SOLAR TUNNEL ASSISTED DRYING OF PARCHMENT COFFEE (*Coffea. arabica* L) FOR BETTER QUALITY AND SAFETY OF RAW BEANS AND BEVERAGE

M.Sc. THESIS

BY

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JANUARY 2020

JIMMA, ETHIOPIA

Solar Tunnel Assisted Drying of Parchment Coffee (*Coffea. arabica* L) For Better Quality and Safety of Raw Beans and Beverage

By

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M.Sc. Thesis

Submitted to the School of Graduate Studies of Jimma University, College of Agriculture and Veterinary Medicines, Department of Post Harvest Management, in Partial Fulfilment of the Requirements for the Degree of Master of Science in Post-harvest Science and Technology

January 2020

Jimma, Ethiopia

SCHOOL OF GRADUATE STUDIES
JIMMA UNIVERSITY

COLLEGE OF AGRICULTURE AND VETERINARY MEDICINE

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Thesis Submission for External Defence Request Form (07)

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Program of the study**: M.Sc. In Post-harvest Science and Technology**

Title: **Solar tunnel assisted drying of parchment coffee (*Coffea. Araica* L) for better quality and safety of raw beans and beverage**

I have completed my thesis research work as per the approved proposal and it has been evaluated and accepted by my advisers. Hence, I hereby kindly request the Department to allow me to present the finding of my work and submit the thesis.

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We, the Thesis advisors have evaluated the contents of this thesis and found to be satisfactory, executed according to approved proposal, written according to the standards and format of the university and it is ready to be submitted. Hence, we recommend the thesis to be submitted for external defense.

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DEDICATION

This piece of work is dedicated to the Almighty Allah who has given me strength and encouragement throughout my life.

STATEMENT OF THE AUTHOR

By my signature below, I declare that this is my original work. I have followed all ethical and technical principles of data collection, data analysis and completion of this thesis. All sources of materials used for this thesis have been duly acknowledged.

This thesis is submitted in partial fulfillment of the requirements for MSc. degree in Postharvest science and technology at Jimma University. The thesis will be deposited in the Jimma University College of agriculture and veterinary medicine library and will be available to borrowers under the rules and regulations of the library. I declare that this thesis has not been submitted previously to any other institution for the award of any academic degree, diploma, or certificate.

Name: Zenaba Kedir

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BIOGRAPHIC SKETCH

Zenaba Kadir was born on July 27, 1995, at Dembi Dollo town, Kellem Wollega Zone, Oromia. She attended her elementary education at Olika Dingil primary school, secondary and preparatory school at Kellem Comprehensive Secondary School, Dembi Dollo. She then joined Jimma University in 2013 and completed her B.Sc. degree in food science and postharvest technology in June 2017. After graduation, she has been employed by Jimma University as a senior technical assistant since September 2017. She was also given a chance to start postgraduate study in Postharvest cience and technology in the same year.

ACKNOWLEDGMENT

First and foremost I would like to thank Almighty Allah, without His will and support; this had never been possible. Second, I am very grateful to my advisors Dr. Yetenayet Bekele and Dr. Addisalem Hailu for their follow up, meticulous guidance, encouragement, and assistance in data analysis, review and comments on this thesis. This thesis would not have been complete without their assistance.

Next, my sincere gratitude extends to Miss Hayat Hassen, Miss Ehtenesh Tilahun, Miss Zara Kedir, and Mr. Abaya Hordofa for their endeavor assistance and cooperation in handling and execution of the fieldwork.

I am also highly grateful to Mr. Tayyib Sultan of Saqqa woreda Agricultural Bureau for his willingness and cooperation in getting me the coffee sample and as well as facilitating and supervising washing.

I am also very thankful to Jimma University College of Agriculture and Veterinary Medicine for providing me financial support for the research and the Ethiopian Commodity Exchange Jimma branch for their permission to work on the part of the study at their laboratory. I am also very grateful for Mr. Muluken Taye Quality control manager of ECX and his team, for their unreserved support and building pieces of advice and as well for the determination of cup quality as part of the panelist.

Finally, I have special thanks and appreciation to my mother, Hawi Mohammed, and my father, Kadir Abdissa, who always inspired me and kept me in their prayers. Thanks to my lovely sister Zara and dear brothers Harun and Habib for their concern, follow up and praiseworthy support.

LISTS OF ABBREVIATIONS

Aw	Water Activity
CQIP	Coffee Quality Improvement Program
CSA	Central Statistical Agency
ECX	Ethiopian Commodity Exchange
EMAN	European Mycotoxin Awareness Network
FAO	Food and Agriculture Organisation
GDP	Gross Domestic Product
GHE	Green House Effect
ICO	International Coffee Organisation
ISO	International Organisation for Standardisation
MoARD	Ministry of Agriculture and Rural Development
MR	Moisture Ratio
OTA	Ochratoxin A
QSAE	Quality and Standards Authority of Ethiopia
RH	Relative Humidity
USD	United states dollar
UV	Ultra Violet radiation

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ABSTRACT

This study was conducted to investigate the combined effect of solar tunnel dryer zones and layer thicknesses on the drying characteristics, quality and safety of washed Arabica parchment coffee. The experimental design was 4 x 3 factorial arrangements in a randomized complete block design with three replications. The first factor was solar tunnel drier zones (zone 1, zone 2, zone 3 and open sun drying) and the second factor was a layer of drying thicknesses (2, 4 and 6 cm). Parameters such as moisture ratio, effective diffusivity, hours to drying, were collected to determine drying characteristics of parchment coffee. Then physicochemical quality parameters such as titratable acidity, total soluble solid, PH, Crude fat, total polyphenol contents, total Antioxidant capacity, IC_{50}, *raw and cup quality) and fungal load were determined. During the drying, drying air temperature and relative humidity were measured continuously at one-hour interval. Moisture ratio was examined by moisture loss at a given time per initial moisture content at every one hour interval. Selected 7 different thin-layer drying models were compared to determine drying kinetics. According to statistical analysis results, the Modified Midilli model has shown a better fit to the experimental drying data as compared to other models. The effective diffusivity varied between (1.2 to* $5.0*10^{-6}$*) and increased with increasing temperature along the drying zones. All collected parameters except TA differed significantly* ($p<0.05$) *concerning drying zones and layer thicknesses. There was no significant variation among the treatments concerning cup quality and all the coffee scored grade one and grade two for the total quality score referring to very good quality for all the coffees. Higher fungal fungal were found for the sun-dried coffee beans with aspergillus genera being the most abundant. The study concluded that drying parchment coffee under zone 2 (solar tunnel drier 50-60* ^0C *and* 18-28% *RH) at a drying depth of 4 cm resulted in desirable effects. Consequently, in the absence of a mechanical drier due to the unavailability of its basic materials, the solar tunnel drier could be a worthy substitute without compromising on coffee bean and cup qualities as compared to traditional open sun drying.*

Keywords: Cup Quality, Drying Kinetics, Moisture Ratio, Parchment Coffee, Solar Tunnel Drier

1. INTRODUCTION

Coffee is the world's favorite beverage and the second most traded commodity after oil on international trade exchanges both in terms of production and value, representing a significant source of income to several developing countries in Africa, Asia and Latin America (Jaconovic *et al*., 2012). Coffee is one of the most important non-alcohol beverage crops grown in over 80 countries in the tropical and subtropical regions of the world, exported in different forms to more than 165 nations, and provides a livelihood for some 25 million coffee-farming families in around the world (Dessalegn *et al.,* 2008)

In Ethiopia, Coffee is mainly produced in the south-western and south-eastern parts of the country and mostly produced by smallholder farmers on average farms of less than 2 hectares. Around 95% of the country's total production comes from these smallholder farmers and forest coffee widely grown in the south-western part of the country (Abu, 2015).

In the country where an about a large amount of the population is under poverty, coffee cultivation plays a vital role both in the cultural and socio-economic conditions of the nation. It is the defining feature of the national culture and identity (Mayne *et al*., 2002) with 50% of the production consumed domestically in Ethiopia (ICO, 2018). It is also the major agricultural export crop, providing 65% of Ethiopia's foreign exchange earnings. According to Ethiopia Revenue and Customs Authority, (http://www.erca.gov.et/index.php/import-export information? view=import-export), in 2018, the country earned 754.8 million USD from green bean coffee exported to different countries

Parchment Coffee it is started with harvesting of red ripe cherries and obtained after wet processing methods. Only manually picked ripe red cherries used for the wet processing method. The red cherries pulped, fermented, washed, and dried to produce good quality parchment coffee. It is labor-intensive and requires careful handling at each step in the process to produce and maintain the desired quality for the international market.

Drying parchment coffee started immediately after wet processing completed to reduce the high moisture content of the beans and to avoid unwanted fermentation (Arcanjo *et al.,* 2009). As a principal post-harvest activity, it plays an important role in the process of formation of the characteristic color, flavor, and taste, which is the result of complex processing starting from green coffee beans to the cup of coffee.

