67% of total coffee exports were from Brazil, Vietnam, Columbia, Indonesia, and India. Moreover, the European Union, United States, and Japan, imported 76% of all coffee beans (Woodill et al., 2014).

1.3. Hawai'i's Coffee Industry

Coffee grown in the United States represents less than 1% of the world's supply, and most of it comes from the state of Hawai'i that produces just 0.04% of the world supply (Woodill et al, 2014). Nevertheless, the value of coffee production is significant to the state of Hawai'i. The value of Hawaiian coffee production grew from 2 million dollars in 1997 to 7 million dollars in 2003, to a current value of ~$24 million annually. Moreover, in 2002 the retail value of the roasted beans and beverages sales was valued at ~$117 million in the state of Hawai'i (Bittenbender and Smith, 2008). Hawai'i coffee production has varied over the past 15 years. Declines in coffee production are likely due to the combination of drought and coffee berry borer (CBB) damage (Woodill et al, 2014).

Coffee is an important part of Hawai'i's agriculture sector. Due to the natural resources of the islands', tropical environment and rich volcanic soil it provides an ideal location to grow coffee. Hawai'i coffee farmers have been dedicated for generations to producing some of the best coffees in the world. On the island of Hawai'i, the Kona coffee belt region includes more than 700 farms and approximately 3000 acres of coffee production valued at ~ $10,000 to $1,000,000 per year (Woodill et al, 2014). These farms, on the west side of the island of Hawai'i, range in elevation from 240 to 670 meter. On the Hawaiian Islands coffee is not only growing on the Big Island of Hawai'i in the Kona area, it also grows on the islands of Oahu, Molokai, Maui, and Kauai. However, the most recognized and the highest value per acre Hawaiian coffee is Kona coffee. Kona produces 1.59 million kg of green coffee annually, with a value of US $35-42 million (Greco and Wright, 2013).

1.3.1. Kona coffee industry

Kona coffee is internationally known and commands some of the highest prices in the world. The arabica variety "Kona Typica" is grown almost exclusively here (Bittenbender and Smith, 2008). In 1817, Don Paulo Marin, who established many tropical plants in Hawai'i for the first time, planted coffee seeds. In 1828, the Rev. Samuel Ruggles, a Congregational minister and teacher, planted the first known coffee trees. He made the first plantings in Kona at Naole, near Kealakekua, after taking coffee slips from plants grown in Manoa on Oahu (Masuda, 2007). In 1975, the Hawai'i coffee industry re-emerged and, especially since the late 1980s, evolved rapidly after a long industry decline following the 1957/58 harvesting season. And, coffee growing expanded to four other major Hawaiian Islands: Kauai, Oahu, Maui, and Molokai beyond the Kona District of the island of Hawai'i.

Farming techniques and farm size are highly diverse in Hawai'i. Operations range from a part-time family farm of less than two acres using the traditional handpicked harvesting method, to one of the world's largest corporate farms with a fully irrigated and mechanized harvesting method. By 2003, the lands used for coffee plantations expanded from 2,400 acres (1975) to 7,300 acres. This total included 3,600 acres in Hawai'i County and 3,400 acres in Kauai County, with Honolulu and Maui counties making up the remaining acreage (Southichack, 2006).

From farming to processing, to selling the finished product, operations are fully integrated in large farms. Many small farms have also become fully integrated operations, and their number is increasing. Moreover, a large number of part-time family farms complete their operations after the coffee cherries are harvested and sold to local processors. Hawaii's coffee industry has a high concentration of small family farms in the Kona region on the Big Island. In 2004, small family farms accounted for 82% of all commercial coffee farms in the state (Southichack, 2006).

The quality of Kona coffee is well known in the specialty coffee market compared to the small production amount in the world commodity market. The Kona brand was established as a gourmet coffee since 1980, and Kona coffee growers have striven to improve product quality. Similar to Blue Mountain coffee from Jamaica, the Kona coffee market is distinguished from price competition in the world coffee market (Masuda, 2007).

The first standard that defined a *Kona blend* coffee went into effect in 1992. A Kona coffee blend must be at least 10 percent Kona coffee, to be labeled as a *Kona blend*. Additionally, the Hawai'i legislature passed a truth-in-labeling law in 2002 that requires coffee packages sold in Hawai'i to have labels which show the geographical origins of the coffees on the package with their exact coffee percentages (Masuda, 2007).

1.4. Coffee growing and production

For coffee production, weather temperature is a key factor, and latitude and elevation strongly influence the temperature. Coffee is grown over a wide range of elevations at any given latitude. Coffee is grown around the world from 24°N to 25°S latitudes and ranging in elevation from sea level to as high as 2133 meter. Humid and hot environments can allow coffee trees to flourish. In countries at or near the equator, such as Kenya, the New Guinea highlands, and Colombia generally, high elevation coffee regions are found. Coffee growing regions can occur in low-elevation subtropical latitudes (22–25°) such as Hawai'i and São Paulo, Brazil. Elevations between sea level and 2500 ft. are suitable for Hawai'i coffee production with favorable rainfall and soil factors (Bittenbender and Smith, 2008).

The three optimal time periods to harvest are April, July, and October, and it differs for each country that falls within one of these groups (Woodill et al, 2014). Lower coffee fruit quality can arise if plants grow too quickly. Excessive fruit ripening during summer's higher maximum temperatures may cause a loss of quality. Coffee trees are resistant to high summer temperature and drought, but physiological stresses, such as the reduction of photosynthetic efficiency can result from an increase of extreme weather conditions. Moreover, the optimum coffee production and quality can be affected by high temperature and dry conditions during the reproductive phase. Adequate air temperature limits for coffee is critical for the distribution and economic exploitation of crop setting (Camargo, 2010).

1.4.1. Coffee species (arabica and robusta)

There are two main coffee species that are employed worldwide, arabica coffee and robusta coffee. Arabica coffee (*Coffea arabica* L.) accounts for approximately 70% of commercial production, and the remaining 30% is from robusta coffee (*Coffea canephora* var. robusta). In Central and South America and in East Africa two-thirds of the coffee stems from *Coffea arabica* (van der Stegen, 2003). Arabica coffee originated from Ethiopia as it is indigenous to Africa, and the origin of robusta coffee is from the Atlantic Coast and the Great Lakes region in Africa (ITC, 2012a).

Coffea arabica (arabica coffee) requires a wet tropical highlands climate at altitudes between 600 and 1600m. In addition, *Coffea canephora* (robusta coffee) can be grown at sea level, but, it too, is often grown in wet tropical highlands. The potency and disease resistance of robusta is superior to arabica (FAO, 2006). Climatic variability and arabica green coffee beans yield productivity is tightly linked, and is strongly influenced by natural climatic fluctuations (Davis et al., 2012).

In the tropical forests of Ethiopia, Kenya, and Sudan, at altitudes of 1500 -

2800m, and between the latitudes of 4°N and 9°N, arabica coffee is the native species. In this region, the mean annual air temperature is between 18 and 22°C and shows little seasonal fluctuation (Camargo, 2010). The optimum mean annual air temperature range for arabica coffee is 18 to 23°C. At these temperatures, fruit development and ripening are accelerated. Once temperatures climb above 23°C, there is a loss in quality. Exposure to daily temperatures as high as 30°C could result in not only depressed growth, but also in abnormalities such as yellowing of leaves. A prolonged dry season associated with a relatively high air temperature during blossoming, may cause abortion of flowers.

In the Northeast and North regions of Brazil, selected cultivars under intensive management conditions have enabled arabica coffee plantations to be spread to marginal regions with mean annual air temperatures as high as 24-25°C, with satisfactory yields. In the regions with a mean annual air temperature below 18°C, growth is also largely depressed. Sporadic occurrence of frosts may strongly limit the economic success of the crop (Camargo, 2010). An annual mean temperature of 22°C and average annual rainfall of 125 cm occurs in the Kona coffee belt on the island of Hawai'i. In the Kona area, spring and summer (April to September) are the rainy seasons, while a low rainfall period occurs in the coldest months (December to February) (Greco and Wright, 2013).

Robusta coffee is native to the lowland forests of the Congo River basin which extends up to Lake Victoria in Uganda. In this region, rainfall is abundant (> 200 cm over 9 to 10 months) and the annual mean temperature ranges from 23 to 26°C, without large fluctuations. If the air is dry, high temperatures can be harmful to coffee trees.

Leaves and fruits do not withstand temperatures below 6°C or long exposures to 15°C. robusta is much less adaptable to lower temperatures than arabica (Camargo, 2010). According to Carmargo (2010), the optimal temperatures, locations, and altitudes for growing arabica and robusta coffee include 1) arabica: 18 - 24°C, Colombia, Central America, Ethiopia, Kenya, and Sudan, 500-2500m altitude; and 2) robusta: 22 - 28°C, Republic of the Congo, Uganda, Angola, Madagascar, Ivory Coast, Indonesia and Vietnam, sea level to 600m.

1.4.2. Organic coffee

The current technologies and production practices in Hawai'i's coffee industry are diverse. Growers can have 1-acre, certified organic, rain-fed farms to 4000-acre, totally mechanized, irrigated plantations. (Bittenbender and Smith, 2008). Masuda (2007) reported that there were 25-30 commercial organic coffee farms in Kona Hawai'i, though the number of organic coffee farms tends to increase over time.

Organic agriculture is defined as a full production management system that promotes and enhances agro-ecosystem health, including biodiversity, biological cycles and soil fertility. Organic production systems are based on specific and precise production, processing and handling standards. Coffee can be marketed as organic only based on regular inspection of all stages of production, processing, transporting and roasting of the coffee, and when it is certified as such by a recognized organization or certifier. In 1967, the first organic coffee cultivation was recorded at the Finca Irlanda in Chiapas, Mexico. In 1985, from the Union Indigenous Communities of the Isthmus Region (UCIRI) cooperative in Oaxaca, Mexico, the first organic coffee was imported into Europe (ITC, 2012c).

With a strict set of government standards, organic coffee production is unlike any other certification standard. These are established by the National Organic Program (NOP) of the U.S. Department of Agriculture (USDA) in the U.S., as it relates to agricultural crop production and must be able to verify that organic integrity is maintained throughout the process. The verification process does not stop at harvest, unlike most other coffee certifications (Dill and Marquardt, 2011). Furthermore, organic agriculture practices do not allow the following: use of synthetic chemicals either for fertilization or for plant protection; irradiation for pest control; and use of genetic engineering in plant and animal breeding (Sosa, et al., 2004).

Growing, certifying, producing and processing organic coffee can affect beverage safety (Dill and Marquardt, 2011). As typically used, chemical fertilizers, pesticides, and/or herbicides, may harm soil fertility and ecology in conventional farming systems. The use of organic fertilizers, which will improve soil fertility and ecology is common in organic farming systems. However, this farming system is relatively labor intensive and a lower yield is expected (Masuda et al, 2010).

2. Coffee Processing

There are two main types of initial coffee processing methods used depending on the type of coffee beans. A wet process is used for arabica coffee where water is abundant.The dry process is applied for robusta coffee where water supply is in shortage (van der Stegen, 2003). Newly planted coffee trees take approximately three to four years to bear fruit. The external skin (exocarp) of the fruit, called the coffee cherry, turns a bright, deep red when it is ripe and ready for harvest. There is typically one major harvest a year, and coffee cherries may be picked by hand or by machine. Once the coffee cherries have been picked, processing must begin as quickly as possible to prevent fruit spoilage (Batista at el., 2009).

Each coffee grain, or bean, is surrounded by a hard layer called the parchment (endocarp) and covered by a spermoderm called silverskin. The mesocarp, also referred to as the mucilage or pulp, is the flesh of the coffee fruit and surrounds the silverskin. The outer skin of the coffee cherry is usually referred to as the exocarp (Brando, 2004). Normally the coffee cherry contains two seeds ("beans"). Some cherries may grow with only a single fertilized seed. The resulting oval (or pea-shaped) bean is known as a peaberry.

The primary steps for post-harvest coffee processing include the following. Removal of the flesh and the skin (pulping) from the coffee cherry by machine. After the pulping stage, over-ripe or damaged coffee beans can be separated by density in water, or can be sorted by size. Beans may be soaked in water-filled fermentation tanks to remove the layer of mucilage that is still attached to the parchment. Then beans may be rinsed and dried in the sun or machine-dried in large tumblers. These dried coffee beans (parchment coffee) are ready for storage for two-month prior milling it (Batista et al., 2009; Viani, 2002).

2.1. Coffee washing process

There are two main types of initial coffee processing methods used depending on the type of coffee beans. A wet process is used for arabica coffee where water is abundant, and where water supply is in shortage, the dry process is applied for robusta coffee (van der Stegen, 2003). In wet processing, the skin of the coffee cherry is removed and the remaining seed (now called parchment coffee), which is enclosed in the inner integument or endocarp, is then dried. The wet processing method uses equipment to remove the fruit skin and part of the mucilage of the fruit. After removing the skin, the parchment coated with mucilage is exposed. To remove the mucilage of the parchment it will be traditionally fermented which can be easily washed afterwards or removed immediately by machine. The wet method is used throughout the Kona coffee region.

In the dry or natural processing, the skin will be left on the seed and then dried together (FAO, 2006). The sensory qualities of parchment coffee are different than the cherry coffee and has a higher market value and is more expensive to produce. Parchment coffee is mostly produced from arabica coffee, while cherry coffee is mostly produced from robusta coffee (FAO, 2006). The dry method, also called the natural method, is used in Kona Hawai'i by small farms to process and dry raisins and/or fresh coffee cherries. After the drying, the coffee cherries are milled to remove the dehydrated pulp, parchment skin and silver skin in one operation. After the completion of any of the previous coffee processing steps, the coffee beans will be further dried either in the sun or by mechanical (artificial) dryers.

2.2. Coffee drying process

Post-harvest processing of coffee includes a drying procedure to reduce the water content of the beans. Even though producers can consistently dry their coffee to

9-12% final moisture, the drying rate and drying time for batches of coffee beans can vary greatly. Controlled and consistent drying procedures for coffee beans may improve coffee quality and discourage mold and mycotoxin formation. The price of coffee beans is influenced by the quality of the beans achieved after processing (Paterson et al., 2014).

The usual way to dry the parchment is by sun after removing the mucilage (FAO, 2006). In dry or natural processing, the intact fruit is directly laid out to dry in the sun. Afterwards, the skin will be removed during the hulling step. Moreover, mechanical drying is important in some capitalized sectors, though sun-drying is the most common drying method for coffee. The mechanical dryers are designed to handle coffee with an initial water content of 35 - 40%, yet sun drying is normally used for a significant part of the drying period (FAO, 2006). The ideal moisture content for both arabica and robusta coffee after drying is 12% and 13%, respectively (Rojas, 2004). Small operations typically use sun-drying to dry their coffee beans by spreading the beans on a drying area evenly, and periodically turning them over. The estimated time needed to complete the coffee parchment drying using this type of method is approximately 4 - 7 days, but with cloudy days more time may be needed.

Artificial (mechanical) drying occurs right after the washing step. Coffee beans can be placed in the mechanical dryer where hot air helps dry the beans in a rotating drum. The mechanical dryer could heat up the air with solar or fuel type energy like propane or diesel fuel. Depending on the type of dryer (stationary or rotary) the average heat temperature is 120-140°F (Bittenbender and Smith, 2008). Some processors may use a combination of both sun-drying and mechanical drying. For this method, the coffee beans can be sun-dried for 24 - 48 hours and then finished in the mechanical dryer.

2.3 Milling and roasting

Coffee beans covered by their parchment skin when dried and ready for milling are referred to as “parchment coffee”. On some farms in Kona Hawai’i, coffee is processed only to the parchment coffee stage, and then sold to a larger plantation or to a miller who then mills (hulls) the parchment coffee to green coffee. Furthermore, as “estate coffee” some farms today have their coffee “contract milled” and “contract roasted” and sell their green or roasted coffee. Although most coffee is sold as green coffee, large farms frequently do all their processing, including roasting. Although, the parchment and silver-skin covering the green bean are removed during hulling. A considerable amount of silver skin may still be attached to the green bean after the parchment skin (hull) is removed. To remove all the silver skin and give the coffee a more attractive, smooth, shiny appearance, coffee is frequently “polished” (Bittenbender and Smith, 2008).

After hulling and grading, the coffee is bagged and shipped. Because roasted coffee will not store as long as green coffee, it is usually not roasted before long distance shipping. Roasted coffee shelf life can be increased greatly by using one-way gas valves on foil bags. If storage conditions are cool and dry, green coffee can be stored for several years. (Bittenbender and Smith, 2008).

2.3.1. Caffeine and decaffeination

As a natural substance caffeine is found in the leaves, seeds or fruits of more than 60 plant species worldwide. Caffeine levels can vary depending on where the trees are grown (soil, altitude, climate, etc.). The caffeine percent available in coffee beans depends on the coffee type- 1–1.5% in arabica coffee beans, and more than 2% in robusta coffee beans.

Caffeine is an alkaloid with stimulant properties that are pleasing to the coffee drinkers, but not to all. Decaffeination serves those who do not want the stimulant effect of caffeine. To both soluble coffee (spray-dried and freeze-dried) and roasted coffee, a decaffeination process is applicable. Decaffeinated coffee is estimated to account for 10% of all coffee sales. An accurate measure of the world consumption of decaffeinated coffee is difficult due to the lack of separate data on this type of coffee in many importing countries (ITC, 2012b).

There are different processes used to extract the caffeine from green coffee beans. Caffeine may be extracted with solvents including water, organic extraction agents or carbonic acid. The processing steps are vaporization, decaffeination and drying (ITC, 2012b). Over the last 15 years' decaffeination process technology has improved and shifted from using methyl chloride to water and carbon dioxide, yet the product is losing market share (ITC, 2012b).

The steps to extract the caffeine from the green coffee beans include the following (ITC, 2012b):

1. Treatment with vapor and water to open up the bean surface and the cell structure to access the crystalline caffeine in the cell walls.

2. Extracting the caffeine with an extraction agent that extracts only the caffeine. The caffeine extraction is a physical process and no chemical changes take place.
3. Once the extraction agent is saturated with caffeine the next processing step removes the caffeine and the extraction agent can be used again. This cycle is repeated until practically all the caffeine is removed from the coffee bean.
4. The wet coffee, from which the caffeine has been removed, is dried until once again it reaches its normal moisture content, and then roasted.

In the European Union, the following decaffeination agents are allowed in all conventional decaffeination methods: methylene chloride, ethyl acetate, carbon dioxide and a watery coffee extract from which the caffeine is removed by active carbon. The caffeine content limit in the United States is less than 3% or a reduction of 97% of the original content. In the European Union, the absolute caffeine content may not exceed 0.1%, or 0.3% in roasted, decaffeinated coffee (ITC, 2012b).

3. Coffee Quality and Safety Concerns

A useful parameter to evaluate coffee quality characteristics are intrinsic factors such as moisture content and a_w, as well as extrinsic factors, such as temperature and relative humidity. Humidity is the most important factor impacting the speed at which coffee beans deteriorate. Moreover, coffee beans are hygroscopic and tend to balance their moisture content with their immediate surroundings generally known as “moisture balance” even if they have been stored in a low moisture environment (Rojas, 2004).

Countries producing and exporting coffee aim to maintain safe, quality products throughout the production chain. Unfortunately, some factors are out of the control of both producers and exporters such as climatic impacts that may result in logistic structure breakdowns, which could cause undesirable changes in crop characteristics, permitting fungal growth and subsequent mycotoxin production (Palacios-Cabrera et al., 2007).

To preserve sensory qualities and product safety, applying practices that restrict the development of certain fungi is needed. These often include 1) managing water availability from the beginning of drying onward, and 2) facilitating the development of competitive micro-organisms and restrictive growth conditions that are not prejudicial to quality, before this point (FAO, 2006). Most of the coffee producing countries worldwide have varied delays between the harvesting of coffee berries and the onset of processing. Delays in processing coffee can negatively impact coffee production, quality and safety. For examples, for both arabica and robusta coffee, ochratoxin A (OTA) contamination could develop, or there can be negative effects on cup quality (Velmourougane et al, 2011).

3.1. Coffee berry borer infestation

A common insect pest in coffee plantations is the coffee berry borer (CBB). This insect (*Hypothenemus hampei*, (Ferrari)), damages coffee berries, reduces coffee yield, and is a suspected vector of various mycotoxin producing molds (Velmourougane et al., 2010). In the coffee berry, the female adult bores a hole where she deposits 20-50 eggs. Upon hatching, larvae feed on the seeds, lowering the quality of the berry and reducing the yield production (Burbano et al., 2011). The female to male sex ratio is 10 to 1, and females mate inside the berry; consequently, once they emerge, they are ready to deposit eggs into another coffee berry (Vega et al., 1999).

It is useful to understand the role of CBB in the coffee growing regions of the world, especially in plantations for production of quality coffee. Throughout the world, CBB is a serious coffee pest, that has now spread to most coffee growing regions in Central Africa, and has been reported in Uganda, Congo, Benin, Togo, Ivory Coast, Kenya, Nigeria, Angola, Ethiopia, Brazil, Colombia, Guatemala, Ecuador, Nicaragua, Honduras, Mexico, Malaysia, Indonesia, Sri Lanka, Jamaica, New Caledonia, India, and other countries (Vega et al., 1999). On the island of Hawai'i, CBB was first discovered in coffee farms, after over 200 years of borer-free coffee production (Chapman et al., 2015). In August of 2010, the coffee berry borer was found in the Kona district (Burbano et al., 2011).

The following fungal species have been isolated from coffee berry borers: *Aspergillus ochraceus, Aspergillus flavus, Aspergillus niger, Fusarium sp., Penicillium chrysogenum, Penicillium brevicompactum and Verticillium spp*. The isolation of *A. ochraceus* suggests that CBB might serve as a vector for this toxigenic fungus (Vega et al., 1999). In a study summary by Velmourougane, et al., (2010), higher microbial contamination was reported in CBB infested beans in both the varieties of arabica and robusta coffee with the presence of toxigenic molds (such as *Aspergillus niger* and *Aspergillus ochraceus*). The results from this study provide adequate baseline information and evidence to understand and correlate the role of CBB with various ochratoxin-producing molds in coffee beans.

3.2. Fungal contamination

On a wide range of agricultural products mold growth can occur, like cereals, grapes, and green coffee beans. Fungal contamination can affect the taste or aroma of coffee, though these fungi may not be the same as those involved in ochratoxin production (FAO, 2006). Coffee fruits and beans are subject to contamination by microorganisms during different developmental stages, like other agricultural products, from field to storage. Fungi presence in the coffee beans does not only affect quality in terms of flavor and aroma of the beverage, but also presents a safety risk (De Fatima Rezende, 2013). The sources for fungal contamination, during postharvest cross contamination, are from soil, equipment and drying-yard surfaces (Paterson et al., 2014).

Coffee processing methods such as wet (parchment coffee) and dry processing (cherry coffee) preparation can contribute tremendously to the growth of toxigenic molds and ochratoxin production (Velmourougane et al, 2011). The risk for mold growth exists for coffee prior to drying and in cases of insufficient drying of the green coffee beans/berries, and when green coffee beans are rewetted by rainfall. On partially dried or rewetted green coffee, *Aspergillus ochraceus* is capable of growing and producing the mycotoxin ochratoxin A (OTA) (van der Stegen, 2003). In coffee cherries, as compared to parchment coffee of both arabica and robusta, the delay in processing was found to favor higher mold incidence. A correlation between ochratoxin A (OTA) contamination and delays in processing coffee cherries and parchment coffee was not definite (Velmourougane et al, 2011).

Mold growth and mycotoxin formation in foods and feeds depends on the effects of multiple variables including pH, water activity (aw), solute concentrations, temperature, atmosphere, relative humidity, composition and time. The two most important factors that influence fungal growth, sporulation, and possible mycotoxin production are water activity (a_w) and temperature (Passamani et al, 2014; Panagou et al., 2003).

Drastic temperature fluctuations which can occur during transportation, can result in increased moisture of previously dried beans. During transportation, moisture transfer can be the result of changes in temperature between regions with a tropical climate, such as Brazil in summer, and those of temperate climates, such as the northern hemisphere (Palacios-Cabrera et al., 2007).

Water activity (a_w) and moisture content of the beans, along with storage time, temperature and relative humidity can greatly influence fungal growth and mycotoxin development. Reducing the water activity below 0.75, especially in the first week of drying, is important for preventing or reducing mycotoxigenic fungi from forming toxins (Paterson et al., 2014).

3.3. Mycotoxins

3.3.1. Mycotoxin contamination and human exposure

Mycotoxins are a group of highly toxic chemical substances that are produced by toxigenic molds that commonly grow on a number of crops including coffee. These toxins can be produced before harvest in the standing crop and many can increase, even dramatically, after harvest if the post-harvest conditions are favorable for further fungal growth and toxin development. Human exposure to mycotoxins can be direct through consumption of contaminated crops. Mycotoxins can also reach the human food supply through livestock that have consumed contaminated feed.

The ingestion of contaminated plant based foods primarily influences exposure. Foods such as cereals, wine and beer, coffee, and animal derived foods may be contaminated with OTA residues. Detection of OTA in human biological fluids is indicative of a frequent exposure of the human population in different countries. Inhalation of OTA with airborne dusts is another non-conventional source of exposure. (Muñoz, 2011). Ochratoxin A (OTA) is considered to be nephrotoxic, carcinogenic, embryotoxic and teratogenic. In various foodstuffs and beverages including variety of cereals, beans, coffee, beer, wine, meat, cocoa, dried fruits, spices, nuts, milk, pig blood and kidney and other tissues of animal origin, OTA occurs. Although OTA in coffee was reported in the 1970s, it did not become a public health concern until the 1990s. Published evidence indicated that OTA was a genotoxic carcinogen, similar to aflatoxin. If true, the significance of any exposure to OTA increases the risk of kidney cancer (FAO, 2006).

Several factors affecting mycotoxin production include the fruit or vegetable type, geographical location, harvest treatments, post-harvest storage conditions and climate (Batista at el., 2009). It is estimated that 25% of the world's food crops are affected by mycotoxin producing fungi, which can lead to significant economic losses (FAO, 2001). For mycotoxigenic fungi and mycotoxin production, a favorable temperature and water activity level are crucial factors that support their growth or presence (Paterson and Lima, 2009).

Ochratoxin A (OTA) has been found in samples of raw, roasted, and soluble coffee from several countries. This indicates that fungi capable of producing OTA have infected the coffee beans at some stage of coffee production or processing. *Aspergillus ochraceus*, *A. carbonarius,* and *A. niger* are the primary fungal ochratoxigenic species that have been found and isolated from various soils and coffee farms (Palacios-Cabrera et al., 2007). In coffee contaminated by *Aspergillus* species, both ochratoxin A and to a lesser extent aflatoxin can occur in raw and roasted coffee beans (FAO, 2006).

3.3.2. Ochratoxin A production

Ochratoxin A production as a consequence of fungal growth can be influenced by intrinsic factors, such as moisture, pH, and the composition of the substrate, and extrinsic factors such as temperature and other implicit factors, such as the competitive endogenous flora of foods (Kapetanakou et al. 2008). Critical factors for fungal OTA production in coffee are environmental conditions, such as temperature, water activity (a_W), pH, nutrients, incubation time, and light. *Penicillium verrucosum, P. nordicum, A. carbonarius, A. niger and A. ochraceus* are some of the known fungal species that produce ochratoxin A *(*Suárez-Quiroz et al., 2004). After harvest and during drying and subsequent storage or transport, these species have been found contaminating raw coffee beans. Following the harvest stage during drying and subsequent storage or transport, these species are commonly found to contaminate raw materials and food commodities in processes. (Muñoz, 2011). Inappropriate drying of the green coffee beans and the rewetting of the green coffee beans are the causes of mold growth. Ochratoxin A (OTA) on partially dried, rewetted green coffee is likely produced by *Aspergillus ochraceus* (Batista at el., 2009).

In the south of Thailand, a small survey on nine farms was conducted in 1996 which revealed extremely high incidences of OTA in dried coffee cherries, and up to 1206 mg/kg OTA detected in the husks of one farm. Coffee cherries contain plenty of water at the beginning of drying step (59-63%) and available free sugars. Coupled with the ambient humid drying environment in the south of Thailand (26-27°C, 77-82% RH), coffee cherries are an ideal substrate for the development of molds. OTA contamination occurred within 5 days of drying, and often continued to increase until the end of 15 or 20 days of drying in most of the drying experiments (Bucheli and Taniwaki, 2002).

Mold growth risk increases during storage of fresh ripe and unripe coffee cherries before processing. Additionally, sun-dried, dry processed coffee beans skin (husks) may have high levels of ochratoxins (Viani, 2002). In Thailand under tropical conditions, robusta coffee was studied for three consecutive seasons for the formation of ochratoxin A. OTA formation in coffee cherries were found consistently after sun drying. Depending on cherry maturity OTA contaminates green coffee, with green cherries being the least, and overripe cherries the most susceptible. The most important source of OTA contamination are defects, and in particular the inclusion of husks. Whether cherries were spread on concrete floor, bamboo tables, or on the ground, OTA contamination occurred independently from the drying surface used (Bucheli et al., 2000).

3.3.3. Ochratoxin A control

If poor control procedures are employed, such as slow drying, the opportunities for OTA accumulation can increase postharvest. Similarly, if inadequate storage conditions are employed, OTA levels can increase, although they can be reduced during processing from sorting, analysis for OTA and segregation, and roasting. OTA-producing fungi require favorable conditions for a period of time to grow and produce the toxin.

OTA can be high in coffee husks and fortunately it is removed during processing. Paterson et al. (2014) reported that coffee beans obtained after falling on the soil and which had been floated as part of processing, were high in OTA and should be avoided. Rojas (2004) reported that drying coffee at a high relative humidity “RH” level of 75% corresponded to a moisture content in the bean of 15-16%. Relative humidity should be kept below 60% to delay or prevent fungal growth. A high RH level, in combination with temperature variations, can lead to the condensation of water which, in turn, contributes to the proliferation of fungi and insects (Rojas, 2004).

The drying process is crucial to delaying or preventing the development of *A. ochraceus* toxin in coffee. During the initial 3-5 days of drying, mold growth and OTA formation could happen due to the high water content in the coffee cherries. If performed incorrectly sun-drying of cherries can lead to OTA contamination. The water activity of coffee cherries should stay in the range of 0.97 to 0.80 for no more than four days. With the main factor being the time taken to get below a critical water activity (a_w) of 0.80. A prolonged time where the water activity is > 0.80 in any coffee processing step from cherry to roasting increases the risk of mold growth and OTA production (Paterson et al., 2014).

The presence of OTA in coffee beans has been vigorously evaluated with contamination levels varying significantly in Brazil. Coffee bean husk is a significant source of OTA, but cleaning and sanitizing methods for harvesting and processing equipment are effective in reducing OTA levels. Up to 90% of OTA levels can be reduced during the processing of coffee beans from green beans to roasting and soluble coffee. In one study, the pulping process step and the subsequent fermentation and drying steps of coffee beans significantly reduced the risk of OTA contamination. Wet processing was less susceptible to infection by *Aspergillus* spp. and OTA contamination. Due to removal of the fruit pulp, the growth of OTA-producing *A. carbonarius* strains, was eliminated (Batista at el., 2009; Viani, 2002).

3.4. Role of weather and climate change for coffee yield quality and safety

3.4.1. Weather conditions in coffee growing regions

A tropical upland climate is defined as a tropical climate (monthly mean temperature >18.0°C) occurring on a high plateau in a mountainous region. In tropical uplands, arabica coffee vegetates and fructifies very well, as in the Southeast area of Brazil. The environmental conditions in these locations, especially the photoperiodic variation and the rainfall distribution and air temperature usually affect their growth stages. This interferes in the crop phenology and consequently, in the coffee bean productivity and quality (Camargo, 2010).

In the state of Hawai'i, the seven regularly inhabited islands are home to over 1.4 million full-time residents as well as a large transient population of visitors. Over the next century anticipated climate change will likely present significant challenges for its inhabitants. Recurrent issues for Hawai'i are sea level rise and a warming ocean surface, with consequent effects on beach erosion and coral health (Zhang et al, 2016).