Coffee drying entails moisture reduction from about 60% after wet processing to an 11% wet basis after drying to achieve a stable storage product. The drying process of coffee grain is a critical step to obtain good quality coffee for a good price. The process reduces the humidity content of the grain to store safe and impedes the microbial action responsible for spoilage. Inappropriate drying (under or over) results in thermal stress and mechanical damage on parchment coffee (Correa *et al.,* 2006) and create the conducive condition for fungal growth and mycotoxin formation.

Ethiopia is the leading coffee producer in Africa, quality of the coffee most of the time, yet of low value, ranking third and fourth in the world market (Nure, 2008). Drying is one of the critical post-harvest steps where quality can be affected.

Sun drying of parchment coffee is still widely practiced in many tropical and subtropical countries. It is the cheapest method of drying coffee but the quality of the dried products is not convincing (Navarro; Noyes, 2001). The conventional way of drying washed coffee in Ethiopia is on open sunbeds and demands high labor input, vast drying space, and longer drying time (Alem, 2006).

Open sun drying condition doesn't guarantee protection from the chance of rewetting of the product. It is also not possible to achieve a uniform and consistent drying. Less uniformly dried parchments when stored together results in migration of moisture among the beans and eventually may elevate the minimum moisture content after drying. Another main constraint in traditional open sun drying of coffee is the possible contamination and growth of mycotoxin producing fungi commonly associated with slow sun drying. Sun drying of coffee takes a week or more in a humid environmental condition which creates a favorable environment for fungi growth and mycotoxin formation (Taniwaki *et al*., 2003).

In the open sun drying method, it is hard to achieve the required quality standard to compete international markets. In such conditions, solar dryers appear increasingly to be attractive as commercial propositions to dry most of the agricultural products (Mekhilefa *et al.*, 2011; Xingxing *et al*., 2012).

In many rural locations of most developing countries, grid-connected electricity and supplies of other nonrenewable sources of energy are scarce or too expensive to use for commercial drying processes. However, solar drying technologies have become a preferred option for drying the majority of agricultural-based products because of their comparative benefits as compared to sun drying. Solar drying of agricultural products in enclosed structures assisted by forced convection is an attractive way of reducing post-harvest losses and maintain a better quality of coffee as compared with conventional sun-drying methods (Jain and Tiwari, 2003). Solar drying offers a better choice in terms of energy, and environmental issues, reduce drying time and improves product quality when compared to conventional drying. The traditional drying system (open sun drying) requires long drying hours which greatly contributes to qualitative and qualitative loss of the product compared to the solar drying system.

Drying layer thickness is another factor that determines the safety and quality of coffee during open sun as well as solar drying methods. According to existing practice in Ethiopia in all parchment coffee-producing wet processing areas, a common drying layer thickness is practiced. So far, no recommendation made to alter the drying layer of coffee as changing weather conditions of wet processing areas. In addition to this, the variation in drying medium temperature and relative humidity in tunnel solar drier not well studied. Therefore this study initiated to address the following issues indicated in the statement of the problem part.

1.1 Statement of the problem

In Ethiopia, like other agricultural product, coffee is dried by conventional drying system which uses open sun by spreading on the ground floor or raised beds. Sun drying is prone to slow drying, rewetting since the coffee subjected to migration of moisture from the ground, humid weather or rain, which may result in physical and structural alterations in the final product, including shrinkage, case-hardening and loss of volatile nutrient components.

Consequently, sun drying yields relatively low quality product that in some instance does not meet the desired international market standards.

During open sun drying highly fluctuating temperature causes to break the parchment layer which in turn reduces the storage life of the beans. The high temperature during open sun drying also causes membrane disruption (Puerto, *2008).* In open sun drying the UV radiation causes extensive discoloration to the beans. In contrary to this, extended drying period under weak solar radiation or cloudy condition prone the beans for mycotoxin formation due to the growth of mold. Especially ochratoxin A can be produced and released by some of the fungal genera of Aspergillus (Rezende, *et al*., 2013). Furthermore, the desired odor and flavor of beans can be altered. To overcome these limitations of open sun drying, these days solar drying is recommended as one of the afordable drying methods. Different works have been done in recent years in solar-assisted drying of coffee at different places. Greenhouse type dryer (Abdullah *et al.,* 2001), mixed solar-type drier (Isquierdo *et al*., 2012), and intermittent drying (Martin, 2009) and studied the thermal, physical and chemical properties of the coffee.

In Ethiopia, solar drying of coffee is at its infancy even though the country has a great capacity of the solar energy resource. Even though the use of solar drying methods as an option to reduce such limitations, the nonuniform drying condition in long tunnel solar driers (~ 16 m long) is also a limiting factor to maintain uniform drying for better quality. Variation associated with drying medium temperature and relative humidity along with the long tunnel result in variation in drying rate (over or under drying) in different parts of the drier. Products exposed to high drying medium temperature with low RH dry faster than their counterparts. It is believed that variation in drying rate among different zones can be harmonized by applying different drying layer thickness. However, so far, no literature data available to show the impact of different solar tunnel drier zone and drying layer thickness on the quality of solar tunnel dried parchment coffee as compared with open sun drying. Therefore based on this, the study aimed to address the following objectives.

1.2 Objectives

General objective

The major objective of this work was to determine the best combination of the drier zone with drying layer thickness for better quality and safety of parchment coffee as compared with conventional open sun drying method.

Specific objectives

i. To determine the best fitting drying kinetic model(s) that best describe drying behavior of parchment coffee in different drier zones
ii. To investigate the impact of different zones of solar tunnel drier on quality and fungal infection of parchment coffee
iii. To investigate the combined impact of dryer zones and drying layer thickness on the quality of raw beans and beverages.

2. LITERATURE REVIEW

2.1 Coffee Production

The genus coffee belongs to the botanical family of Rubiaceae which comprises more than 90 different species (Davis, 2001). Coffee grows at various altitudes, ranging from 550 to 2750 meters above sea level. However, Arabica coffee is best thrives and produced between altitudes of 1300 and 1800 meters above sea level with annual rainfall amount ranging from 1500 to 2500 mm with an ideal minimum and maximum air temperatures of 15 and 25°C, respectively. The total area covered by coffee in Ethiopia is about 600,000 hectares, with a total of annual coffee production ranges from 300,000-350,000 tones, which is about 600 kg ha-1. Out of this, more than 90 % of the coffee is produced by small-scale subsistent farmers, while the remaining comes from private and government owned large-scale farmers (Workfes and Kassu, 2000; MoARD, 2008).

The coffee beans are green when immature and they gradually change to yellow as they ripen, and then become fully red after several months. The beans ripen between ten to eleven months for the Robusta *spp* whereas for the Arabica *spp*, it takes between seven to nine months (Amoah, 2000). The coffee plant takes about 3 years to develop from the seed to first flowering and fruit production. Furthermore a well-managed coffee tree can be productive for more than 80 years, but the economic span is rarely more than 30 years (Wintgens, 2004).

In Ethiopia, coffee production is important to the economy with about more than 15 million people directly or indirectly making a living on it (Nicolas, 2007). Coffee is also a major Ethiopian export product contributing up to 25% of the country's total export earnings (Girma *et al*., 2008: Abu and Teddy, 2013). A market share of 7-10 % makes Ethiopia the major coffee producing country in Sub-Saharan Africa and the fifth producer worldwide, next to Brazil, Vietnam, Colombia, and Indonesia (Girma *et al.,* 2008; Geremew, 2016).

Coffee production is almost exclusively situated in the regions of Oromiya and the Southern Nations Nationalities and People Region (SNNPR) (Abu and Teddy, 2013). It is produced by several types of production systems, including plantation coffee, forest, semi-forest, and garden coffee. These different production systems make up about 5, 10, 35 and 50%

respectively of the total production (Senbeta and Denich, 2006; Taye, 2012). Several factors from the field to post-harvest processing and secondary processing determine the quality of coffee (Musebe *et al*., 2007). For this reason, quality control is necessary for all production and processing stages as the final quality will determine the market price.

Forest coffee is wild coffee grown under the shade of natural forest trees, and it doesn't have a defined owner. Semi-forest coffee farming is a system where farmers clear and select forest trees to let sufficient sunlight to the coffee trees and to provide adequate shade. It is normally fertilized with organic material and usually inter-cropped with other crops. Plantation coffee is planted by the government or private investors for export purposes. Areas covered by coffee production are estimated to be about 800,000 ha with a production of about 400,000 tons of green coffee. In year 2014/15 only, Ethiopia produced 397,500 tons of green coffee (Abu, 2015).

Table 1: Ethiopia's market share of coffee

Ethiopia's share of the world coffee market (1000, 60kg bag)						
	2012/13	**2013/14**	**2014/15**	**1015/16**	**2015/17**	**2017/18**
Ethiopia's coffee production	6,325	6,345	6,508	6,515	6, 532	6,574
World coffee production	154,933	155,671	149,535	150,122	180,000	212,000
Ethiopia's contribution to world coffee market	4.1%	4.1%	4.4%	4.3%	4.3%	4.7%

2.2 Importance and uses of Coffee

Coffee production in Africa accounted for about 12.3% of global production and less than 11% of global exports of the product for the 2017/18 season. Ethiopia accounts for about 4.7 percent of global coffee production. Coffee is Ethiopia's most important cash crop, which plays a central role in Ethiopia's economy and as the country's leading export is an important source of foreign exchange. In addition to its economic importance, coffee is highly related to the country's social, cultural and historical identity. Despite the small contribution of Africa's production, the commodity constitutes a large proportion of both GDP and exports share in some of the small economies in Africa (Coffee Annual, 2018).