The European Coffee Federation (ECF) has conducted green coffee storage and transport trials in shipping containers, to evaluate the impact of environmental conditions on coffee processing. During the cold season, temperature fluctuations may occur which may lead to condensation, wetting of the top layer, propagation of mold, and OTA contamination, during overland transport to export harbor, and again on unloading at import ports in the consumer countries. Storing coffee in the hold of ships in closed, non-aerated containers was found to be the safest way of transporting coffee so that the risk of temperature fluctuations, moisture condensation, and subsequent spoilage during the ocean trip are reduced. The top layer must be protected in the container, as it is the most exposed to the risk of wetting and spoilage (Viani, 2002).

Kona is situated on the leeward slopes of the Mauna Loa and Hualalai volcanoes. The uplands of Kona are distinct from most other leeward areas in the archipelago, since the volcanoes create a localized weather system and a wet environment. Rainfall increases upslope from as little as 600 mm/year at the coast to as much as 2000 mm/year at ~600 m elevation, yet declining again at higher elevations (Lincoln and Ladefoged, 2014). Related to changes in weather conditions there are significant concerns in Hawai'i about the possible effects of changing rainfall and evapotranspiration on freshwater resources, as well as, impacts of atmospheric and surface warming on plant and wildlife habitats (Zhang et al, 2016).

3.4.2. Climate change potential in coffee growing regions

The United Nations (UN) Convention on Climate Change defines climate change as ‘‘a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is, in addition to natural climate variability, observed over comparable time periods" (Miraglia et al., 2009). Due to diminishing amounts of snow and ice and rising average sea level, the warming of world climates is undeniable and has been associated with trends such as increasing atmospheric and oceanic temperatures (IPCC, 2013). Future predictions of several emissions scenarios suggest increased intensity of extreme weather events along with rising temperatures of these trends over the twenty-first century. Through both direct and indirect routes these climatic changes are expected to result in a global increase in the risk of food and waterborne diseases (Hellberg and Chu, 2016). Climate changes including temperature increase, variation in precipitation, drought, and atmospheric carbon dioxide (CO_2) have been identified as relevant for agriculture and food safety (Miraglia et al., 2009).

In Hawai'i climate change issue of special concern, and it impacts on biodiversity with implications beyond Hawai'i's own population. Hawai'i stands out globally as a ''hot spot'' of terrestrial biodiversity despite its small land area. Naturally found only in Hawai'i there are more than 1000 species of flora and 100 species of bird's endemic (Zhang et al, 2016). The Hawaiian Islands rely on local water resources, which may be very sensitive to climate change. An increased trend, as a result of warming climate, shows evidence of climate change in Hawai'i including historical observations of temperatures and changing sea-level data. Researchers have reported that extreme climate change may cause frequent incidents of flooding and drought, shortage of water supply, landslides, soil erosion, and damage to existing infrastructures globally. In Hawai'i some of these problems have already been documented (Leta et al, 2016).

For the Hawaiian Islands, recent studies on climate change have shown that rainfall is expected to decrease during the nominal wet season (November to April) but marginally increase during the dry season (May to October). Hawai'i is expected to face an overall reduction in annual rainfall leading to a decline in sustainability of groundwater recharge given that approximately 70% of the annual rainfall happens during the wet season. In the Hawaiian Islands it is anticipated that air temperature to increase in the future which will drives evapotranspiration of components from the hydrologic cycle (Leta et al, 2016).

Coffee crops are particularly sensitive to climatic conditions. Slight increases in temperature can produce devastating heat waves as it is grown in tropical regions. Disrupted by climate change, coffee quality is a result of a delicate mix of rain, humidity, and day and nighttime temperatures (Rising et al, 2016). The importance of climate change on coffee production and mycotoxin contamination require urgent consideration. Because of the hot humid conditions encountered, which are optimal for these mycotoxigenic fungal growth, coffee commodities are susceptible to the fungi (Paterson et al., 2014, Tirado et al., 2010). In the atmosphere, the increase of greenhouse gas emissions (GHG) is causing wide changes in atmospheric events, influencing climate change and variability with critical impacts on vegetation. Plant metabolism is known to be disturbed by high temperatures. As a usual practice in Brazil, coffee cultivation is in the open, which increases the leaf exposure to high irradiance and the absorption of more energy by photosynthesis. On sunny days in unshaded crops temperatures can reach 40°C or above, especially if stomata are closed. And, such conditions may cause an energy overcharge and lead to an overheating of leaves (Camargo, 2010).

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Chapter III

Evaluating Drying Rate of Kona Hawai'i Coffee Beans by Measuring Water Activity and Moisture Content

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Keywords: moisture, water activity, coffee, drying, Hawai'i

ABSTRACT

Coffee grown in the United States represents less than 1% of the world's supply, and most of it comes from the state of Hawai'i. Kona coffee, grown on the western side of the island of Hawai'i, is the most recognized and the highest value Hawaiian coffee. The majority of this coffee is sun-dried after harvest and washing. Sun-dried coffee should reach 12-13% moisture within 4 to 6 days. Sun-drying will reduce both the moisture content and the water activity (a_w). Reducing a_w below 0.75, especially in the first week of drying, is important for preventing or limiting mold growth. The purpose of this study was to compare drying rates of Kona coffee bean batches using a_w and moisture content % measurements. Ten farms in the Kona coffee region of Hawai'i were visited in the fall of 2017 to record daily measurements of coffee moisture level and water activity from three samples from each of 30 batches during drying. Most sun-dried batches reached ~13% moisture in 6 to 10 days. Initial moisture content (31.6 ± 4.3%), and drying yard characteristics varied greatly among farms. Coffee batches reached 0.75 a_w within 6 days on average, but some batches required more than 10 days. Moisture content and a_w measurements were weakly correlated and water activity level increased at times during drying for some batches. Drying coffee parchments within 7 days post-harvest can inhibit growth of molds that may impact quality or molds that could produce mycotoxin. Controlling the drying conditions, including monitoring moisture content and/or water activity, can accelerate or improve the consistency of batch drying time.

1. Introduction

The Arabica variety “Kona Typica” is grown almost exclusively in Kona Hawai’i (Bittenbender and Smith, 2008). Coffee is an important part of the agriculture industry on the Hawaiian Islands. Due to the natural resources of the islands’ tropical environment, and rich volcanic soil, Hawai’i is an ideal location to grow coffee. On the Hawaiian Islands coffee is not only grown on the Big Island of Hawai’i, primarily in the Kona region, but also on Oahu, Molokai, Maui, and Kauai. However, Kona coffee is the most recognized and the highest value per acre coffee on the islands.

The Kona region on Hawai’i produces ~1.6 million kg of green coffee with a value of $35-42 million annually (Greco and Wright, 2013). This includes more than 700 farms and approximately 3000 acres of coffee production valued at ~ $ 10,000- 1,000,000 per year (Woodill et al, 2014). The majority of farms are less than two acres and many take their harvested coffee cherries to a processor for washing, drying and storage. The region is approximately 2 miles in width and 20 miles in length and includes more than 700 farms ranging in elevation from 240 to 670 meter. This region defines Hawaiian coffee for most people. Kona coffee is internationally known and commands some of the highest prices in the world. (Bittenbender and Smith, 2008). Coffee grown in the United States represents less than 1% of the world’s supply and most of it comes from the state of Hawai’i (Woodill et al, 2014).

1.1. Processing of coffee cherries:

In Kona Hawai’i varies types of coffee processing are used including wet, dry and semi-wet (some time referred to semi-dry) (van der Stegen, 2003; Brando, 2004).

The wet processing method is also used throughout Kona. This process includes pulping (Figure 1), fermentation (Figure 2) of the mucilaginous layer on top of the parchment skin, rinsing and then drying the coffee parchment (Bittenbender and Smith, 2008; Brando, 2004; FAO, 2006). It is used for all Arabica beans other than those mentioned above and only for a small percentage of Robusta, although the trend to wet process Robusta is increasing (Brando, 2004). The coffee beans will be further dried either in the sun (Figure 3a, 3b, 3c) or by mechanical (Figure 4) (artificial) dryers (Bittenbender and Smith, 2008). Coffee beans can be placed in a mechanical dryer where hot air helps dry the beans in a rotating drum. Some processors use a combination of both sun-drying and mechanical drying. For example, the coffee beans can be sun-dried for 24 - 48 hours and then finished in the mechanical dryer. Depending on the type of dryer (stationary or rotary) the average heat temperature is 120-140°F (Bittenbender and Smith, 2008).

Another method used to process coffee is called semi-wet (pulped natural). In the dry process, the mucilage is not removed after pulping, and parchment and mucilage are dried together (Figure 5) (Brando, 2004).

In the dry or natural process, the intact fruit is directly laid out to dry in the sun (Figure 6), and afterwards the skin will be removed during the hulling step. The dry method is used in Kona Hawai'i by small farms to process and dry fresh coffee cherries. After the drying, the coffee cherries are milled to remove the dehydrated pulp, parchment skin and silver skin in one operation (Bittenbender and Smith, 2008; Brando, 2004; FAO, 2006).

The dry process method is used for more than 80% of Brazilian, Ethiopian and

Yemen arabica, and for almost all robusta coffees in the world (Brando, 2004).

1.2. Post-harvesting handling and storage:

Post-harvest processing of coffee includes a drying procedure to reduce the water content of the beans. Even though producers can consistently dry their coffee to 9-12% final moisture, the drying rate and drying time for batches of coffee beans can vary greatly (Paterson et al., 2014). The whole ripe fresh cherry is about 65% water content. Lowering the water content of fresh coffee cherries to about 11-12% enables preservation during long-term storage (Brando, 2004). Controlled and consistent drying procedures for coffee beans may improve coffee quality and discourage mold and mycotoxin formation. The price of coffee beans is influenced by the quality of the beans achieved after processing (Paterson et al., 2014). The ideal moisture content for both arabica and robusta coffee is 12% and 13%, respectively (Rojas, 2004). The estimated time needed to complete the coffee parchment drying using this type of method is around 4-6 days on a sunny day, but may take longer with cloudy days.

After drying, the whole hull dried pulp and parchment is then removed mechanically to obtain green coffee (Brando, 2004). On some farms, coffee is processed only to the parchment-coffee stage. Then, these beans may be sold to a larger plantation or to a miller who mills (hulls) the coffee. Although most coffee is sold as green coffee, large farms frequently do all their processing, including roasting (Bittenbender and Smith, 2008).

During the post-harvest handling, processing and storage, a variety of fungi may be able to infect and grow in coffee due to their ability to tolerate low water activity

(Olagunju et al, 2018). The presence of fungi in on coffee beans, not only affects the sensorial quality of the coffee beverage, but may present a health risk attributed to the production of mycotoxins by some of these fungal genera (Geremew et al, 2016). The most important factors governing fungal growth and mycotoxin production are the amount of nutrients available, the ambient temperature, water activity, oxygen, and storage time (Kokkonen et al, 2005; Geremew et al, 2016). The delays between harvesting the coffee cherries and onset of processing increases the risk of ochratoxigenic mold growth and ochratoxin A contamination in coffee (Velmourougane et al, 2011).

The most frequently detected fungi at the different stages of coffee processing from harvest to storage belong to the genera *Fusarium*, *Penicillium*, and *Aspergillus* (Urbano et al, 2001). Some of these molds can produce mycotoxins, which are heat-stable and can be carried over into processed foods. Ochratoxin A is the primary mycotoxin that has been detected in contaminated green coffee beans and can be present during various stages of processing (Velmourougane et al, 2011). Water activity level and temperature have been shown to strongly affect ochratoxin A production by *Aspergillus ochraceus* and *Aspergillus carbonarius* (Kapetanakou et al. 2008).

Preventive measures to control mold growth in coffee can be achieved through appropriate processing, storage and handling of products and their process environment (Olagunju et al, 2018). Water activity (a_w) and moisture content of the beans, along with storage time, temperature and relative humidity can greatly influence fungal growth and mycotoxin development, and therefore should be controlled or monitored, if possible. Reducing the water activity of coffee beans below 0.75, especially in the first week of drying, is important for preventing or reducing mycotoxigenic fungi from forming toxins (Paterson et al., 2014). In this study, the daily water activity of sun-dried Kona coffee batches is compared with daily moisture content to learn if both water activity of 0.75 and ~13% moisture can be achieved in one week.

2. Materials and methods

2.1 Farm selection:

Coffee farms contacted for this study are located on the western side of the island of Hawai'i in the Kona coffee belt. The majority of farms in the Kona region are less than two acres and many take their harvested coffee cherries to a processor for washing, drying and storage. Forty-eight Kona coffee farms were contacted by e-mail. The farms were selected from among those who had readily available contact information via internet websites or processor recommendations. Grower contact information was generally available through the Hawaii Coffee Association website (www.hawaiicoffeeassoc.org) and through the Kona Coffee Farmers Association (KFCA) website contact list (www.konacoffeefarmers.org), and from websites that promoted visitor tours of coffee farms. The selection of these coffee farms was further enabled through one-on-one contacts made during a visit to Kona coffee farms during October 2016, and during the Hawaii Coffee Association (HCA) conference in July 2017 on the island of Maui.

2.2 Coffee sample selection:

Samples from 30 coffee bean batches (1 to 5/farm) were collected from 10 farms in the Kona coffee belt area. These were all batches that initially started drying during November 13 to December 01 2017. Moreover, 25 of these batches (from 8 farms) were sun-dried exclusively and the remaining batches were partially dried mechanically with propane gas heat. Due to differences in harvest dates and harvest volume between farms, all farms did not start drying new coffee batches on the same date or start drying a new coffee batch every day during the sample period for this study. Additionally, some farms began to dry more than one coffee batch on the same day.

For farms that exclusively sun-dried coffee, three coffee bean samples (~40 g each) from each batches were collected daily (every 24±2h) Samples were collected from an area approximately one meter from the edge of the drying yard and the distance between the samples was ~ 2 meters. Batches were sampled on the first full day of drying (day 1) and daily thereafter until they reached 9-13% moisture content and/or were moved to a storage area. For mechanically dried coffee, three coffee bean samples (~40 g each) from each batches were collected on the first day of drying and at least once per day until they reached 9-13% moisture and/or were moved to a storage area. Samples were collected from the dryer top hopper.

2.3. Water activity measurement:

Water activity was measured with a HygroPalm HP23-AW-A Portable Analyzer with 40 mm (depth) sample cups (Rototronic Instrument Corp, Hauppauge NY). This instrument can measure sample water activity (0 to 1), relative humidity (0 to 100%) and temperature (-10 to 60°C). The day when the first reading is taken was considered day one. Each batch was sampled at least once per day. After water activity measurements, all samples were returned to continue drying. Measurements from three samples (~5 g each) were averaged to determine a drying rate over time.

2.4. Moisture content measurement:

The moisture content of coffee samples was measured using a Agratronix, 08150 Portable Coffee Moisture Tester (Best Harvest, Largo, FL). The day of the first measurement was considered day 1. Each batch was sampled at least once per day. After moisture content measurements, all samples were returned to continue drying. Measurements from three samples (~40 g each) were averaged to determine a drying rate over time. A total of 676 measurements each of moisture content and water activity were collected.

2.5 Statistical analysis

Descriptive statistics (means and standard deviations) were computed with Microsoft® Excel® 2016. The JMP® Pro Version 14.0.0 statistical discovery software (SAS Institute Inc., Cary, NC, USA) was used for one-way analysis of variance (ANOVA) to determine significant differences between means for each variable tested at a statistical significance of $\alpha = 0.05$. Where the ANOVA indicated a difference between means, Tukey-Kramer's multiple range test was used to assess significant differences between means.

3. Results

Ten farms agreed to participate and allow data collection at their location. Collectively, these farms performed a variety of processing operations (wet, semi-wet or dry) (Figure 1), (Figure 5), (Figure 6) and drying methods (sun drying, mechanical drying or sun drying followed by mechanical drying) (Figure 3a, 3b, 3c), (Figure 4). The location of these farms are noted on the map in (Figure 7). The 10 farms selected for this project represent ~40% of the coffee cherry production for the Kona region on Hawai'i. The annual sales from these 10 farms were ~$ 11-13 million in 2017. Small farms (<2 acres) were excluded since these farms may harvest irregularly and they often sell their coffee cherries to other commercial farmers more often than process their own coffee. The farms that were selected all have continuous production in the fall and process coffee from their own farms.

Among these ten farms, eight used sun drying exclusively (seven used a washed process, one used a semi-washed process) and one farm used a dry process (natural process) and another farm used wet process both farms used mechanical heated drying. These farms were visited during November and December 2017 to record measurements of moisture content and water activity of coffee bean batches and to record observations on the post-harvest handling and storage of coffee beans and the environmental conditions that may affect the quality and microbial contamination of drying coffee.

The initial and final moisture content and water activity for all sampled sun-dried coffee batches are listed in Table 1. Measurements from batch W (farm 7) are not included since access to this batch ended prematurely (after day 3). The initial moisture content of sun-dried batches ranged from 24.7 to 38.1% with a mean of 31.6 ± 4.3% (Table 1). The initial water activity of sun-dried batches ranged from 0.75 to 0.99 with a mean of 0.90 ± 0.07(Table 1). Some coffee batches were sun-dried in 6 days to a target moisture level (9-13%), but some batches required at least 12 days to reach this moisture level. For batch G and H, the target moisture and water activity level was not attained by the end of the study sampling period.

Figures 8, 9 and 10 display examples of the change of daily moisture content and water activity over time for three coffee batches. In figure 8 batch A shows an example were the target water activity and moisture level achieved in less than seven days. In figure 9 batch D shows an example were the target water activity and moisture level achieved in seven days with fluctuating water activity. In figure 10 batch F shows an example were the target water activity and moisture level achieved in more than seven days with fluctuating water activity.

From each figure, a trendline was produced that provided a daily rate of moisture content change, and daily rate for change in water activity. These rates and other calculations based on the trendlines are shown in Table 2 for all sun-dried batches. From batch A, farm 1 (Figure 8) the coffee beans had a low initial water activity (0.800) on the first day of sampling compared to other batches in this study (~0.90). Water activity level steadily declined during the drying process and achieved the target a_w < 0.75 in the first two days of the drying process. Moisture content percent also showed a stable and a steady decrease (2-4% per day) during the drying process. For this batch, the required moisture content (12-13%) was achieved in six days.

The drying progress of coffee for batch D (farm 2) is shown in Figure 9. For this batch, water activity measurements increased twice during the drying period. The a_w of this batch may not have stayed below 0.75 until 4 to 5 days of drying, yet the trendline indicates that this water activity level could be reached in 3.3 days (Table 2). Coffee batches from farm 3 were generally the slowest drying coffee in this study, even though their initial water activity and moisture content % was close to the average for all batches. In Figure 10, batch "F" beans from this farm required at least 17 days to reach a moisture level of 13%. And, the moisture content % remained near 18% from day 6 to 13. Water activity of this batch dropped to 0.75 or lower on day 9, 12 and 14 with an increase between those days.

The drying times required to reach $a_w < 0.75$ ranged from 2 to 13 days with an average of 6.0 days for the 25 sun-dried coffee batches (Table 2). And, the time estimated for bean batches to reach 13% moisture ranged from 6 to 32 days with an average of 10.5 days. Additionally in Table 2, the daily drying rates of each batch are expressed as mean Δmoisture content %/ day and mean Δa_w / day. The mean Δ moisture content per day for all sun-dried batches was 2.22 $\pm$ 0.71 % (decrease) and the mean Δ a_w / day was 0.046 $\pm$ 0.023 (decrease). Drying rates and drying time of coffee batches varied between farms and between batches in the same farm. For example, for batches A, B and C from Farm 1, the estimated time to reach $a_w < 0.75$ ranged from 1.7 to 4.3 days, even though beans were dried under similar conditions using similar drying technique.

In Table 3, sun-dried batches are grouped for each farm. Coffee batches (2) from farm 2 had the fastest drying rates for moisture and water activity, while coffee batches (3) from farm 3 had the lowest drying rates. The daily change in mean moisture content was 2.9% and 0.8% for farms 2 and 3, respectively. The Δ mean moisture content / day (0.8%/day) was significantly different (lower) for batches from farm 3 compared to other sun-dried batches. While there was not a statistically significant difference between mean Δ a_w / day among farms, the estimated time to reach 0.75 a_w was significantly ($p<0.05$) longer for farm 3 batches (mean of 14.0 days).

Four coffee batches (AA, BB, CC, DD) from two farms (9 and 10) were primarily dried using a heated mechanical dryer. For this report, the measurements on these batches is generally not compared to the fully sun-dried batches. These four batches could achieve a 13% final moisture content in four days or less and were estimated to be dried to 0.75 water activity in 1 – 2 days (Table 4). The two batches from Farm 9 were dried with their skin on (dry or natural process) and needed approximately twice as long to dry as the two batches from Farm 10 which used a wet process (four vs. two days).

In Figure 11, the mean moisture content % for all sun-dried batches is plotted against the mean a_w for all sampling days. The r^2 value of 0.73 from the regression line indicates that these drying rates (change in water activity or moisture content) have a weak correlation. Therefore, daily changes in mean moisture content are weakly correlated to daily changes in water activity for the 25 sun-dried batches. Note that a comparison of drying rates is presented since there is a wide variation in initial water activity and moisture measurements along with a wide variation in total days of drying and number of batches sampled per farm.

4. Discussion

Monitoring the drying process of coffee after the initial washing step can be critical for ensuring the quality of parchment prior to storage and prevention of mold growth and mycotoxin formation. Moisture content (%) is the common measurement to determine the coffee bean dryness for both sun-dried and mechanically-dried beans to ensure that the coffee beans are ready to be transferred to storage. Producers are required to dry coffee beans to between 9-12% as required by the Hawaii Department of Agriculture (2014). The impact of a prolonged drying period could impact the quality of the coffee beans. Beans that take more than 4 to 7 days to reach 13% moisture are more susceptible to mold and insect damage (Paterson et al., 2014; Rojas, 2004). Some growers who participated in this study indicated that the maximum time needed to dry coffee to their target moisture level was "24 days". The target moisture content level can be achieved in less than 48 hours when using a mechanical dryer depending on the coffee bean volume and initial moisture content.

A controlled drying procedure that prevents a delay or fluctuation in water activity (a_w) level can increase the chance of reducing $a_w < 0.75$ within one week. In this study, the use of a_w as a moisture control measurement showed instability and variation over the drying time for several batches. The variability in water activity over time could be related to weather conditions, or to drying practices such as, and not limited to, batch thickness, batch volume, raking frequency, water pickup during a washing step, and use of a pre-dry step (centrifuge device or allowing excess water to drain). Furthermore, variability in drying rates (water activity or moisture content change) and drying time could be influenced by drying yard facility characteristics such as floor surface material, protection from rain, direct sun exposure, airflow or use of a fan. The stability of a_w over time can be greatly affected by small changes on one of the practices or facility characteristics above.

Even though water activity is not typically measured by Hawaiian coffee producers, some food processors worldwide may value measurement of water activity during a drying step. For example, Copetti et al. (2010) reported on the use of water activity measurement for drying cocoa beans in Brazil. They report that after cocoa beans are fermented, water activity remains high, then beans are transferred to drying decks to gradually reduce the a_w. The beans were transferred to storage after the a_w level was sufficiently low.

The number of days needed to sun-dry coffee beans in the Kona coffee belt is based on moisture content measurements. Once the target moisture content (9-13%) is achieved the coffee beans then will be transferred to bags and stored in a dedicated location. Throughout the drying process the coffee beans may be raked and moisture content may be monitored more than once per day to ensure that they are drying properly.

Sun-dried coffee beans in this study required an estimated average of 6 days to reach a_w <0.75. Some batches may have needed 10 or more days before water activity was consistently below 0.75. Beans with an extended drying time are more prone to mold contamination and mold growth. Certain drying practices may contribute to an increase or decrease in the rate of change for a_w and/or moisture content.

The coffee beans that were mechanically dried showed a significant reduction in a_w (to <0.75) and moisture content (to 9-13%) to a safe level in just 48 ± 10 hours depending on the batch size and initial moisture content prior to drying. This rapid drying will significantly prevent or delay mold growth and possible mycotoxin development. However, differing quality characteristics between sun dried and mechanical dried coffee beans, and the higher energy costs of mechanical drying imply that the sun-dried process will continue to be employed by many coffee processors on Hawai'i, either exclusively or in combination with mechanical drying.

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Figure 1: Pulping machine used to remove the coffee cheery skin prior wet processing the coffee beans

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Figure 3b: Sun-drying coffee parchment

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Figure 4: Mechanical dryer used for drying coffee parchment

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Figure 6: Dry “natural” coffee beans

Figure 7: Locations of 10 Kona Coffee farms on the island of Hawai'i identified for sampling. Northernmost and southernmost locations separated by ~20 miles.

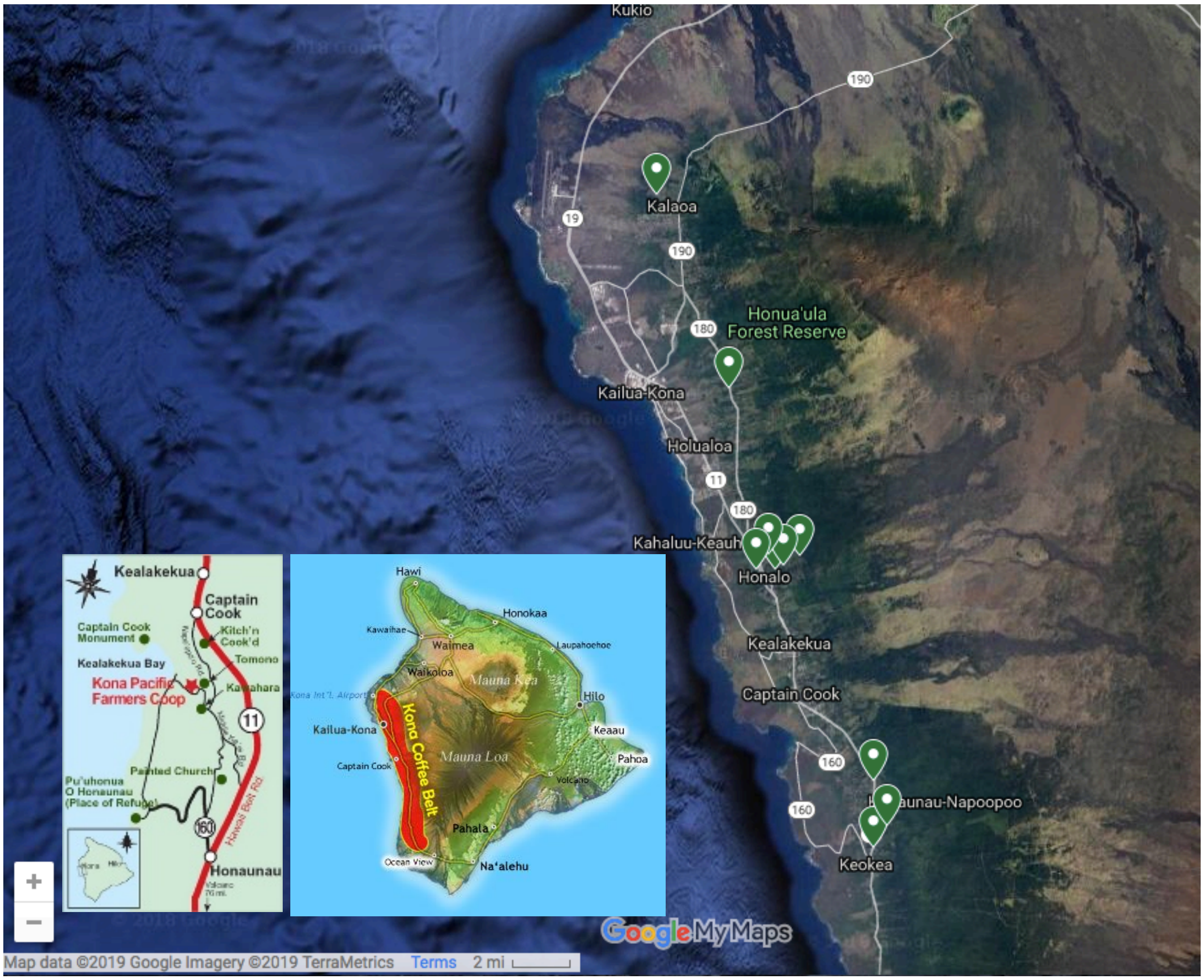


Figure 8: Farm 1 batch A, wet process, moisture content % and water activity of sun-dried coffee beans on a wood stand with wire mesh

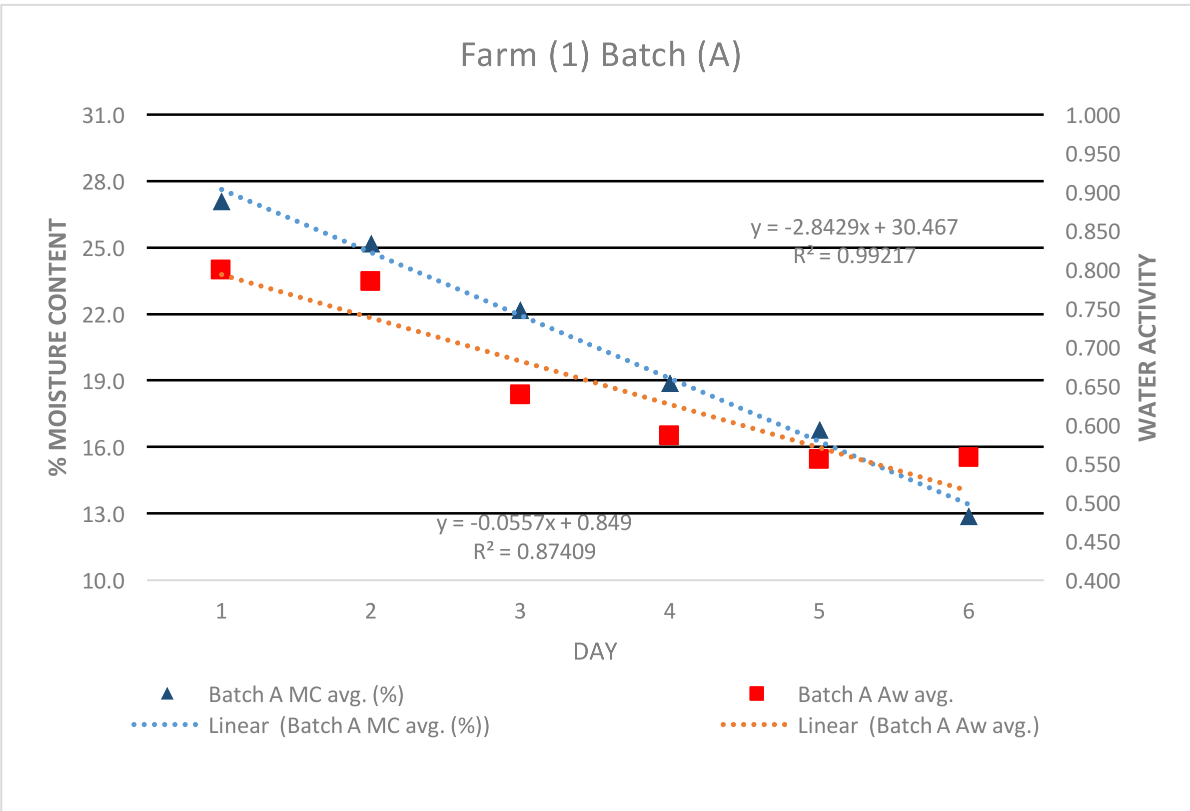


Figure 9: Farm 2 batch D, wet process, moisture content % and water activity of sun dried coffee beans on a concrete floor surface with a ceiling fan and open side walls