Coffee consumption for year 19/20 is estimated to reach 210,000 metric tons, a little increase from the previous year. About 50 percent of production is consumed in country with the rest going for export. Higher-grade coffee is reserved for export, while the lower-grade is consumed in country. Even though most of the coffee is still consumed at home, there is nowadays a new restaurant style coffee shops and road side coffee stand is highly trending. Ethiopia is the biggest coffee consumer in Africa and one of the largest consumers in the world (Coffee Annual, 2018).

Coffee is used almost exclusively in the drinks industry, and is offered to consumers as instant coffee, ground, and also as roasted beans. It is one of the most popular beverages of the present times. In most important consumer countries, roasted coffee is almost always sold as a blend of different origins and qualities. People drink coffee to relieve mental pain and to increase mental alertness. Coffee is also used to prevent Parkinson's disease, gallstones, type

2 diabetes, gastrointestinal, and lung and breast cancer. It is also used to treat headache, low blood pressure, obesity and attention deficit-hyperactivity disorders. An important constituent of the coffee bean is caffeine. The amount of caffeine present in the coffee dependent on the coffee type, variety, the site conditions and other factors. It works by stimulating the central nervous system, heart and muscles (WebMD, 2011).

2.3 Post harvest handling and processing of coffee

2.3.1 Coffee processing methods

According to the method used for processing the well ripened coffee cherries, the world coffee bean production is classified as dry natural, pulped natural, wet hulled or fully washed. Coffee processing is a critical operation in the production of quality coffee. The quality of coffee can be enhanced or compromised in the course of processing. Coffee beans are produced from coffee cherries by one of three methods wet method, dry/ natural method and semi-dry method (Avallone *et al.,* 2002; Masoud *et al.,* 2004; Jackels and Jackels, 2005; Silva *et al.,* 2008; Vilela *et al.,* 2010). These processes are applied to remove the mucilage and to reduce the moisture content of the bean. A tonne of ripe Arabica cherry yields about 120 kg of mucilage in which sugars represent about 9 kg of the dry mass. Mucilage sugars constitute the fermentable carbohydrate for coffee fermentation (Viniciuis *et al*., 2017).

Coffee cherry processing methods are selected and used according to regional climatic characteristics. The process applied to remove the fruit outer layers influences the development of flavours. The pulped natural process is the one that relies least on fermentation, followed by the process, with minimum fermentation and acidity; by the washed process, with controlled fermentation and more acidity; and finally by the natural (dried in the fruit) process, with the longest fermentation times. Mechanically washed coffee (not based on fermentation) can be of comparable quality with the fermented product. “Natural” coffees (naturals) tend to have a more complex presence of flavour-active compounds that provide the high “body” (silky mouth feel), less acidity, and a wider spectrum of fruity notes compared to washed coffees. On the other hand, naturals tend to score lower in terms of the cleanliness, i.e., absence of sensory defects, of the cup. They are also more vulnerable to damage, given the longer periods of exposure to external agents (Mazzafera and Padilha-Purcino, 2004; Anwar 2010; Ameyu, 2017).

Methods of coffee processing in Ethiopia are sun drying of unpulped cherries and wet processing, of which sun drying is preferred by farmers. From the total coffee production of Ethiopia, the highest proportion accounts for dry processed coffee. Washed coffee accounts for 29% while sun-dried accounts for 71% of the processed coffee (Musebe *et al.,* 2007). Similarly, Ethiopia exports about 65-70% natural or sun-dried coffee and 30-35 % wet-processed coffee (Russell, 2008). Quality is the most important parameter in the world coffee trade. It is estimated that the quality of coffee is determined by 40% in the field, 40% at post-harvest primary processing and 20% at secondary processing and handling including storage (Musebe *et al.,* 2007). This underscores the importance of primary processing in enhancing the quality and value of coffee. Quality losses occur due to poor post-harvest on-farm processing, including poor storage infrastructure and contamination with other products.

2.3.1.1 Dry method of coffee processing

This method involves the drying of red cherries without using water at any stage. The harvested ripe cherries spread over a raised bed, concrete, or on any other suitable drying material and raked at regular intervals to prevent fermentation and to ensure even drying. The cherries dried from moisture content of about 65% to 12%. The cherries are dried on beds constructed from chicken wire and fixed on wooden frames raised about 80 cm above the ground. A synthetic black shade net is then placed over the chicken wire before the cherries are spread on top of it. A Hessian cloth is used to cover the drying coffee during mid-day to protect from strong sun. In the night and during rain, the Hessian cloth also serves to protect the coffee from coming in contact with the overlying polythene sheet. Local coffee growers dry the cherries on a manually woven carpet made of palm tree leaves, on bamboo mat and other locally available spreading materials (Anwar 2010; Tsegaye *et al*., 2015).

2.3.1.2 Wet processing method

The wet method involves use of water in most stages. This method involves several stages whereby ripe cherries are transformed into parchment coffee. In fully-fledged conventional wet processing, red cherries are pulped, fermented under water until the mucilage is degraded so that it can be easily washed off. The parchment is then washed and dried to attain moisture content of 10-11.5%.This method has been used normally for *Arabica* coffee as it has a thicker pulp than *Robusta* coffee (Clarke and Macrae, 1987). Briefly, the coffee cherries are pulped and placed into the fermentation tank to remove the mucilage layer of coffee beans using natural microbes for 12–60 hr depending on the environmental temperature and the maturity of the coffee cherries (Avallone *et al.,* 2002; Masoud *et al.,* 2004). Then, the coffee beans are sun-dried on a platform for 7 days to reduce the moisture content to 12%. The parchment coffee is stored with good ventilation before hulling in order to prevent moisture absorption in the green beans.

2.3.1.3 Semi dry method

The semi-dry method is a modification of the wet process as the pulped coffee beans are naturally fermented without water. However, the coffee quality is not as good as from wet processed coffee (Jackels and Jackels, 2005; Vilela *et al.,* 2010).

2.4 Drying of Coffee

Coffee drying is one of the major steps in coffee processing, and has a significant effect on the quality (flavor and aroma) of coffee beans after processing. The coffee is mainly dried by spreading on bare earth surfaces, where it is exposed to the sun's radiation (Alem, 2006). Although it is cheap and fairly effective, it has certain outstanding drawbacks such as increased cost of free land that restricts the sun drying floor area, high labour requirements, contamination from dust and dirt and exposure to erratic rains during the drying process. These drawbacks lead to high moisture of coffee, which is prone to attack by mould. Moreover, the coffee quality will decline drastically. This consequently results into low prices fetched by farmers (Nehemiah, 2008). Singh (1994) reported that because the use of the traditional open sun drying method made the drying rates slow, about 30% of crops were lost in the developing countries. Several efforts have been made to address the drawbacks associated with open sun drying using bare earth surfaces. These include use of alternative drying surfaces such as tarpaulins, concrete surfaces, mats, black polythene sheets, raised tables or trays with wire mesh which keeps the coffee clean and free from contamination (IBERO, 2005: Alem, 2006). Others include use of natural circulation solar dryers which depend on solar radiation, ambient air temperature, relative humidity and wind velocity (Alem, 2006).

According to (Vanderhulst *et al.,* 1990), the objective of solar drying is to supply the product with more heat than is available under ambient conditions, thereby increasing sufficiently the vapour pressure of the moisture held within the crop and decreasing significantly the relative humidity of the drying air. This consequently increases the moisture carrying capacity of drying air, which sufficiently lowers the equilibrium moisture content of the product being dried (Vanderhulst *et al.,* 1990). Experiments conducted in many countries have clearly shown that solar energy can effectively be used to dry agricultural crops (Sarsavadia, 2007). The drawbacks of open sun drying of coffee have been particularly addressed through the development of the greenhouse effect (GHE) solar dryer which in addition minimizes the need for labour to move the crop for safe storage at the end of the day (Alem, 2006).