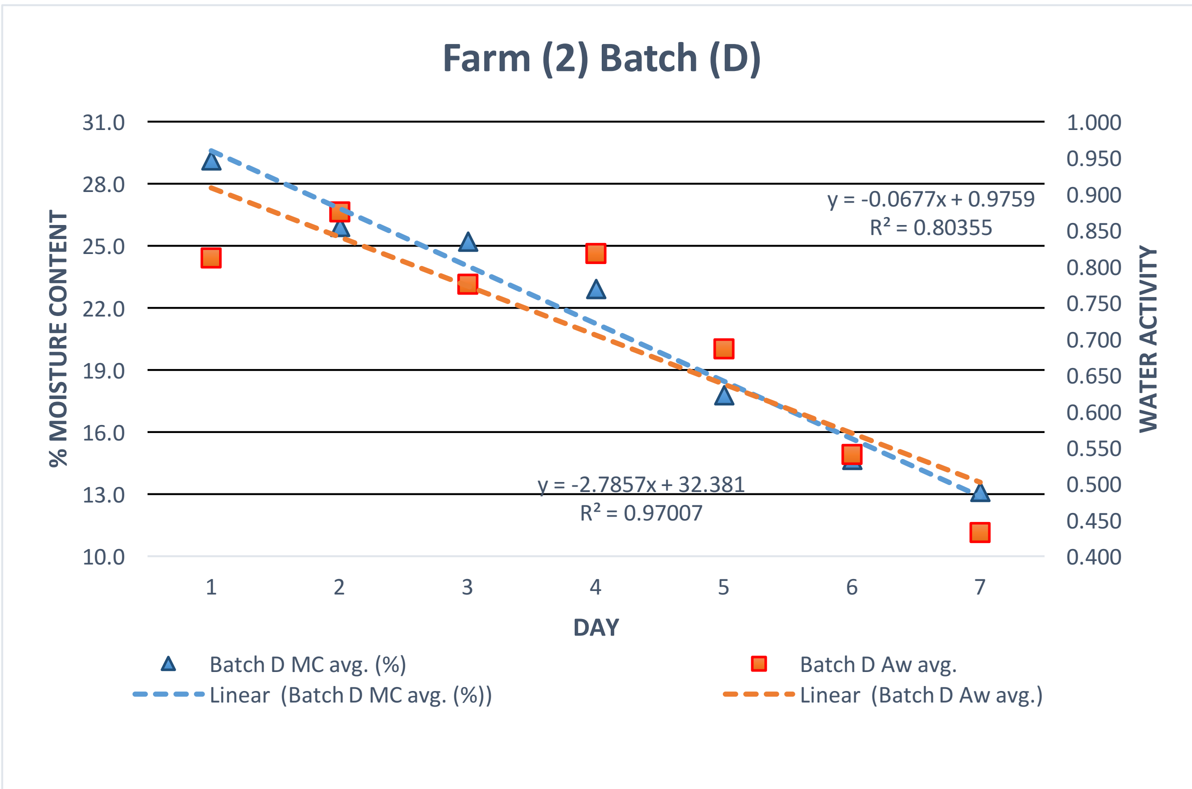


Figure 10: Farm 3 batch F, wet process, moisture content % and water activity of sun dried coffee beans on a concrete floor surface with an open side walls

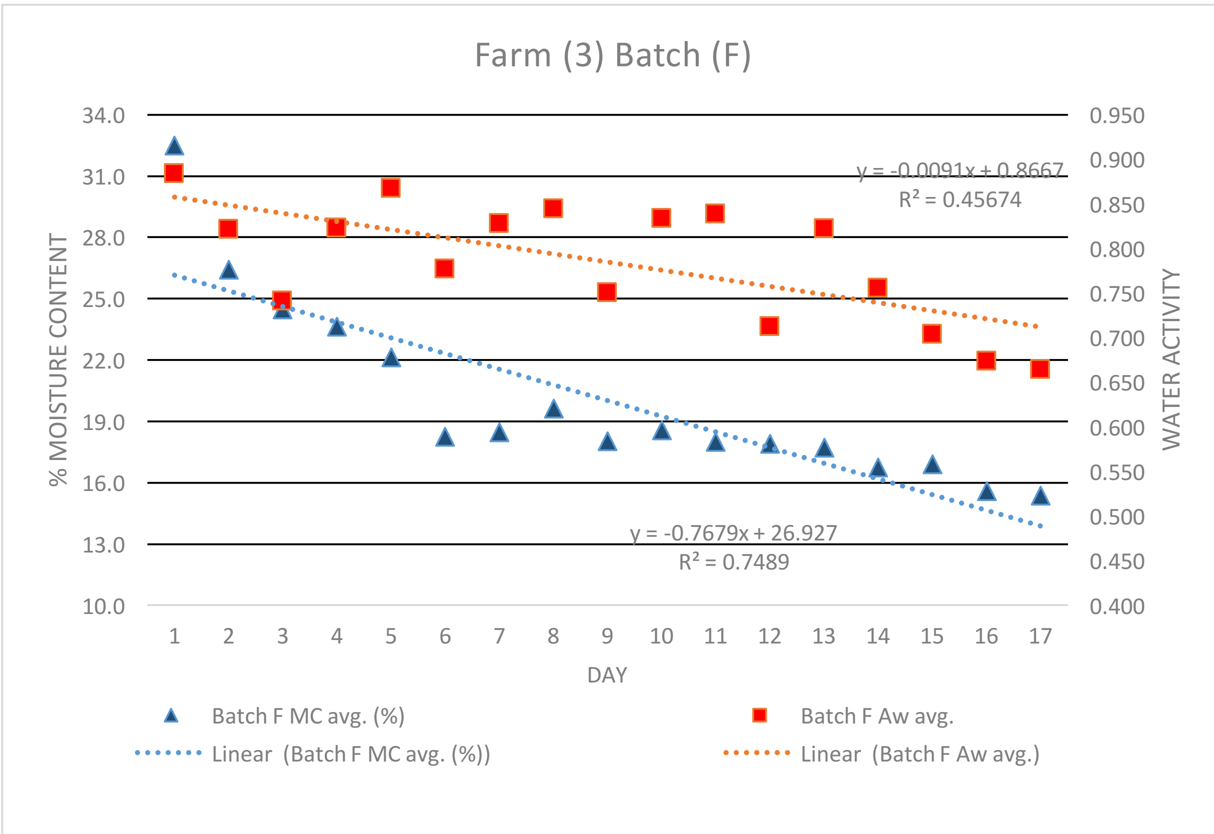
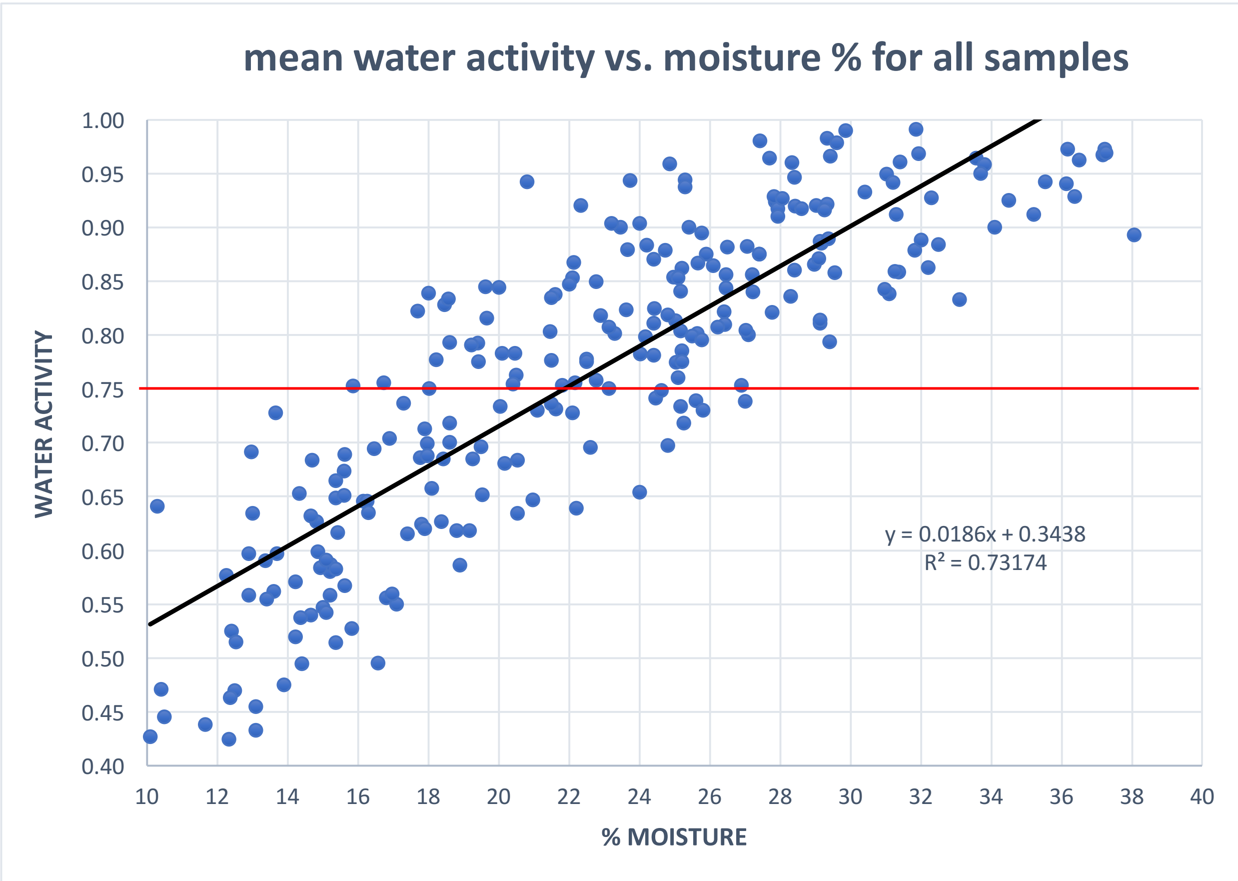


Figure 11: Relationship of measurement of moisture content % to water activity



Tables

Table 1: Initial and final water activity and moisture content

Farm	Batch	Drying Days	Process type *	Drying type **	Initial Moisture		Final Moisture content (%)		Initial Water activity		Final Water activity	
					mean	± SD	mean	± SD	mean	± SD	mean	± SD
1	A	6	W	S	27.1		12.4		0.800		0.475	
1	B	8	W	S	27.4		12.9		0.875		0.558	
1	C	12	W	S	29.6	0.2	13.9		0.858	0.025	0.475	
2	D	7	W	S	29.1	0.3	13.4	1.9	0.811	0.036	0.433	0.044
2	E	7	W	S	35.2	0.8	15.0	1.8	0.912	0.028	0.547	0.055
3	F	17	W	S	32.5	0.9	15.4	2.7	0.884	0.016	0.664	0.016
3	G	13	W	S	29.2	1.1	20.5	0.8	0.885	0.032	0.763	0.029
3	H	10	W	S	35.5	0.7	24.8	1.7	0.942	0.027	0.818	0.031
4	I	10	W	S	36.4	0.2	12.9	0.7	0.928	0.044	0.597	0.055
4	J	10	W	S	38.1	0.8	14.2	1.1	0.893	0.036	0.520	0.056
4	K	10	W	S	36.5	0.8	13.4	1.1	0.962	0.015	0.554	0.044
4	L	10	W	S	37.2	0.9	14.4	1.1	0.972	0.002	0.538	0.043
4	M	10	W	S	36.2	1.2	12.5	0.8	0.973	0.003	0.470	0.020
5	N	9	W	S	29.3	0.9	10.1	1.7	0.983	0.014	0.470	0.020
5	O	8	W	S	31.9	1.7	12.5	1.7	0.968	0.015	0.515	0.039
5	P	8	W	S	29.6	0.8	14.8	3.2	0.978	0.003	0.626	0.021
5	Q	10	W	S	37.2	1.3	15.4	0.7	0.967	0.007	0.648	0.023
5	R	10	W	S	37.3	1.3	18.0	1.2	0.969	0.001	0.699	0.039
6	S	7	W	S	27.4	2.2	12.3	1.5	0.980	0.004	0.425	0.054
6	T	6	W	S	28.3	0.8	12.3	2.0	0.836	0.021	0.576	0.063
6	U	8	W	S	29.1	2.2	10.3	0.8	0.814	0.026	0.641	0.023
6	V	7	W	S	24.7	0.8	14.7	1.1	0.878	0.019	0.683	0.019
7	X	10	W	S	31.9	4.6	15.6	3.8	0.991	0.001	0.567	0.117
8	Y	6	SW	S	26.9	1.6	12.4	0.3	0.753	0.005	0.463	0.029
8	Z	9	SW	S	31.2	1.0	13.0	2.0	0.941	0.035	0.634	0.056
			mean initial MC %:		**31.79**	**± 4.3**	**mean initial a_w :**		**0.91**	**± 0.07**		

n=3 for all means expect for batch A, B.

Code Definition

*W: Wet or Wash: Coffee beans are washed and soaked in water for 12 to 24 hours prior to processing them.

*SM: Semi Wash: Using a demucilager to reduce the water content of the coffee prior to drying them.

**S: Sun drying: A traditional method to dry the coffee by only using the sun as a source of heat.

Table 2: Drying rates of individual sun dried coffee bean batches

Farm	Batches code	Processing type *	Δ Mean Moisture Content (%/day)	Mean Δ Aw / day	Mean Days needed to reach 0.75 Aw	Days needed to reach 13% MC	Moisture content when Aw = 0.75
6	T	W	3.46	0.067	3.1	5.6	18.6
8	Y	S/W	3.09	0.077	2.3	6.1	19.7
2	E	W	3.05	0.064	4.3	7.5	24.4
1	A	W	2.84	0.056	1.7	6.1	25.6
2	D	W	2.78	0.068	3.3	6.9	23.2
5	O	W	2.71	0.070	5.1	7.9	23.5
6	U	W	2.65	0.027	3.5	6.4	20.1
4	I	W	2.59	0.041	4.9	8.9	23.7
4	J	W	2.54	0.037	5.7	9.6	27.5
1	B	W	2.52	0.060	2.1	6.8	20.2
6	S	W	2.52	0.094	3.3	6.2	20.6
4	L	W	2.47	0.042	6.8	10.4	28.8
4	M	W	2.41	0.048	5.4	9.9	27.2
4	K	W	2.35	0.040	7.9	10.7	28.8
5	P	W	2.26	0.063	4.5	8.3	22.8
8	Z	S/W	2.16	0.043	4.9	8.7	21.1
5	N	W	2.08	0.072	4.9	7.7	18.9
5	Q	W	1.98	0.025	10.6	11.8	28.4
6	V	W	1.86	0.023	4.8	8.6	21.1
5	R	W	1.77	0.027	9.2	13.6	30.0
7	X	W	1.75	0.049	6.5	12.7	23.2
1	C	W	1.40	0.023	4.3	12.3	24.7
3	H	W	1.09	0.013	13.4	20.0	30.9
3	F	W	0.77	0.009	12.7	18.3	17.2
3	G	W	0.52	0.011	15.8	31.9	27.4
		Avg.	**2.22**	**0.046**	**6.0**	**10.5**	**23.9**
		S.D.	**0.71**	**0.023**	**3.7**	**5.7**	**3.9**

*W: Wet or Wash: Coffee beans are washed and soaked in water for 12 to 24 hours prior to processing them.

*S/W: Semi Wash: Using a demucilager to reduce the water content of the coffee prior to drying them.

Table 3: Drying rates of sun dried coffee beans by farm

Farm	# of batches	Processing type *	Drying days range	Δ Mean Moisture Content (%/day)	Mean Δ Aw / day	Mean Days needed to reach 0.75 Aw	Days needed to reach 13% MC	Moisture content when Aw = 0.75
1	3	W	6,12	2.3 [A]	0.046 [A]	2.7 [A]	8.4	23.5
2	2	W	7	2.9 [A]	0.066 [A]	3.8 [A]	7.2	23.8
3	3	W	9,17	0.8 [B]	0.011 [A]	14.0 [B]	23.4	25.2
4	5	W	8,9	2.5 [A]	0.042 [A]	6.1 [A]	9.9	27.2
5	5	W	7,9	2.2 [A]	0.051 [A]	6.9 [A]	9.9	24.7
6	4	W	5,7	2.6 [A]	0.053 [A]	3.7 [A]	6.7	20.1
7	1	W	10	1.8 [AB]	0.049 [A]	6.5 [A]	12.7	23.2
8	2	S-W	6,9	2.6 [A]	0.060 [A]	3.6 [A]	7.4	20.4
			Avg.	**2.2**	**0.047**	**5.9**	**10.7**	**23.5**
			S.D.	**0.7**	**0.016**	**3.6**	**5.5**	**2.4**

*W: Wet or Wash: Coffee beans are washed and soaked in water for 12 to 24 hours prior to processing them.

*S-W: Semi Wash: Using a demucilager to reduce the water content of the coffee prior to drying them.

Means within a column followed by the same uppercase letter are not significantly different (P< 0.05) from each other.

Table 4: Drying rates of mechanically dried coffee bean batches

Farm	Batch code	Processing type *	Drying type **	Drying days range	Δ Mean Moisture Content (%/ day	Mean Δ Aw / day	Mean days needed to reach 0.75 Aw	Days needed to reach 13% MC	Moisture content when Aw = 0.75
9	AA	D	M	4	3.61	0.082	0.76	3.3	22.5
9	BB	D	M	4	6.7	0.128	2.23	4.1	25.4
10	CC	W	M	2	17.9	0.302	1.60	2.1	23.6
10	DD	W	M	1.5	29.8	0.640	1.20	1.5	22.2
				Avg.	14.5	0.288	1.45	2.7	23.4
				S.D.	11.9	0.253	0.62	1.2	1.4

*D: Dry or Natural: Coffee fruit is dried with skin on them.

*W: Wet or Wash: Coffee beans are washed and soaked in water for 12 to 24 hours prior to processing them.

**M: Mechanical drying: propane or diesel fuel.

Chapter IV

Evaluating factors affecting the drying time of sun-dried Kona coffee

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Keywords: moisture, water activity, coffee, drying, Hawai’i, temperature, humidity

ABSTRACT

Kona coffee, grown on the western side of the island of Hawai'i, is the most recognized and the highest value Hawaiian coffee. The majority of this coffee is sun-dried after harvest and washing. Sun-dried coffee should reach 12-13% moisture within 4 to 6 days. And, reducing water activity (a_w) below 0.75, especially in the first week of drying, is important for preventing or limiting mold growth. The purpose of this study was to evaluate factors affecting the drying time of sun-dried Kona coffee, and to provide recommendations for post-harvest processing to optimize quality and safety. Ten farms in the Kona coffee region of Hawai'i were visited in fall, 2017 to measure the drying rate of coffee bean batches, and to record observations on the post-harvest handling and storage of coffee beans, and the environmental conditions that may affect the microbial quality of drying coffee. Daily measurements of coffee temperature, moisture level, water activity, and depth of bean layers were recorded along with air temperature, relative humidity and cloud cover during drying for 30 batches. Most sun-dried batches reached 13% moisture in 6 to 10 days. Coffee batches reached 0.75 a_w within 6 days on average, but some batches required more than 10 days. The coffee drying surfaces, physical enclosures, fan use, and elevation varied among farms. Allowing airflow around drying beans and maintaining a bean layer depth of less than 5 cm appeared to improve drying rates. Drying coffee parchments within 7 days post-harvest can inhibit growth of molds that may impact quality or molds that could produce mycotoxin. Controlling the drying conditions, including raking the layered beans, and monitoring moisture content can accelerate, or improve the consistency of, batch drying time.

1. Introduction

Mold growth and mycotoxin formation in foods and feeds depends on of multiple effects and variables including pH, water activity (a_w), solute concentrations, temperature, atmosphere, relative humidity, composition and time. The principal controlling factors determining the potential for growth generally are water activity and temperature (Panagou et al., 2003). The crucial step to support growth for mycotoxigenic fungi and mycotoxin production are favorable temperature and water activity (Paterson and Lima, 2010). Mycotoxins can be produced before harvest in the standing crop and production can increase, sometimes dramatically, after harvest if post-harvest conditions are favorable for further fungal growth (Batista at el., 2009).

Coffee fruits and beans can be contaminated by toxigenic fungi, including those that produce Ochratoxin A (OTA). This toxin is a secondary metabolite produced primarily by *Penicillium verrucosum* and *Penicillium nordicum* and by several species of the genus *Aspergillus*. Ochratoxin A (OTA) is considered to be nephrotoxic, carcinogenic, embryotoxic and teratogenic (Batista et al., 2009; Urbano et al, 2001; Velmourougane et al, 2011; Vecchio et al, 2012: Suárez-Quiroz et al., 2004).

OTA can be found in various foodstuffs and beverages including cereals, beans, coffee, beer, wine, meat, cocoa, dried fruits, spices, nuts, milk, pig blood and kidney and other tissues of animal origin. Raw materials and food commodities are commonly found to be contaminated with these species during drying and subsequent storage or transport, in processes following the harvest stage (Muñoz, 2011). Inappropriate drying of the green coffee beans and the rewetting of the green coffee beans are the causes of mold growth. The presence of OTA and ochratoxigenic fungal species in coffee beans has been studied extensively. Ochratoxin A (OTA) on partially dried, rewetted green coffee is primarily produced by *Aspergillus ochraceus* (Batista at el., 2009). Critical factors for fungal OTA production in coffee are environmental conditions, such as temperature, water activity (a_w), pH, nutrients, incubation time, and light (Suárez-Quiroz et al., 2004). If poor control procedures are employed such as slow drying, the opportunities for OTA accumulation can increase postharvest. Similarly, if inadequate storage conditions are employed, OTA will increase, although it will be reduced during processing from sorting, analysis for OTA and segregation, and roasting. OTA-producing fungi require favorable conditions for a period of time to grow and produce the toxin. The sources for fungal contamination, during postharvest cross contamination, are from soil, equipment and drying-yard surfaces (Paterson et al., 2014).

Coffee bean skin is a significant source of OTA, but cleaning and sanitizing methods for harvesting and processing equipment are effective in reducing OTA levels (Batista at el., 2009). Additionally, Paterson et al. (2014) reported that coffee beans obtained after falling on the soil, and which had been floated as part of processing, were high in OTA and should be avoided. A reduction in OTA levels of up to 90% may occur during the industrial process of converting coffee beans into roasted coffee and soluble coffee. In one study, the pulping process step and the subsequent fermentation and drying steps of coffee beans significantly reduced the risk of OTA contamination. Wet processing was less susceptible to infection by *Aspergillus* spp. and OTA contamination. Due to removal of the fruit pulp, the growth of OTA-producing *A. carbonarius* strains, was eliminated (Batista at el., 2009). However, this contamination can be related to post-harvest problems including unfavorable (a) climates for drying, (b) drying practices, (c) quality control, and/or (d) storage conditions. During the initial 3-5 days of drying, mold growth and OTA formation could happen due to the high water content in the coffee cherries. If performed incorrectly, sun-drying of cherries can lead to OTA contamination. The water activity of coffee cherries should be reduced from approximately 0.97 to 0.80 in no more than four days. Drying time to get below a critical water activity (a_w) of 0.80, is crucial to delaying or preventing the development of *A. ochraceus* toxin (Paterson et al., 2014).

The coffee berry borer (*Hypothenemus hampei*, (Ferrari)) is a common insect pest for coffee grown in many parts of the world. This insect is also a suspected vector of various mycotoxin producing molds (Velmourougane et al., 2010). In August 2010, the coffee berry borer (CBB) was found in the district of Kona on the island of Hawai'i and appears to be restricted to that area (Burbano et al., 2011). On the island, CBB was first discovered in coffee farms, after over 200 years of borer-free coffee production (Chapman et al., 2015). Vega, et al. (1999) reported that the following fungi were isolated from coffee berry borers: *Aspergillus ochraceus, Aspergillus flavus, Aspergillus niger, Fusarium sp., Penicillium chrysogenum, Penicillium brevicompactum and Verticillium sp*. The isolation of *A. ochraceus* suggests that CBB might serve as a vector for this toxigenic fungus. In a study summary by Velmourougane et al. (2010), higher microbial contamination in CBB infested beans was reported in both the varieties of arabica and robusta coffee with the presence of toxigenic molds (including *A. niger* and *A. ochraceus*). The results from this study provide adequate baseline information and evidence to understand and correlate the role of CBB with various OTA producing molds in coffee beans.

The economic impact on coffee crops due to *H. hampei* may worsen if the geographic distribution of this insect increases due to rising temperatures linked to climate change. For example, since 2000, the coffee berry borer has increased its distribution range (and damage to coffee crops) in East Africa as temperatures have increased. Jaramillo, et al. (2011) used climate models to forecast that the situation with *H. hampei* will worsen in many of the current *Coffea arabica* producing areas of East Africa. In many regions, the coffee berry borer was restricted to plantations at altitudes of 1,500 meters and below, but by 2050 its range will shift upward to 1,600-1,800 meters. Not only could the pest populations shift toward additional growing areas, but also, its rate of reproduction could more than double.

Climate changes including temperature increase, variation in precipitation, drought, and atmospheric carbon dioxide (CO_2) have been identified as relevant for agriculture and food safety (Miraglia et al., 2009). Furthermore, the importance of climate change to coffee production and the effect of on mycotoxin contamination, require urgent consideration. Due to the hot and humid conditions typical of coffee growing regions, coffee is susceptible to fungal contamination, growth of fungi that may or may not produce mycotoxins (Paterson et al., 2014, Tirado et al., 2010).

Historical weather observations of temperatures and sea-level data show for the Hawaiian islands indicate a warming climate and evidence of climate change. Researchers have reported that extreme climate change may cause frequent incidents of flooding and drought, shortage of water supply, landslides, soil erosion, and damage to existing infrastructures globally. In Hawai'i, some of these problems have already been documented (Leta et al, 2016). In Hawai'i, climate change issues are of special concern, since they may impact biodiversity with implications beyond Hawai'i's own population. Hawai'i stands out globally as a ''hot spot'' of terrestrial biodiversity despite its small land area. Naturally found only in Hawai'i there are more than 1000 species of flora and 100 species of endemic birds (Zhang et al, 2016).

Kona is situated on the leeward slopes of Mauna Loa and Hualalai volcanoes. The weather in the uplands of Kona is quite distinct from most other leeward areas in the archipelago because the volcanoes create a localized weather system and a wet environment. Rainfall increases upslope from as little as 600 mm/year at the coast to as much as 2000 mm/year at ~600 m elevation, declining again at higher elevation (Lincoln and Ladefoged, 2014).

Over the Hawaiian Islands, recent studies on climate change have shown that rainfall is expected to decrease during the nominal wet season (November to April) but marginally increase during the dry season (May to October). Hawai'i is expected to face an overall reduction in annual rainfall leading to a decline in sustainability of groundwater recharge given that approximately 70% of the annual rainfall happens during the wet season. In the Hawaiian Islands it is anticipated that air temperature to increase in the future which will drives evapotranspiration of components from the hydrologic cycle (Leta et al, 2016).

For the growth of all crops it requires special climatic conditions, coffee in particularly is sensitive to climate conditions. Slight increases in temperature can produce devastating heat waves as it is grown in tropical regions. Disrupted by climate change coffee quality is a result of a delicate mix of rain, humidity, and day and nighttime temperatures (Rising et al, 2016). The threat of pests and diseases to coffee can likely increase due to climate change. For examples, a fungi, such as the coffee rust *Hemileia vastatrix*, and pests, such as the coffee berry borer, are both expected to increase their activity and rates of spread due to higher temperatures in the next century (Rising et al, 2016).

Post-harvest processing of coffee includes a drying procedure to reduce the water content of the beans. Even though producers can consistently dry their coffee to 9-12% final moisture, the drying rate and drying time for batches of coffee beans can vary greatly. Controlled and consistent drying procedures for coffee beans may improve coffee quality and discourage mold and mycotoxin formation. Furthermore, the price of coffee beans is influenced by the quality of the beans achieved after processing (Paterson et al., 2014). Water activity (a_w) and moisture content of the beans, along with storage time, temperature and relative humidity can greatly influence fungal growth and mycotoxin development. Reducing the a_w from an initial level of ~0.90, to < 0.75, especially in the first week of drying, is important for preventing or reducing mycotoxigenic fungi from forming toxins (Paterson et al., 2014). Ten farms in the Kona coffee region of Hawai'i were visited in the fall of 2017 to record data on the drying rate of coffee bean batches and to record observations on the post-harvest handling and storage of coffee beans and the environmental conditions that may affect the quality and microbial contamination of drying coffee. This paper reports on the influence of post-harvest handling practices and environmental conditions on the time needed to sun-dry coffee to a safe water activity level and final moisture percentage.

2. Materials and methods

2.1. Geography of selected coffee farms and coffee drying yards

Forty-eight Kona coffee farms were contacted by e-mail. The farms were selected from among those who had readily available contact information via internet websites or processor recommendations. The Kona coffee belt on the island of Hawai'i is approximately 2 miles in width and 20 miles in length and consists of more than 700 farms ranging in elevation from 800 to 2200 feet. The majority of farms are less than two acres and many take their harvested coffee cherries to a processor for washing, drying and storage. Farms selected for this study utilized a variety of processing types (e.g. dry or wet (washed or semi-washed)) and drying methods (sun drying and mixture of both sun and mechanical drying followed by mechanical drying), have continuous production in the fall, and process coffee from their own farms (and sometimes from other farms). Further details on the selection and location of 10 farms used in this study can be found in Chapter III.

2.2. Observations of post-harvest handling and storage of sun-dried coffee

Drying techniques and drying yard facilities vary at each farm visited for this study. Eight farms exclusively sun dry their coffee and two farms use a mix of sun drying and mechanically heated driers. This paper will focus on the farms that exclusively use sun drying for coffee bean batches.

The size and materials used in the drying yards' floor is different from farm to farm. For each farm, the following observations were recorded for each visit (at least 10 per farm):

- Drying yard floor surfaces (concrete, wood and wood stand with wire screen)
- Drying yard walls (number of open sides, permanent or temporary)
- Use of fans to circulate air

Additional observations of drying techniques were recorded at each farm and for each batch of beans sampled. These included:

- The thickness of the sun-dried coffee bean layer
- Presence of a cover or ceiling or roof over the coffee beans during drying
- Presence of more than one batch of coffee drying at the same time

The depth of the coffee bean batches was measured in 3 locations, on each day of drying, with a rigid ruler. Measurements were averaged and rounded to the nearest cm. The depth of the mechanically drying bean batches were not measured.

2.3. Moisture content and water activity measurement of sun-dried coffee

From selected coffee drying yards, both moisture content and a_w measurements was recorded daily on a total of 30 batches of coffee beans throughout their drying periods. Batches were sampled for an average of 9 days each during November 13 through December 6 of 2017.

One to five coffee bean batches at each farm were sampled on a daily basis for moisture content percent and water activity. Three samples from each batch (~40 g each) were separately analyzed for moisture content and water activity every 24±2 h. Sun drying coffee samples were collected from an area approximately one meter from the edge of the drying yard and the distance between the samples was ~2 meters.

Batches were sampled on the first full day of drying, and until they reached ~9-13% moisture content.

Water activity was measured with a HygroPalm HP23-AW-A Portable Analyzer with 40 cm (depth) sample cups (Rototronic Instrument Corp, Hauppauge NY). The percent moisture content of coffee samples was recorded using a Agratronix, 08150 Portable Coffee Moisture Tester (Best Harvest, Largo, FL). After moisture content and water activity measurements, samples were returned to continue drying.

2.4. Environmental conditions at time of sampling

At each farm visited, the following environmental conditions were recorded:

- Temperature (°C) of each coffee sample
- Relative humidity (%) of each coffee sample
- Air temperature (°C) at time of sampling
- Cloud cover at time of sampling (where sunny, partly sunny, partly cloudy and cloudy were recorded as 10%, 40%, 60%, and 90% cloud cover, respectively)

The temperature of the samples was measured with the HygroPalm HP23-AW-A Portable Analyzer. Air temperatures and relative humidity at the sampling site were measured with a LESHP Portable Hand-Held Digital Thermometer Hygrometer Tester. Cloud cover was recorded as a personal observation by the sample collector.

2.5. Daily weather conditions during drying to <13% moisture

Coffee farms were visited over a 24-day period in 2017 (Table 1). At each sun-drying location, the geographical coordinates and elevation were measured with the

Google Earth. The location of the drying areas is not necessarily the location where most coffee trees are located or the mailing address listed for each farm. The distance between the northernmost and southernmost drying yards was 33 km. And, the elevation of the drying yards ranged from 1,095 to 1,981 feet (334 to 604 meters).