Freshly harvested and pulped coffee has high moisture content. For example, after the parchment coffee has been washed and drained, it will have a moisture content of 50-65%. Drying is thus the process of reducing the moisture content of this product down to 10-11.5%. Green coffee that is high in moisture (greater than 12 %) can deteriorate due to bacteria, mould, or yeast, especially if the seed is killed. If the seed remains alive, enzymatic activity will cause the cupping quality to change (Gautz *et al*., 2008). Drying of pulped coffee is a critical operation and is done with care, as coffee of excellent origin can lose its quality if drying is not done properly. Under-drying cause's rapid fading of bean color while over-drying leads to unnecessary weight losses and quality degradation. At 10.5% moisture content the parchment is fully dry and safe for storage. At this moisture content and 60% relative humidity, the coffee suffers no quality losses if properly stored (Gautz *et al.,* 2008). Though similar methods are used for drying both cherry and parchment coffee, drying area requirement for dry method is, however, larger for the same quantity of drying cherries

The drying operation is one of the most important steps in the coffee post harvest processing that influences the final quality of the coffee (IBERO, 2005: Corrêa *et al*., 2006). Drying can affect the physical appearance, the yield at hulling and the taste of the beverage (Aregba *et al*., 2006). According to (Cirovelásquez *et al.,* 2009), drying is one part of the post harvest process that is responsible for the removal of excess moisture to a level that is safe for long time storage without any impact to aroma or taste of the final beverage. Several factors affect the coffee drying process including the drying method, drying air temperature, relative humidity, drying air velocity and the drying time (Corrêa *et al.,* 2006).

Various options are open to farmers to dry coffee with minimal risk of re-wetting, quality deterioration and OTA. Reduction in the drying time by using a tunnel of polyethylene to protect the coffee, or a solar dryer to speed up drying or wet processing cherry coffee to parchment, which also reduces drying time as the skin and mucilage are removed from the fresh cherry. Also, coffee may be dried on the cement of a patio or on tables to reduce contamination and hopefully reduce defects in coffee bean quality and OTA levels. The work conducted at the Chumphon Horticulture Research Centre (CHRC), in south Thailand involved comparing demucilaged parchment and cherry coffee dried on tables or cement in or outside polythene drying tunnels (Chapman *et al*., 2006).

Drying is one of the oldest methods of preservation, practiced since ancient times through the removal of moisture to a safe level to maintain quality during storage. Microbial deterioration in the food product is controlled and the rates of other deterioration reactions are reduced. The dried food product is lighter and easier to store and transport. The structural configuration of the dryer must be specific for the product whether grains, fruits, vegetables or other food products. All dryers reduce quality, but many drying methods have been developed to be least detrimental to food product quality. The reduction of product quality is due to enzymatic reactions, mycotoxin development, microorganism growth and insect infestation. Researchers have studied from conventional methods such as open sun drying to the advanced technologies method such as impulse drying to accomplish this task. Open sun drying has been practiced for a thousand of years. Usually, crops require a large area for drying and are spread out and occasionally mixed to ensure uniformity. Since traditional sun drying is a relatively slow process, considerable losses may occur. Furthermore, drying by sun method requires laborers to spread, mix, and protect the product. Sun drying is vulnerable to spoilage of the product due to weather, rodents, birds, and overheating (Alem, 2006; Chapman *et al*., 2006).

Mechanical drying, offers a solution to all of the problems encountered by open sun drying, at a cost. The mechanical drying process is flexible, providing an optimum drying condition by adjusting the temperature in the dryer. The major drawback of mechanical drying is the high capital and operating costs. Economies of scale make this possible for companies, but generally impractical for farmer (Abdullah *et al*., 2001)

2.4.1 Open Sun Drying

There is a significant loss with open sun drying due to exposure to rodents, birds, insects, microorganisms and weather. The use of sun drying becomes limited because of spoilage due to rehydration during unforeseen rainy days. It has also been noticed that direct exposure of agricultural products to solar radiation during high-temperature days may cause case hardening. In case hardening, a hard shell develops on the outside of the agricultural products. It traps moisture inside the shell, which may cause spoilage of the agricultural products. The unpredicted rain or storm further worsens the situation. In addition to that, over drying, insufficient drying, contamination by external materials like dust, dirt, insects, and microorganism as well as discolouring by UV radiation are the main drawbacks of open sun drying. For these reasons, the application of solar dryers with freely available sun energy can be used. Solar dryers also ensure good quality of dried product (Kumar and Tiwari, 2006).

2.4.2 Solar Drying

Solar dryer is an elaboration of conventional open sun drying methods which concentrates solar energy allowing faster drying. An enclosed dryer offers an alternative which can dry the food product in clean, hygienic and sanitary conditions to national and international standards, with the appeal that the energy is from solar radiation, so it is free. Solar dryers have been mainly used in small scale food process industries and are more convenient to rural farmers as it is generally cheaper than mechanical dryers (Abdullah *et al*., 2001).

It is the method to make drying a cheaper process while producing the same quality of dried product as mechanical drying. Solar dryer has an advantage as it produces zero emission, as it needs no fuel to run, but instead uses direct energy from the sun as the energy source. The solar dryer on the other hand has significant weaknesses which are; (i) it is consumes more time for drying and (ii) it is totally dependent on weather conditions for good drying effect. But this can still be bearable as drying in a solar dryer can always be aided with having fan and other auxiliary heating installed in the dryer for better drying (Sarsavadia, 2007).

Basically, solar drying can be classified into three main types, which are direct, indirect and specialized solar dryers (Sharma *et al.,* 2009). Direct solar dryers means that the product to be dried is exposed directly to solar radiation, by placing it in an enclosed dryer that has transparent material covering it. Solar radiation is absorbed by the product itself as well as by the internal surfaces of the drying chamber. For the indirect solar dryers, solar radiation is not directly incident on the material to be dried, but instead solar heated air in the collector is channelled to the drying chamber. Specialized dryers, also known as hybrid solar dryers are normally designed specifically to a product and are distinguished by extra features installed in the dryer, for example solar drying with photovoltaic cells, solar assisted dehumidification system and many more (Fudholi *et al.,* 2010).

2.4.3 Mechanical Drying

In mechanical drying the beans are heated by the passage of hot air which also carries the moisture away. Temperatures must be monitored during natural and artificial drying. Coffee temperature should not exceed 40°C for parchment and 45°C for cherries. It is often thought that overheating can occur in mechanical dryers. There are mainly 2 types of dryers, static and revolving. In revolving dryers, there are tray dryers with stirrer, vertical dryers and rotary dryers, cascade driers, column driers, and flex driers. In all the cases woods, coffee husk, other solid fuel, fuel oils, diesel, gases are used as the main fuel or energy sources. In case of mechanical dryers drying time varies from 20-60 hours according to the type of driers used (Abdullah *et al.*, 2001).

The main disadvantages of the mechanical dryers are that of the fuel cost. Installation cost is also not practical where the majority of producers are small scale farmers like in case of Ethiopia. In addition to that the combusted air which is released from the drier has environmental impact (Abdullah et al., 2001; Kumar and Tiwari, 2006).

2.5 Fungal contamination of coffee

Like other crops, coffee beans are subjected to contamination and consequent colonisation by fungi during production and postharvest stages. No coffee producing country is free from fungal contamination (Taniwaki, 2006). Microbial contamination can occur in the cherries and during harvesting, fermentation, drying and storage of the coffee beans (Silva *et al.,* 2008). Bacteria, yeasts and filamentous fungi have already been reported in the pulp and beans of coffee processed in Brazil, India, Hawaii, Congo, Argentina, Colombia, Costa Rica, Ethiopia and Mexico (Silva *et al.,* 2008).

Extensive studies have been carried out on the mycobiota of coffee in African, Latin American, Middle East, and Asian countries (Ilic *et al*., 2007; Noonim *et al*., 2008; Taniwaki, 2006). It is not currently known however, at which point during coffee growth, harvest and processing most fungal contamination occurred and more likely that levels increase when drying and storage are inadequate (Taniwaki, 2006). Fungal contamination in coffee and an associated ochratoxin A (OTA) problem was due to faults in harvesting and storage practices (Urbano *et al*., 2001). OTA production was earlier believed to be restricted to *Penicilliumverrucosum* (Pitt, 1987; Pitt and Hocking, 1991 and 1997) and *Aspergillus ochraceus* (Ciegler, 1972; Hesseltine *et al*., 1972) with *P. verrucosum* is predominating in temperate regions and *A. Ochraceus* producing OTA in warmer areas (Moss, 1996). However, a number of additional *Aspergillus* species can produce OTA particularly those belonging to *Aspergillus* Section Nigri: *A.* a*wamori*, *A. foetidus*, *A. niger*, *A. carbonarius*, *A. lacticoffeatus* and *A. sclerotioniger* (Abarca *et al*., 1994; Samson *et al*., 2004) as well as those belonging to *Aspergillus* section Circumdati: *A. cretensis*, *A. flocculosus*, *A. pseudoelegans*, *A. roseoglobulosus*, *A. steynii*, *A.* s*ulphurous* and *A. westerdijkiae* (Frisvad *et al*., 2004). In tropical zones, OTA is mainly produced in coffee beans by *A. ochraceus, A. carbonarius* and

A. westerdijkiae (section Circumdati), which was recently dismembered from A. ochraceus, due to their important OTA production and occurrence (Bacha *et al*., 2009).

In coffee, ochratoxigenic fungi may develop on ripe and unripe cherries (Joosten *et al.,* 2001), on beans, during fermentation (Batista 2009, Kouadio, 2012, Rezende *et al*., 2013), during storage, packaging and during roasting and brewing (Tozlovanu and Leszkowicz, 2010; Malir *et al.,* 2014).