The hourly weather on each sampling day was obtained from publicly available data for the Kona International Airport at Keahole Station (location: 19.74 °N, 156.05 °W, elevation 14 meter). This weather station was the closest one to the drying yard locations with available hourly weather data (temperature, relative humidity, precipitation) records for all sample days. For example, weather data for November 13, 2017 was selected from the following website: https://www.wunderground.com/history/daily/us/hi/kailua/PHKO/date/2017-11-13?cm_ven=localwx_history .

2.6. Statistical analysis

The linear mixed model procedures of the JMP® Pro Version 14.0.0 statistical discovery software (SAS Institute Inc., Cary, NC, USA) was utilized to learn the impact of drying facilities, drying technique and environmental conditions on drying rates.. Descriptive statistics (means and standard deviations) were computed and analyses of variance were performed for the fixed effects and up to one way. Tukey- Kramer was used to determine significant differences between least square means. Differences are reported at a significance level of 95%.

3. Results

3.1. Environmental conditions during sun-drying

The hourly mean temperature each day ranged from 22.2 to 25.6°C during the 24-day sample period (Table 1). Air temperatures at the time of sampling (ranged of 23.8-32.0 °C) were higher since most samples were collected between 9am and 6pm when the temperatures were higher (Table 2). During the sampling period, the average relative humidity (RH) each day was 59% (range of 42 to 69% for daily RH) (Table 1).

The temperature of the air at time of sampling, and the temperature of bean samples were measured with separate devices. These measurements were similar in most cases. In Table 2, these measurements are averaged for all the days that each batch was sampled. The mean daily temperatures of the samples and the air are nearly the same (28.42°C and 28.24°C, respectively). Similarly, the relative humidity of the samples, averaged for each batch, of 56.47% was similar to the weather station reported averages (57.88%).

Even though cloud cover, expressed as a percentage, was averaged over several days for each batch, there were relatively large differences in observed cloud cover at time of sampling. Mean cloud cover at time of sampling for each batch ranged from 14 to 66% (mean of 46 $\pm$ 12%).

For coffee that was exclusively sun-dried (8 locations) the altitude of the drying yards from 330 to 603 meters. Air temperatures measured on the same day at one elevation may have been higher or lower than temperature at another elevation. In many cases, temperatures on the same day at different elevations may have occurred several hours apart.

3.1.1. Relationship of environmental conditions to moisture content or water activity

The wide variation in in the rate of change for daily moisture content, daily a_w and the time needed to complete the coffee beans drying process was reported in Chapter III. Both the daily water activity level and the daily moisture content of the bean batches had a statistically significant effect on the total days of drying time needed to reach 13% moisture ($p < 0.05$). Generally, moisture content declined on a daily basis for all batches. While water activity generally decreased on a daily basis for the sun-dried batches, a_w increased on one or more days for some batches. In these cases, a new batch was added adjacent to a batch that had already started the drying process.

The sample temperature and air temperature at sampling time did not show a statistical significant effect on moisture content reduction per batches or on days of drying time. Mean relative humidity at sampling time had a statistically significant effect on moisture content reduction, water activity but not for moisture content time for sun-dried batches ($P < 0.05$).

The cloud cover at time of sampling showed a statistically significant effect on moisture content reduction per day and water activity reduction per day ($p < 0.05$). Furthermore, in the same farm weather conditions during sun drying coffee parchment batches showed some fluctuations between batches as cloud cover in farm 1 batches A, B and C was reported as 42, 41 and 66 % respectively. Differences in the degree of cloud cover may lead to delays in drying of the coffee. For these batches, the days needed to dry to 13% moisture were 6, 8 and 12 respectively for batches from the same farm.   Since cloud cover was only determined once per day (for several days each batch) concluding a link between drying time and cloud cover may not be appropriate.

3.2. Post-harvest handling and storage of sun-dried coffee

The farms in this study used a range of surfaces to sun-dry coffee beans. Differences in the drying facilities and drying techniques can accelerate the drying period or daily drying rate. Commonly used materials for the drying floor surface are wood stands with wire mesh (screen), concrete, and wood (painted and unpainted). These floor surfaces were observed among all the coffee farm drying yards visited, including three that used a concrete surface, four that used wood surfaces, and one that used chicken wire screens. The various surface types could influence the drying rate of the coffee parchments.

Some farms were designed with open walls and a fixed roof and others with an open wall with a portable roof. Another design used closed walls, which opened from one side only. Three farms used a concrete surface with all open walls (four sides open). Two farms with wood surfaces had a three side open design, two other farms had wood surfaces with one wall side open, and finally one portable roof shed was "Hoshidana" style with the traditional wood surface on the roof top. The farm that used a chicken wire screen-drying surface did not have walls, except they could move the coffee under the roof of a shed during rainfall. Also, the roof and walls material used at the drying yard varied from transparent flexible polymer to corrugated polymer. In the concrete surface drying yard both materials were used to cover the roof top of the building. Similarly, the same material was used in the wood surfaced drying yards.

Two farms used fans to circulate air. One of these farms used a ceiling fan and the other was a standing floor-level fan. These fans were usually running at the time of sample collection. The coffee batches sampled from these two farms (farm 2 and 8) dried at a faster rate and in a shorter time than the average of batches from most of the other six farms (Table 3).

The coffee beans layer thickness for the 25 batches (Table 3) from all farms varied depending on the drying methods. Coffee beans were spread in layers ranging from 2 to 12 cm when using a sun drying technique. Some of the batch thicknesses exceeded the recommended limit of 2 inches (5 cm) in depth. Coffee beans that were piled to a depth of 5+ cm took a longer time to dry. Farms 3 and 7 had a mean coffee layer depth of 5 cm or more, and batches from these farms dried slower than most of the other batches.

The surface type did not have a statistically significant effect on moisture content reduction per day or on days of drying. Yet, the combination of the surface and coffee thickness layer variables had statistically significant effect on moisture content reduction per day, water activity reduction per day, and days of drying time ($p < 0.05$). The drying wood stand with wire screen and the concrete surface had a statistically significant effect on batch water activity reduction ($p < 0.05$).

3.2.1. Relationship of post-harvest techniques and facilities to moisture content or water activity

The drying rate of the coffee beans obtained from all 25 batches using similar sun drying technique showed variation individually in moisture and a_w reduction. A gradual reduction in average moisture content of ~2 - 2.5% per day, resulted in a shorter drying period. However, the individual coffee batches that reported a drying rate of < 2% moisture per day resulted in a prolonged drying period with an increased potential mold growth. For batch F, one of the slowest drying batches studied, visible mold growth was observed during the drying process.

Coffee layer thickness can impact the drying process as 5cm is the recommended parchment coffee bean depth, and 8cm is the recommended depth for sun-dried natural coffee beans. The 25 coffee parchments in this study were layered at 4 ± 3 cm in thickness with 11± 6 days to complete the drying process to 13% moisture (Table 3). Batches with the recommended thickness of 5 cm or less could complete the drying process in 9 ± 2 days. Moreover, batches with an average depth of 2 cm from farms 2 and 8 could reach 13% moisture in approximately 7.3 days.

Individual coffee parchment batches using certain type of drying surfaces reported a wide range of drying periods and drying rates per day. Moreover, individual batches dried on wood stands with wire screen (Figure 1) from farm 1 reached 13% moisture in an average of 8.4 days (faster than the average of all batches sampled), yet water activity was reduced the fastest (Table 3). For these three batches from farm 1, a 0.75 a_w level could be attained in less than 3 days on average. The chicken wire screen rack was raised 10 cm raised from the ground that may have enhanced airflow around the beans and allowed moisture to dissipate more rapidly.

In most of the drying yards, coffee beans were laid directly on the ground and evenly spread to a consistent depth. Drying rates and drying times were variable for bean batches dried on concrete or wood surfaces (Figures 2, 3). For both surfaces, the addition of floor and/or ceiling fans could accelerate the drying process. In most cases, batches dried more rapidly in facilities with three or four open sides (Table 3). An absence of walls could also facilitate airflow and increase drying rates. Conversely, open or limited walls may allow some rainfall to reach the beans.

4. Discussion

The combination of multiple factors and elements impact the time for drying and the drying rate including relative humidity, initial moisture, drying surfaces, airflow around the beans, and raking the coffee parchments. The 25 sun dried coffee batches varied in the drying rate based on multiple factors and not limited to batch size, thickness, drying yard design, elevation of the farm and initial moisture content. A higher moisture level (after washing) could potentially prolong the drying period. And, low drying daily rates could potentially promote mold growth on the coffee parchments.

The drying coffee parchments are impacted by multiple extrinsic factors and drying characteristics. The wide range of results indicates coffee beans drying period and drying rate is influenced by environment conditions and preparation of the batch. The drying yard characteristic, location, elevation and design influenced the coffee beans drying period and daily reduction rate. Moreover, the favorable conditions such as availability of nutrient, temperature, moisture content and prolong drying period of the coffee beans can cause mycotoxigenic fungus from growing and producing mycotoxins.

Moisture content % is a quality parameter that is widely used in the Hawaiian coffee industry. Although, a_w is an important food safety measure that can be adapted to control mold and mycotoxin presence in the coffee beans, it is not yet introduced in the

Hawaiian coffee industry. In this study, the estimated time (days) to dry the batches was significantly related to moisture content reduction ($p<0.05$), but not to water activity ($p>0.05$). And, individual measurements of a_w only had a weak correlation with moisture %. Nevertheless, a_w level could be used to estimate moisture content or conversely, moisture content level measurements could be used to indicate if a batch has reached a target a_w. For example, when moisture content reaches 22%, the average water activity is ~0.75 based on measurements in this study.

The speed of drying coffee is reflected in the decrease in moisture content. The fastest batches that decrease > 2%/ day in moisture content reached 13% final moisture in shorter times (~ 8 days). Coffee producers can follow the recommendation to reach a a_w of 0.75 in 4 to 7 days to mitigate the development of mycotoxins. In this study, the average batch reached this water activity level within 6 days but some batches needed more than 10 days. Moisture content is a recommended and commonly used measure to indicate proper sun-drying of coffee that may ultimately indicate its quality. Additional measurement of water activity during sun-drying may not be useful on a routine basis due to variability of this measure during drying, and also if coffee can be dried to 22-24% moisture within 4 to 7 days, then a water activity level less than 0.8 can be achieved. Mold growth at this reduced water activity will likely not occur.

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Figures

Figure 1: Wood stand chicken screen drying technique.

Figure 2: Concrete drying surface.

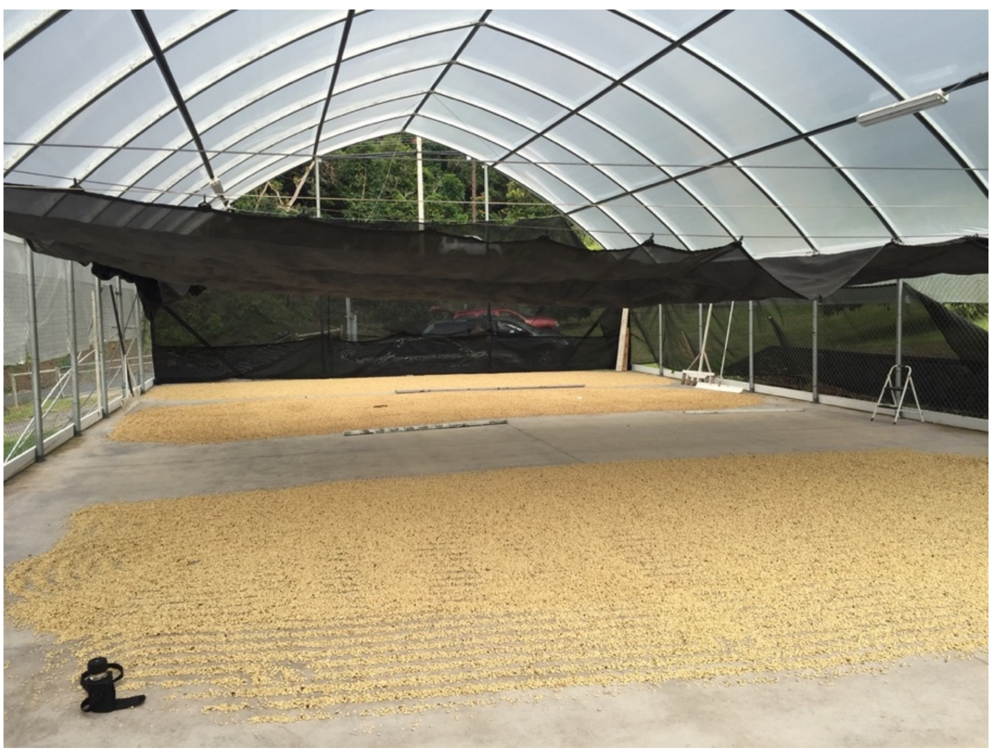

Figure 3: Wood drying surfaces.

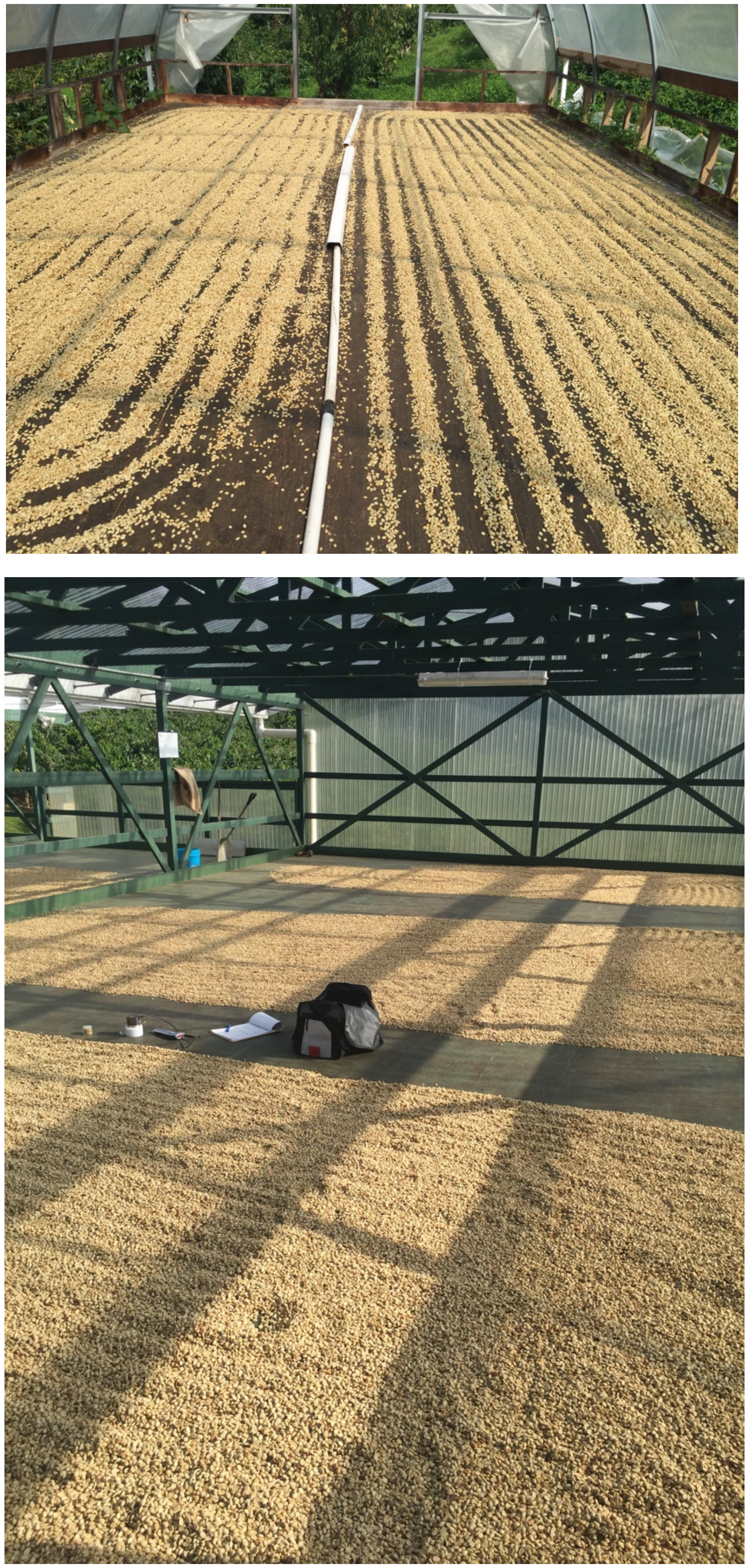

Figure 4: Shallow and deep coffee piles during drying.