Kouadio (2012) analysed the mixing of coffee cherries dried on aerated beds and the frequency of mixing on the fungal growth and production of OTA and defined the temperature and water activity conditions for the production of ochratoxin A by fungi grown on a coffee-based culture medium. Subsequently, they showed the development of toxigenic fungi after cherry harvest before the start of sun-drying, in Robusta varieties (Kouadio, 2014). To avoid toxigenic fungi growth, recommendations about the correct drying process have been established (Santino *et al*., 2005). The coffee beans need to be harvested intact, and kept on aerated beds, eventually covered

The OTA-producing fungi require favourable conditions during a certain period of time to grow and produce the toxin. The level of available water is the most important factor to be considered. At high water activity (aw > 0.95) OTA-producing fungi will not likely grow, as fast-growing hydrophilic fungi and yeasts grow first. At lower water activity (aw <0.80) the OTA-producing fungi can be present but not produce the toxin, and at aw below 0.78–0.76 they cannot grow. Therefore the most important point is to control the period of time in which coffee remains in the drying yard, in the range of water activity where OTA-producing fungi can grow (aw 0.8–0.95). According to experimental results, 5 days or less in the drying yard is enough and effective to prevent OTA accumulation. In general, a maximum aw of 0.67 to 0.70 and moisture content < 12.5% (wet basis) is sufficient for protecting parchment coffee from damage by fungi (Kaudio, 2012).

2.6 coffee Bean Quality

According to the International Organization for Standardization (ISO), quality is a set of inherent characteristics of product, system or process which fulfils the requirement of customers and/or interested parties (Viadiu *et al.,* 2006). These inherent characteristics are collectively called attributes. Coffee quality is attributable to its botanical variety, weather and topographical conditions, handling and care during growing, harvesting, storage, preparation for export and transport.

Coffee quality deals with price, taste, flavour, effects on health, alertness, geographical origin, environmental and sociological aspects (Viadiu *et al*., 2006). More specifically, (ISO, 2004) defined a standard for green coffee quality (ISO 9116 standard) as, it requires several pieces of information, like the geographical and botanic origins of the coffee, the harvest year, the moisture content, the total defects, the proportion of insect-damaged beans and the bean size. These ISO standards define methods of measurements for several of these qualities such as, defects, moisture content, bean size, some chemical compounds and preparation of samples to perform cup tasting.

According to the definition of quality and standards authority of Ethiopia (QSAE) (2000) a quality is conformance with requirements or fitness for use in which the parties involved in the industry (customer, processor, supplier, etc) should agree on the requirements and the requirements should be clear to all stake holders involved in the process. On the other hand, Coffee quality control and auction Centre was established with a key objective of maintaining coffee quality control (Asfaw, 2007).

2.7 Quality parameters of coffee bean.

2.7.1 Bean physical quality

The International Coffee Organization, (ICO, 2002) has implemented the Coffee Quality Improvement Program with recommendations to exporting countries. According to the program, it is not recommended to export coffee with the following characteristics: for Arabica, in excess of 86 defects per 300 grams sample and for Robusta, in excess of 150 defects per 300 grams). It is not recommended to export coffee with the characteristics having foreign material of non coffee origin; foreign materials of non bean origin, such as pieces of parchment or husk; abnormal beans for shape regularity or integrity; abnormal beans for visual appearance, such as black beans; abnormal beans for taste of the cup after proper roasting and brewing. Bean size, which is usually determined by screening, is of particular importance to roasters since bean of the same size would be expected to roast uniformly. In addition, these size and shape differences of coffee beans were influenced by botanical variety and environmental growth circumstances (Ponte, 2002).

2.7.1.1 Moisture content

The moisture content of coffee bean is an important attribute and indicator of quality. High moisture content of the beans is a loose sensorial defect. If coffee beans are too wet (above12.5 % moisture), can mould easily during storage. In addition, if the beans are too dry (below8 % moisture) they lose flavour (Leroy *et al*., 2006). The moisture content can influence the way coffee roast and the lost of weight during roasting. Green coffee with low moisture contents tend to roast faster than those with high moisture content (Leroy *et al*., 2006; ITC, 2002).

Moisture is an important attribute and indicator of quality. Quality deterioration occurs due to an increase of moisture content of the bean, the spoiling of the raw appearance of the bean by loss of colour fading or tainting, or to the introduction of unpleasant flavours, by infestation of storage insects or by infection with moulds or bacteria (Behailu *et al*., 2008). A market survey conducted in Europe in 1998-1999 for the common fund for commodities concluded that for Arabica coffee beans the most important defect for a trader or a roaster is the moisture content (CFC, 2004). As reported by (Woelore, 1995), coffee could not be stored in parchment form in the primary stores beyond 4 to 5 months.

2.7.1.2 Drying characteristics of parchment coffee

Thin-layer drying is widely used to determine the drying kinetics of crops and has been carried out in various types of dryers (Lee and Kim, 2008; Alara *et al.*, 2018; Jiang *et al.,* 2017The drying behavior of crops have been predicted the drying behavior of a product to design a dryer using thin-layer drying mathematical modeling (Aidani *et al*., 2016; Mahjoorian *et al.,* 2017; Mujaffar and John, 2018; Naderinezhad *et al*., 2016; Younis *et al*., 2018)

The quality of Coffee depends on the drying methods. Because too fast drying or too slow drying can affect the physical and chemical contents of the product. During wet processing of coffee, the parchment needs to be dried quickly to prevent microbiological activities, such as mould and yeast growth which can result in coffee cup defects and also develop toxins which can brings health problem to consumers. Uneven drying due to fluctuation of drying air flow rate and drying air temperature interrupted drying which is rewetting the bean due to moisture migration and excessive drying temperature brings cup quality defect and breakage during hulling and transportation (Borem *et al.,* 2017)

2.8 Post harvest factors affecting parchment coffee quality

2.8.1 Effect of processing method on coffee quality

In Ethiopia, both dry and wet processing methods are operated, which accounts for 70% and 30% of coffee production respectively (Jacquet *et al*., 2008). According to Bytof *et al*., (2007), report the defined ambient conditions of any post-harvest processing can have a high effect on the time course of the metabolic reactions that occur during that processing period. Recently, it has shown that the variation in the drying procedure in the course of dry and wet processing strongly affects the abundance of various sugars, representing essential aroma precursors (Kleinwächter and Selmar, 2010). High mean values for good cup quality (attributes like acidity, body and flavour) and bean physical quality (attributes like odour) as compared to the dry processing method. From his result it can be concluded that wet processing method is the best approach to obtain fine and typical quality flavour in the cup that attract consumers according to their preference in the international market. The perceived acidity of washed coffees is also significantly higher than the acidity found in naturally (dry) processed coffees. This is likely due to an increase in the body of naturally processed coffees relative to wet processed coffees since body masks the coffee’s acidity (Yigzaw, 2005). Other outhors recommended that effort should be concentrated on the very critical post harvest practices such as harvesting, processing, drying, storing and transporting of coffee cherries, which are liable to be a major influence components of the quality of the cup.

2.8.2 Effect of drying Temperature on Coffee Bean Quality

The natural limits to the postharvest life of all types of fresh produce are affected by biological and environmental conditions. Temperature, without a doubt, is the most important factor affecting postharvest life. This is because temperature has a profound effect on the rates of biological reaction, e.g., metabolism and respiration. The Van"t Hoff Rule states that the rate of a biological reaction increases 2 to 3 fold for every $10^{o}C$ rise in temperature. An increase in temperature causes an increase in the rate of natural breakdown of all produce as food reserves and water content become depleted (Kitinoja and Kader, 2002). Coffee with moisture content as low as 11.0% is said to loss their quality after six months under a temperature of $35^{0}C$ whereas others with moisture content above 15.0% maintains their quality at temperature as low as $10^{0}C$. Coffee, therefore, needs to be maintained at low storage temperatures in order to reduce its rate of metabolism and respiration. The duration for light exposure (day length) and the intensity of light have both been reported to affect coffee quality (Avellino *et al.,* 2005). Shelf life is shortened at lower altitudes by approximately three months. However, for those stored above 1400m, the natural shelf life can be as long as eight (8) months. High altitudes as locations for coffee storage however, will be most appreciated by importers, exporters and industrialists (Wintgens, 2004).

2.8.3 Effect of Moisture content on Coffee Bean Quality

The moisture content of the coffee bean is a very critical parameter of coffee and is an important attribute and indicator of quality. At higher moisture content, the coffee can lose its sensory effects and at lower moisture content (< 9.0%moisture content) may be irreversibly damaged in colour, as well as in their cup test, flavour and consistency which means that it is not worth reducing the moisture content to such a low level when drying (FAO, 2010).

If the beans are too wet, for example, more than 12.5% moisture, the beans can easily grow mouldy during storage, whiles, if too dry (below 8%) they lose flavour. The way coffee roasts are influenced by the amount of moisture in the bean as well as its weight loss. (Leroy *et al.,* 2006) indicated that Green Coffee tends to roast faster when the moisture content is lower than those with higher moisture content. Internationally, coffee should not be exported when the moisture contents are outside the internationally accepted levels (8.0% $\leq$ X $\leq$ 12.5%), (Viadiu *et al*., 2006).

2.8.4 Effect of RH on coffee bean quality

Studies have also revealed that at moisture levels 15% - 16%, the corresponding Relative Humidity (RH) level is 75%. According to Souza, (2008), levels like these are seen as critical for fungal development according to the Henderson balance. A RH level of less than 60% is most acceptable to keep down further fungal growth. Reducing the available water down to the safe storage level of water activity, the chemical reactions and microbial developments are slowed down considerably (Christensen and Kaufmann, 2006). One of the most indicative effects of high RH in combination with temperature variations allow for condensation of water which facilitates fungal and insect infestation. However under ideal conditions, the general losses of coffee during storage should not exceed 1% in order to maintain the weight during storage and transportation (Wintgens, 2004).

Relative humidity is the ratio of the partial pressure of the water vapour to the equilibrium vapour pressure of water at the same temperature. The relative humidity of air is an indicator of the drying capacity of the air. A low value of RH is generally an indication of a high drying capacity.

3. MATERIAL AND METHOD

3.1 Experimental site and sample preparation

The experiment was conducted at Jimma University College of Agriculture and Veterinary Medicine, Food Science and Postharvest Technology demonstration field, located at 356 km southwest of Addis Ababa at about 70 33''N latitude and 360 57''E longitudes and altitude of 1710 meter above sea level (m.a.s.l). The mean maximum and minimum temperatures are 26.8°C and 11.4°C, respectively and the maximum and minimum relative humidity are 91.45% and 39.92%, respectively (Bpedors, 2000).

Coffee (*Coffee Arabica* L.) fruits were harvested from Saqqa chokorsa woreda, Wokito Kebele. The coffee was harvested manually, selecting only mature fully ripe red cherries. After that, fruits with lower specific weight (dried out, attacked by insects, malformed, etc.) were removed through separation in water, and then one more time manual selection was made for removal of under ripe and overripe fruits. The mean initial moisture content of the fruits was determined in an oven at 105 ± 3°C (Leicester, LE67 SFT England) for 16 hours (ISO, 2003). The fruits were subjected to wet processing methods, pulped, fermented for 24hr and finally washed there at the washing site *wokito* farmer's union wet mill to obtain washed parchment coffee**.** The washed coffee was transported to drying sites on the same date in less than an hour.

Right before transferring the washed coffee to the solar drier, hand picking was also done to remove coffees with pulp attached, machine is broken, parchment removed, etc. to reduce biases of the result. Coffees with broken parchment, burnt or discolored bean were removed before tasting to minimize the disturbance/interference caused by other external factors rather than the main factors under investigation

3.1.1 Description of tunnel solar drier

The solar tunnel drier has a length of 24 meters and a width of 2 meters as indicated in figure 1. It is laid on brick stands which have a height of 0.8 meters. The solar absorber is 8 meters long and the drying zone is 16 meters long. The fan located at the entrance of the solar drier has a capacity of 75 watts to suck and mix ambient air with air in absorber section to reduce the very hot temperature before it enters to zone one of the drier. The fan operated by power collected by solar panel (WS 80/85 Mono RHA/D, Germany) attached at the top of the front side of the absorber. Function of the fan was to suck and push the heated air in the solar collector area to the drier zone.

Solar panel attached with the fan as energy source during day time, the fan sucks and push ambient air into the absorber to be heated. The absorber is black in color (8 meters long and 2 m wide). Total drier zone of 16 m meters subdivided into three zones each having 5.33 meters long. The drier zones were determined after collecting preliminary data of temperature and relative humidity (RH) patters in different drier zones with the help of data acquisition devices (Testo, model 184 H1, Germany). According to a preliminary experiment and from the result, three drying zones are identified with a temperature range of 40-50^{0}C, RH 25-35% (ZONE 1); 50-60^{0}C, RH 18-28% (Zone 2); and 60-70^{0}C, RH 11-21% (Zone 3).

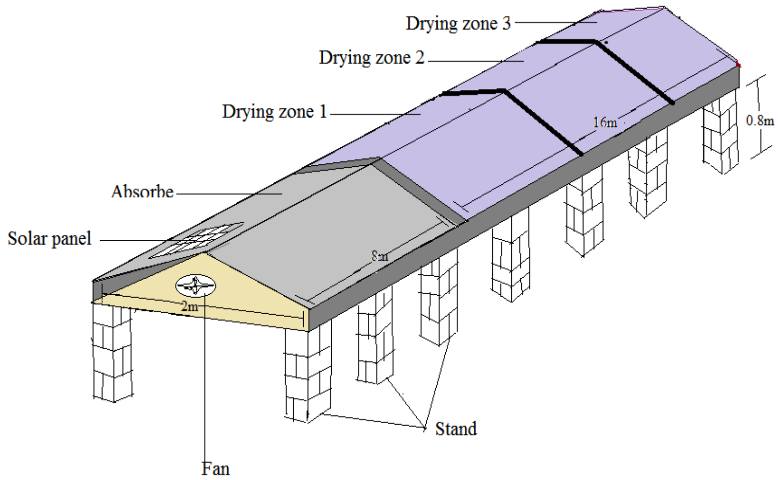


Figure 1: Schematic diagram showing details of solar tunnel drier used for the study

3.2. Experimental Design

A factorial experiment laid out, considering two factors of drier zones and drying layer thickness each factor having three levels. Solar tunnel dryer levels were zone 1, zone 2, zone 3 as indicated in figure 1 assuming variation in drying medium temperature and relative humidity among the zones. Open sun of drying also considered as the fourth level to compare results. Drying layer thickness 2, 4, and 6 cm in each drier zone as well for open sun method.

The experiment was laid as 4X3 factorial combination arranged in Randomised Complete Block Design (RCBD) and replicated three times in 36 experimental units.

3.3 Determination of Physical property and drying characteristics

3.3.1 Temperature and Relative humidity Measurement

Ambient air temperature and relative humidity were measured inside and outside of the tunnel using a temperature and relative humidity data logger (Testo, 184 H1, Germany). Both parameters were measured in the one-hour interval during the day time (9:00 am to 5:00 pm). Drying was performed between December 2018 up to June 2019.

3.3.2 Moisture content of the parchment coffee

The moisture content of parchment coffee after washing as initial moisture content and after drying was determined by drying of 3 replicate samples each having 5 g using the convective oven (Leicester, LE67 SFT England) at 105^{0}C for 16 hours (ISO, 2003). The average value of MC (%) was determined using Eq. 1.

$$MC\ (\%) = \frac{W1-W2}{W1} * 100 \quad \text{...} \ (1)$$

Where

W_1= Initial weight

W_2 = final weight after drying

MC=Moisture content

3.3.3 Determination of Moisture Ratio of the parchment coffee

Concerning drying data analysis, the moisture ratio (*MR*) is essential for describing the various models of thin-layer drying. The moisture ratio during drying was determined using the following equation.

$$MR = \frac{(M-Me)}{(Mo-Me)} \quad \text{......................................}\textit{equation 2}$$

where *MR* is the dimensionless moisture ratio;

M is the moisture content at any time in %;

M_e is the equilibrium moisture content in %;

M_0 is the initial moisture content in % wet basis

However, MR is simplified to M/M_0 in place of the above equation since the relative humidity of the drying air fluctuated continuously under the sun drying (Diamente and Munro, 1993). The value of M_e is relatively small for long drying times, compared to values of M and M_0, so the equation can be simplified to M/M_o (Balbay and Sahin, 2012). weight loss in terms of moisture was measured at every one-hour interval during drying starting from 9:00 am to 5: 00 pm in the evening to determine moisture ratio using the above formula.

3.3.4 Determination of Drying Kinetics of the parchment coffee

A good understanding of the drying rate is important to develop a drying model (Gupta and Patil, 2014). Kinetic modeling helps to describe changes occurring during drying and their rates quantitatively. The understanding of the basic mechanisms is vital for quality modeling and quality control. The rate with which drying proceeds is the resultant of the driving force and the resistance against change. There is thus an intimate link between thermodynamics and kinetics (Boekel and Tijskens, 2001). Hence, drying kinetics aids in identifying appropriate drying methods and controls the processes of drying. It is sometimes expensive to conduct a full-scale experiment to determine the suitable conditions for drying. But, drying kinetics commonly used to express the moisture removal process and its relation to the process variables.

3.3.5 Drying kinetic models

To select a suitable model(s) to describe the drying process of coffee beans, seven different thin-layer drying models were selected to fit the experimental data. The selected drying models are presented in Table (2). Coefficients of the models were determined and their goodness of fit was evaluated by various statistical parameters such as root mean square error (RMSE) and chi-square value (x^2). For the best fit, R^2 value should be higher and RMSE and x^2 value should be lower.