Tables

Table 1: Sampling days for coffee batches during Nov. 13 to Dec. 06, 2017.

Farm #	Batch code	13-Nov	14-Nov	15-Nov	16-Nov	17-Nov	Nov 18	19-Nov	Nov 20	21-Nov	22-Nov	23-Nov	24-Nov	25-Nov	26-Nov	27-Nov	28-Nov	29-Nov	30-Nov	1-Dec	2-Dec	3-Dec	4-Dec	5-Dec	6-Dec
1	A					x	x	x	x	x	x														
1	B					x	x	x	x	x	x	x	x												
1	C												x	x	x	x	x	x	x	x	x	x	x	x	
2	D				x	x	x	x	x	x	x														
2	E				x	x	x	x	x	x	x														
3	F							x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
3	G												x	x	x	x	x	x	x	x	x	x	x	x	x
3	H															x	x	x	x	x	x	x	x	x	x
4	I			x	x	x	x	x	x	x	x	x	x												
4	J				x	x	x	x	x	x	x	x	x	x											
4	K														x	x	x	x	x	x	x	x	x	x	
4	L															x	x	x	x	x	x	x	x	x	x
4	M															x	x	x	x	x	x	x	x	x	x
5	N	x	x	x	x	x	x	x	x	x															
5	O					x	x	x	x	x	x	x	x												
5	P						x	x	x	x	x	x	x	x											
5	Q															x	x	x	x	x	x	x	x	x	x
5	R															x	x	x	x	x	x	x	x	x	x
6	S		x	x	x	x	x	x	x																
6	T								x	x	x	x	x	x											
6	U										x	x	x	x	x	x	x	x							
6	V										x	x	x	x	x	x	x	x							
6	W														x	x	x	x							
7	X			x	x	x	x	x	x	x	x	x	x												
8	Y					x	x	x	x	x	x														
8	Z						x	x	x	x	x	x	x	x	x										
9	AA																		x	x	x	x			
9	BB																			x	x	x	x		
10	CC				x	x																			
10	DD																				x				
Number of samples in a day		1	2	4	8	12	13	14	15	14	15	11	13	9	8	12	12	12	10	11	12	11	10	9	7
Weather condition	Mean Air Temperatur	25.6	24.4	26.1	26.1	25.6	24.4	25.0	23.3	23.3	23.9	23.9	25.6	24.4	24.4	24.4	25.6	25.6	25.6	25.6	25.6	26.1	23.3	24.4	22.2
	Mean relative humidity RH %	63.0	58.0	58.0	55.0	59.0	62.0	56.0	65.0	54.0	52.0	57.0	48.0	56.0	56.0	67.0	67.0	69.0	68.0	67.0	68.0	53.0	58.0	42.0	45.0

Table 2: Environmental conditions at time and day of coffee sampling

Farm code	Batch code	Days of drying time	Sample Temp. Avg. (°C)	Temp. at time of sampling (°C)	Relative humidity at time of sampling (%)	Cloud cover at time of sampling (%)	Daily mean air Temp (°C)	Daily mean RH (%)	Elevation of drying yard "meters"
1	A	6	28.9	26.8	55.1	42	24.3	58	363
1	B	8	28.8	27.0	53.9	41	24.4	57	363
1	C	12	29.1	27.8	59.5	66	25.1	60	363
2	D	7	29.0	29.2	49.8	37	24.5	58	529
2	E	7	29.8	30.3	50.9	46	24.5	58	529
3	F	17	30.5	30.1	57.2	61	24.7	57	411
3	G	13	30.6	30.1	57.2	61	24.7	57	411
3	H	10	30.0	30.1	57.2	61	24.7	57	411
4	I	10	30.5	30.4	47.7	41	24.3	57	487
4	J	10	31.1	31.1	45.4	41	24.3	56	487
4	K	10	29.7	29.8	58.2	49	25.2	61	487
4	L	10	30.1	29.9	57.3	51	24.7	57	487
4	M	10	32.0	30.2	56.8	54	24.7	61	487
5	N	9	28.1	27.5	57.6	39	24.8	59	603
5	O	8	27.9	28.2	52.4	40	24.3	57	603
5	P	8	28.1	27.8	53.2	49	24.3	56	603
5	Q	10	23.8	26.2	66.8	54	24.7	57	603
5	R	10	26.5	26.2	66.8	54	24.7	57	603
6	S	7	28.8	27.3	59.4	47	25.0	60	350
6	T	6	27.7	26.5	55.5	27	24.3	56	350
6	U	8	24.1	24.9	66.2	51	24.9	60	350
6	V	7	25.0	24.3	67.9	63	25.1	61	350
7	X	10	29.5	28.6	53.0	14	24.3	57	334
8	Y	6	25.4	28.6	53.2	33	24.3	58	450
8	Z	9	25.7	27.4	53.7	33	24.2	55	450
AVG		**9.12**	**28.42**	**28.24**	**56.47**	**46**	**24.59**	**57.88**	**459**
S.D.		**2**	**2.2**	**1.8**	**5.8**	**12**	**0.30**	**1.73**	**95**

Table 3: Drying yard characteristics and practices of selected processors

Farm code	# of batches	Processing type *	Drying type **	Mean coffee beans layer Thickness (CM)	Surface type	Wall type	Ceiling	Fan	Drying days range	Δ Mean Moisture Content (%/day)	Mean Δ Aw / day	Mean Days needed to reach 0.75 Aw	Days needed to reach 13% MC
2	2	W	S	2	Concrete	Four sides open	Transparent/ Permanent	Ceiling fan	7	2.9	0.066	3.8	7.2
8	2	S-W	S	2	wood	Three side open	Transparent/ Permanent	Floor standing fan	6 to 9	2.6	0.060	3.6	7.4
6	4	W	S	4	Concrete	Four sides open	Transparent/ Permanent	No	5 to 7	2.6	0.053	3.7	6.7
4	5	W	S	4	Wood	Three side open	Transparent/ Permanent	No	8 to 9	2.5	0.042	6.1	9.9
1	3	W	S	3	Drying racks (4x8 wire screen)	None	None	No	6 to 12	2.3	0.046	2.7	8.4
5	5	W	S	2	Wood	One side open	Transparent/ Permanent	No	7 to 9	2.2	0.051	6.9	9.9
7	1	W	S	5	Wood	Variable	Transparent	No	10	1.8	0.049	6.5	12.7
3	3	W	S	12	Concrete	Four sides open	Transparent/ Permanent	No	9 to 17	0.8	0.011	14.0	23.4
								Avg.		**2.2**	**0.047**	**5.9**	**10.7**
								S.D.		**0.7**	**0.016**	**3.6**	**5.5**

*W Wet or Wash: Coffee beans are washed and soaked in water for 12 to 24 hours prior to processing them.
*S-W Semi Wash: Using a demucilager to reduce the water content of the coffee prior to drying them.
**S Sun drying: A traditional method to dry the coffee by only using the sun as a source of heat.

Chapter V. Conclusions

1. Recommendations for sun-dried Kona coffee techniques to optimize quality and safety

All ten farms in this study applied a wet process on their coffee cherries, yet a small proportion (<10%) were processed through the dry “natural” method. The wet process steps start from the coffee cherry skin removal and ends after the fermentation step is complete. Typically, the parchment coffee will be fermented for 14 to 24 hours depending on the coffee processor. This prolonged fermenting step could lead to coffee parchment with a higher water content prior to spreading for sun drying. The initial moisture level of sampled batches on the first day of drying ranged from ~25 to 38%. Coffee that fermented (in water) longer tended to have higher water levels at the start of sun drying. Some farms used perforated wheelbarrows to strain water from the coffee parchments after the fermentation step to reduce the initial water content. Some coffee batches in this study were processed as “semi-wet”, which is similar to the wet process with the exception of the fermenting step. After the coffee cherry skins are removed, ~40% of the fruit pulp will stick to the coffee parchment, now referred to as “honeydew coffee”. Leaving some of the fruit pulp on the parchment helps it pick up and retain moisture during the drying process. After removing the skin with a demucilager, the coffee parchments are then laid on the ground to begin the sun drying process. A third, commonly used, method to process coffee is the dry “natural” process where the skin is left on the coffee parchment, followed by a drying step. In this study, the two batches that were dry processed were passed through a mechanical dryer rather than sun dried.

The dry (natural) method is used by few processors due to the prolonged time needed to complete the drying process and the potential for mold growth on the coffee cherries.

The main advantage of using artificial or mechanical drying method is to dry the coffee faster with a more controlled process. This rapidly dried coffee can differ in sensory quality compared to the traditional sun dried coffee. As a common practice, coffee parchments may spend 24 to 48 hours in the sun and are then moved to an artificial dryer to finish drying. Some coffee processors use an artificial dryer directly after their coffee parchments have completed the washing process.

After completing the washing step, the coffee parchment or coffee naturals were transferred to the drying yards. The drying yards could be made with wood or concrete surfaces and in some cases made of wood stands with a wire screen to improve air circulation during drying. In this study, a difference in drying rates was not observed for batches dried on wood or concrete.

Farms that used a floor or ceiling fan during sun drying had greater reductions in moisture per day compared to other coffee parchments that did not apply a fan. Sufficient airflow designs can improve drying rates and shorten drying times. We observed that faster moisture reduction in coffee parchments occurred in batches where the drying area had at least three open sides.

During the study period, we observed processors utilizing any empty space to lay a new batch for drying. In some cases, a new coffee batch was placed adjacent to a batch that had been drying for two or more days. When new batches were placed next to our sampled batches we observed fluctuation of water activity (a_w) levels (including increased a_w) more than moisture content during the first day or two. Tracking the placement and movements of coffee parchment prior to placing down a new batch may help mitigate this fluctuation.

Maintaining the recommended coffee parchments layer depth of less than 5 cm can shorten drying time or facilitate a consistent reduction in moisture and water activity during the drying period. In this study, moisture content could be reduced more rapidly for batches with a depth of less than 5 cm. Coffee batches that were layered more than 10 cm deep required more than 15 days to reach 20 to 24 % moisture content. Moreover, maintaining the coffee parchments depth with proper raking of the coffee can improve the sun drying process. Raking coffee parchments 4 to 6 times per day during sun drying is a recommended procedure.

Processors can collect valuable data to help them understand how rapidly they can expect their coffee to dry and how they can control a drying process that preserves the quality and safety of their product. Daily measurement of coffee moisture percent can be used to improve quality control and to learn when to intervene to accelerate the drying step. Processors may also want to record measurements of temperature, humidity, rainfall, and degree of direct sun to learn if these can affect the drying time for their batches. Additionally, processor should consider following a strict plan for raking frequency, maintaining consistent bean depths of less than 5 cm, placement of new batches or distance needed between new and previously laid batches. The absence of historical data, over more than one growing season, recorded on the coffee parchments and natural batches behavior during the drying step make it difficult to improve the quality control measures. Data collection for some of the variables that effect drying will allow better decisions to advance the quality control of the coffee parchments that may add value to the final product.

Practices that restrict the development of certain fungi on processed coffee are needed to preserve sensory quality, enhance microbial safety, and maintain yields. These practices include 1) managing water availability from the beginning of drying onward, and 2) facilitating the development of competitive micro-organisms and restrictive growth conditions that are not prejudicial to quality (FAO, 2006).

During the production and postharvest stages green coffee beans can be infected by fungi. The most common coffee contaminants isolated from production to postharvest stages fungi belongs to the genera *Aspergillus* and *Penicillium* (Alvindia and Guzman, 2016). Drying coffee cherries to adequate moisture and water activity levels is important for preventing the colonization of molds that may be able to produce mycotoxins. Oliveira et al. (2018) reported that temperature and water activity (a_w) play an important role in the biosynthesis of ochratoxin A from toxigenic fungi. Toxigenic *Aspergillus* species on processed coffee are more likely to contaminate coffee during the drying step (Taniwaki, Pitt, Magan, 2018). Although mycotoxigenic fungi can still contaminate washed coffee beans, wet processing can potentially remove fungi from coffee beans (Culliao and Barcelo, 2014).

The production of a high quality coffee beans requires a suitable drying yard. The location and elevation of the drying yard in a farm is essential, exposing the coffee beans to maximum sunshine is expected with minimal risk of flooding or cross-contamination by animals (Velmourougane, et al., 2014). Moreover, types of flooring required and used in the drying yard to ensure a good drying of the coffee beans are concrete, tiles, brick, granite or any other hard surface to prevent contamination the beans. The drying surface should be free of cracks that could harbor microbial contaminants.

The efficiency of drying of parchment coffee may be compromised by the environmental condition in the province which is characterized as low daytime temperature and high humidity (Barcelo et al, 2017). To remove excess moisture after washing the coffee beans, the use of tray drying is recommended. In an experiment the use of (2 m × 1 m × 5 cm) tray drying accelerate the drying process of the coffee beans. Comparing to the direct dried coffee beans the tray dried coffee beans attracted less mold contaminants (Velmourougane, et al., 2014).

Small operations in Kona typically use sun-drying to dry their coffee beans by spreading the beans on a drying area evenly and periodically turning them over. The estimated time needed to complete the coffee parchment drying using this type of method is around 4-6 days on a sunny day, but on a cloudy day it takes more time (Bittenbender and Smith, 2008). Coffee beans should be raked or stirred 4–6 times a day to enhance removal of moisture to prevent mold growth (Velmourougane, et al., 2014).

Countries producing and exporting coffee aim to obtain good quality, safe products and maintain it throughout the production chain. But, some factors are out of the control of both producers and exporters such as climatic impacts that may result in logistic structure breakdowns which could cause undesirable changes in the grain characteristics, permitting fungal growth and subsequent mycotoxin production (Palacios-Cabrera et al., 2007). Coffee growers in several areas of Benguet Philippines who wet process their coffee beans promote good agricultural practices (GAP) in an effort to minimize fungal contamination of coffee. Moreover, fungal contamination is common in coffee processing especially during post-harvest (Barcelo et al, 2017). In plants and plant- derived products fungi are common inhabitants. The conditions that promote the contamination of coffee beans by ochratoxigenic fungi and the production of OTA such as weather, plant susceptibility, temperature, damage caused by insects, and deficient storage (De Fatima Rezende et al, 2013). Moreover, multiple factors affect the time required to dry coffee beans and cherries, the drying yard, thickness of the layer, number of raking or stirring a day, initial moisture content of the beans, sunshine, temperature, and relative humidity. The correct layer thickness accelerates and uniform the drying of parchment and casing of cherry without any mold contamination (Velmourougane, et al., 2014).

The highest impacting factor on the speed at which coffee beans deteriorate is humidity. Moreover, coffee beans are hygroscopic and tend to balance their moisture content with their immediate surroundings generally known as “moisture balance” even if it has been stored in a low moisture content yet humidity is still very active factor (Rojas, 2004). A higher fungal and mycotoxin contamination could be a result of a longer drying times, and beans dried above 5 cm thickness in parchment and above 8 cm in cherry lead to a lower cup quality (Velmourougane, et al., 2014). Quality of coffee brew may be decreased by defective coffee beans caused by fungal contamination (Barcelo et al, 2017).

2. Future directions

Further understanding is needed for the many variables affecting the traditional sun-drying technique of Kona Hawaii coffee beans. Here are a few of the further directions that could be important for Kona Hawai'i coffee through focusing on moisture content and water activity relations to the traditional drying method. Focusing on understanding the correlation between moisture content reduction per day and atmospheric condition during the drying time. (For example: temperature, relative humidity %, cloud coverage etc.). Moreover, studying the daily moisture content reduction of > 2 % which might indicate a good coffee beans drying process using the traditional sun-drying method. In addition, study application of basic good practices in handling the coffee batches. Such as, and not limited to raking the coffee beans batches continually during the time of drying, maintaining the required depth of coffee beans and ensuring enough space between old and new batches are of concern in the daily moisture reduction. That will eventually support the coffee beans drying process and enhance the sun-drying method. Studying the influence of the drying surfaces, number of walls and the use of fans on the spread of drying the coffee beans. Monitoring each and every step of the coffee beans drying procedure support further decision making to improve the quality and safety of the coffee beans.

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