The value of each drying constant was determined using the Microsoft Excel Solver. The best-fitted model was selected based on its R^2 value, and the Root Mean Squared Error (RMSE) (Eq. 3) and Chi-squared (χ^2) (Eq. 4), the R^2 value was computed using the RSQ function of Microsoft Excel. R^2 was used as the primary comparison criteria for selecting the best model to fit the models tested to the experimental data. The primary selection criteria for these models are the simplicity of use and few variables are involved.

$$RMSE=\sqrt{\sum_{i=1}^{N}\frac{\left(MR_{pre,i}-MR_{exp,i}\right)^2}{N}} \quad \text{.......................equation 3}$$

$$\chi^2=\sum_{i=1}^{N}\frac{\left(MR_{exp,i}-MR_{pre,i}\right)^2}{N-n} \quad \text{.......................equation 4}$$

The characteristics of the moisture ratio across the drying time were then fitted to the thin layer drying models depicted in Table (2). The models were used by (Muhidong *et al.*, 1992), (Corrêa *et al.*, 2006), (Kingsly *et al.*, 2007), (Yadollahinia *et al.*, 2008), (Hii *et al.*, 2008), (Ibrahim *et al.*, 2009), (Meisami-asl *et al.*, 2009), and (Muhidong, 2011) during drying of coffee berries and parchments under different drying condition. These models are often used for agrifood products since they assume that mass transfer during drying is mainly controlled by diffusion into the product (Measami-asl *et al.*, 2009).

Table 2 : Models used to determine drying characteristics of parchment coffee in a solar tunnel drier and open sun condition

No	Model Name	Equation	Reference
1	Modified Midilli	MR=exp(-kt^c)+bt	Ghazanfari *et al*., (2006)
2	Diffusion Approach	MR=a*exp(-bt)+(1-a)exp(-bkt)	Muhidong *et al*., (2013)
3	Modified Page	MR = exp(-(a.t)b)	Kingsly *et al*., (2007)
4	Newton	MR = exp(-a.t)	Muhidong *et al*., (2011)
5	Henderson and Pabis	MR = a.exp(-b.t)	Ibrahim *et al.,* (2009)
6	Two Term	MR = a.exp(-b.t) + k.exp(-d.t)	Meisami-asl *et al.,* (2009)
7	Verma	MR = a.exp(-b.t) + (1-a).exp(-k.t)	Hii *et al*., (2008)

Where; t represents elapsed drying time in hours; and a, b, k and e; are drying constants.

3.3.6 Determination of Effective diffusivity of parchment coffee

Fick's second law of diffusion (Crank, 1975) describes a phenomenon of liquid diffusion in the drying of food materials assuming unidimensional moisture movement volume change (Muhidong *et al.,* 2013; Siqueire *et al*., 2017; Deeto *et al*., 2018). The analytical solution for diffusion for long drying time is given by (Akpinar, 2006) (Eq. 5).

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} exp\left(-\frac{(2n-1)^2 \pi^2}{4L^2} Dt\right) \text{--------} \textit{equation 5}$$

where *MR* is moisture ratio, *M* is the moisture content at any time (kg water/kg dry matter), M_o is the initial moisture content (kg water/kg dry matter), *n* = 1, 2, 3, . . . the number of terms taken into consideration, t is the time of drying in second, *D* is effective moisture diffusivity in m^2/s and *L* is half of the thickness of the parchment of Coffee (in meter). Only the first term of equation (5) is used for long drying times (Lopez *et al*., 2000) (drying longer than 5 min), hence Eq. 5 reduced to Eq. 6**:**

$$MR = \frac{8}{\pi^2} exp\left(-\frac{\pi^2}{4L^2} Dt\right) \text{------------------} \textit{equation 6}$$

Rearranging equation (6), the effective moisture diffusivity can be obtained from the plot of ln MR versus drying time. The slop of the graph of natural logarithm experimental moisture ratio versus drying time gives as $\frac{-Deff}{4L^2}$. Knowing the experimental moisture ratio and the parchment Coffee thickness the effective moisture diffusivity was calculated.

3.4 Determination of Physicochemical property of dried parchment coffee

3.4.1 pH

pH value determined according to the method described in Tawfik and EL Bader (2005). The pH was determined by taking 2.25 g of ground coffee, cooled to room temperature and mixing with 10 ml of hot water at 80^0C temperature and the pH was determined using digital pH meter (portable CP-500, Taiwan) at ambient condition.

3.4.2 Total Titratable acidity

Titratable acidity of the coffee bean was determined by mixing green coffee powder (10 g) with 75 mL of 80% ethaol and kept under gentle agitation for 16 h. A portion of 25 ml of the extract was diluted to 100 ml with distilled water. Titratable acidity was then determined by titrating with fresh 0.1N sodium hydroxide solution. The volume of sodium hydroxide required for neutralization was noted and titratable acidity was calculated according to (AOAC, 2000). It was expressed in mL of NaOH 0.1N consumed.

3.4.3 Total soluble solid content

Total soluble solids of the powdered coffee sample determined by refluxing coffee powder (2 g) with hot water (200 ml) for 1 h and made up to 500 ml. An aliquot (50 ml) was evaporated to dryness in the oven (Leicester, LE67 SFT England) followed by heating in a hot air oven at 105 ± 2^{o}C for two hours to get concurrent weights and the amount of total soluble solids was determined using a refratometer (DR201-95, Germany) (AOAC, 2000).

3.4.4 Ether extract

The ether extract (Crude fat) content of the dry samples was performed gravimetrically following AOAC Procedure of Soxhlet method 960.39 (AOAC, 2007). Five gram of ground coffee sample was introduced into a Soxhlet thimble and then extracted for at least six hours on the Soxhlet extractor with diethyl ether as the solvent. The extracts were then evaporated in an oven (Leicester, LE67 SFT England) at 60^{0}C until all the diethyl ether evaporated. The collected fat then weighed and the result expressed as weight percent.

3.4.5 Total phenolic content

Total phenolic content in powdered green coffee determined by using the Folin-Ciocalteu reagent according to the colorimetric method (Singleton and Rossi, 1965). Approximately 2 mL of filtered extract was mixed with 30 mL of sodium carbonate solution at 7.5% (w/v) and 7.5 mL of Folin-Ciocalteu reagent. Subsequently, 200 µL of distilled water added and the solution was mixed. The mixture was heated at 60 ºC for 5 minutes and allowed to cool at room temperature. The absorbance was measured using a spectrophotometer (UV-CE CIL Instrument, China) at 700 nm. A calibration curve was made from Gallic acid standard solution (100, 150, 200, 250 and 300 mg/L) (Appendix Figure 1; R^2=0.989) and the blank prepared with distilled water. The total phenolic content was expressed as milligram Gallic acid equivalent (GAEs) per dry weight material using the standard curve.

3.4.6 Total Antioxidant Capacity

The free-radical scavenging capacity (RSC) of the extracts was evaluated by DPPH radical assay, as described by (Singleton *et al*., 1999) Briefly, a 1.0 ml freshly prepared methanolic solution of DPPH (2,2-Diphenyl-1-picrylhydrazyl) radical (100 μM) mixed with the tested extract solution at various concentrations (0.5-100 μg/ml). The contents were vigorously mixed, incubated at room temperature in the dark for 20 min, and the absorbance measured at 517 nm. The measurement conducted using a UV-VIS spectrophotometer (UV-CE CIL Instrument, China). In each experiment, the tested sample alone in methanol used as a blank and DPPH alone in methanol was used as the control. The percentage Radical Scavenging Activity (RSC) of the tested extracts calculated using Eq. 7.

$$\text{RSC (\%)} = \frac{(\text{Acontrol} - \text{A sample})}{\text{Acontrol}} * 100 \text{ ....} \textit{equation 7}$$

where *A control* and *A sample* are the absorbance values of the control and the test sample, respectively.

Moreover, to compare the radical scavenging efficiency of the extracts, the IC_{50} value indicating the concentration that caused 50% scavenging of the DPPH radical calculated from the graph plotted by Radical Scavenging Capacity percentage against the extract concentration. All experiments were carried out in triplicate and average values were reported.

3.5 Determination of raw bean and cup quality

3.5.1 Raw bean quality

First, the moisture content in the samples was measured on the same day of analysis using the digital electronic moisture taster (mini CAG, Germany). Based on the given parameter raw quality was assessed for shape and make color and odor. The raw quality assessed from primary and secondary defects (10% each), color (10%) and shape (10%). The total raw bean quality score reported out of 40% (CLU, 2007 and Gabre-Madhin, 2012).

3.5.2 Cup quality

3.5.2.1 Coffee roastingand grinding

For cup quality analysis, 350g of the green coffee bean was used. For roasting purpose, 100g of the green bean was used from 350g. The 100g reweighed before roasting for accuracy and added to the cylindrical roaster. The roasting temperature was adjusted to 220^0C and the roasting lasted for 6-10 minutes (Gabre-Madhin, 2012). While roasting, samples were taken to monitor the process. The roasting stopped when the color of the bean became light-dark. The roasted coffee is then allowed to settle and cool down before grinding. Before grinding a small amount of the roasted bean per sample used to clean the grinder and to avoid discrimination might be introduced from the previous grinding. Then the coffee was ground to a fine powder which is directly added to the testing cup.

3.5.2.2 Preparing brew

Eight grams of coffee powder were used in each cup, with 180 ml capacity. The ratio of coffee powder to boiled water is similar to (CLU, 2007) and (Gabre-Madhin, 2012). Freshly boiled water was poured on to the ground coffee up to about half the size of the cup, followed by stirring the content to ensure the homogeneity of the mixture before filling the cup to full size, the volatile aromatic quality and intensity parameters were evaluated by sniffing. Then, cups filled to the full size (180 ml) and left to settle, the floater skimmed and the brew ready for cup tasting by five trained panelists. Liquor evaluated for acidity, body and flavour. finally, the mean of each variable by the panel used for statistical analysis. Five cups per sample prepared for each tasting session. The samples replicated for each sample was arranged at random. The sensory evaluation of each sample and the cup quality was carried out by a group of five trained panellists and evaluated out of 60%, which is the sum of cup cleanness, acidity, body and flavor each of them contributing 15% of the overall scores.

3.6 Determination of fungal Infection

Fungi isolation was performed by direct plating technique (Perrone *et al.,* 2007), on PDA medium (potatoes extract 4 g/L, dextrose 20 g/L, agar 15 g/L, distilled water 1 L) using the method of (Leong *et al.,* 2007) as follows. Fifty beans per sample were plated and incubated at 28^{o}C for 7 days in the laboratory incubator (Heraeus, Germany). The parchment coffee was placed aseptically on PDA on 9 cm Petri dish, 5 beans per plate replicated three times. Determination of fungi genus was made by studying the morphological analysis macroscopically by visualization through the binocular microscope and microscopically by observing a piece of mycelium and conidial head, with the objective (x40), between the slide and coverslip.

Fungi infection percentage: The infection percentage (%) of coffee beans by fungi determined as the ratio of infected seeds over the total number of coffee seeds tested, as indicated in Equation 8.

Mean ratio of seed infection= $\frac{No.of\ seed\ on\ which\ a\ fungal\ species\ identified}{No.of\ Seed\ tested} * 100$ ***.....equation 8***

3.7 Data analysis

Data for physicochemical and sensory property were subjected to analysis of variance (ANOVA) using Minitab version 16 statistical computer software program. Tukey HSD method at 95% confidence level used for treatment means separation whenever significant difference occurred.

For the determination of drying characteristics, Microsoft Excel Solver add-ins were used to predict the constants values.

Fungal infection analysis was done using the formula mentioned in equation 8 and after that, the result obtained were subjected to ANOVA using Minitab and analyzed in the same manner done for the physicochemical and Sensory parameters.

4. RESULTS AND DISCUSSION

4.1 Drying temperature and relative humidity during drying time

The average temperatures recorded during the drying period from 09:00 am; to 17:00 (between December 31/ 2018 up to January 5/ 2019) were 23, 45, 55 and 64°C for ambient, zone 1, zone 2 and zone 3 respectively. On the other hand, the average relative humidity values were 47, 30, 23 and 15% for ambient, zone 1, zone 2 and zone 3 respectively. The solar tunnel dryer, therefore, generates relatively higher air temperatures and lowers relative humidity to improve drying rates of parchment coffee as compared to open sun conditions. The highest drying temperature and the lowest relative humidity were achieved at 13:00 pm for all the drier zones and open sun, while the lowest temperature and the highest relative humidity recorded at 9.00 am. Figure 2 shows the recorded average ambient and dryer temperatures and relative humidity during the drying periods starting from 9:00 am to 17:00 pm.

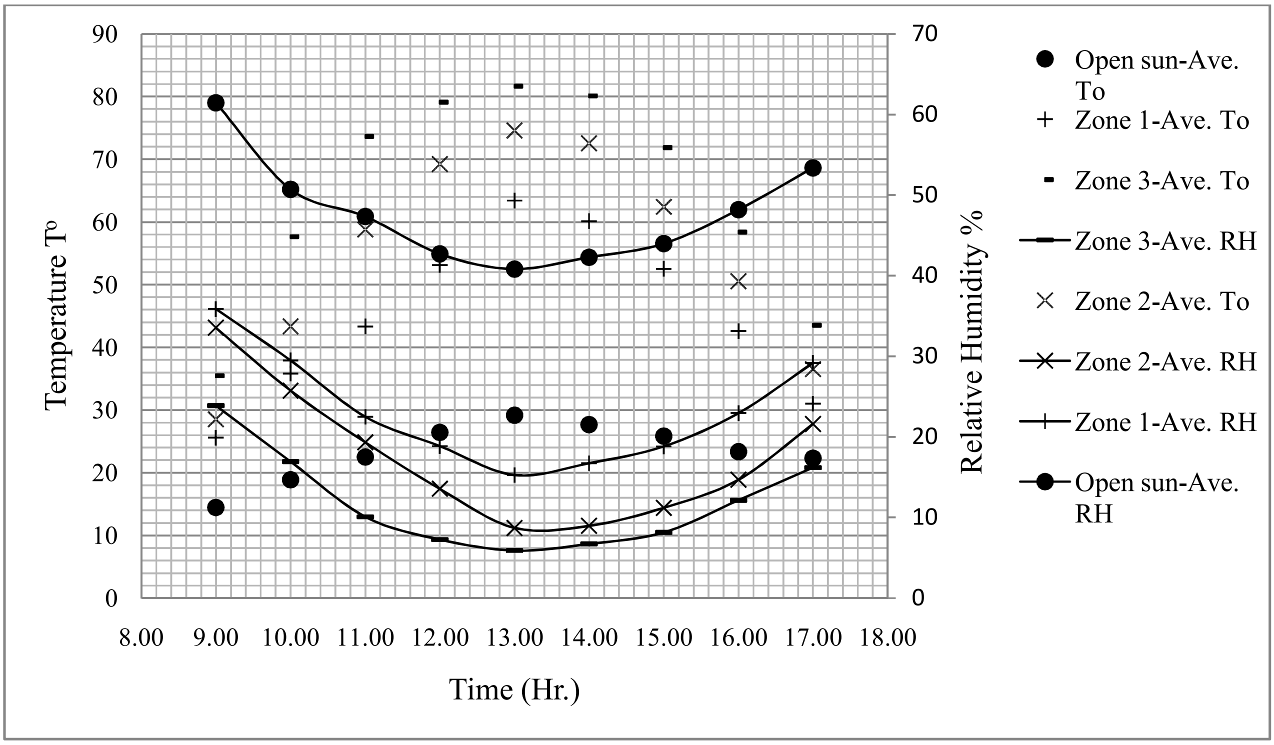


Figure 2: Average hourly temperature and relative humidity during drying starting from 9:00 am to 17:00 pm.

4.2 Effect of drying zones and layer thickness on drying characteristics

4.2.1 Hours to drying

Table (3) shows significant ($p<0.05$) variation among drying zones and level of layer thicknesses. The coffee parchment dried under zone three with drying thickness of 2 cm took the shortest drying time (14 hr) followed by the coffee dried in the same zone with drying thickness of 4 cm (17.3 hr). While the coffee dried under open sun having a layer thickness of 6 cm took the longest (47 hrs) drying hours. Among the three thicknesses dried under zone one, the coffee dried with a thickness of 2cm dried faster than the other two thicknesses. Under zone two conditions, the parchment coffee with a thickness of 2 cm and 4 cm resulted in a statistically similar result (20.7 and 21 hrs) respectively. While the coffee dried with a thickness of 6 cm showed the longest drying hours (32 hrs). The longest drying hours were recorded for the open sun drying in all the three drying thicknesses tested (Table 3). Generally, amongst the three different zones of solar tunnel drier, coffee dried under zone three was the fastest to dry in all the three thicknesses.

Generally solar tunnel drier showed reduced drying time which ranged from 14 to 39 hrs compared to the conventional open sun drying which took 32, 36 and 47 hours for drying thickness of 2, 4 and 6cm respectively. Compared to the solar tunnel dryer zones, open sun drying resulted in longest drying hours, which is not good for the quality of the coffee as extended drying can compromise the quality attributes.

The finding of the present work supported by (Lower *et al*., 2007) pointed out that coffee beans may require more days to dry depending on the methods of drying and the density at which the beans dried. The increase in air temperature and lower RH resulted in a greater water vapor difference, which makes water removal easier and quicker (Siqueira *et al*., 2012). The result from this study indicated, different zones of the drier exhibited different drying times for different layer thicknesses. If a constant drying layer of 4 cm considered, the time required to attain optimum drying was 17 hours at zone 3, 21 hrs at zone 2 and 28 hrs at zone 1. As indicated in table 5, to compensate for the impact of relatively higher drying temperature at zone 3 the drying layer can be increased to 6 cm as compared to drying layer thickness of 5.5 cm (interpolated) for zone 2 and 4 cm layer thickness for zone 1. Therefore the variation in drying temperature and relative humidity at different zones of the drier can be compensated by varying the drying layer thicknesses to achieve uniform drying along with the long tunnel solar drier.

Table 3: Influence of drier zones and layer thicknesses on the drying hours of parchment coffee.

Dryer Zones	Layer thickness	Hours to drying
	2cm	32.7±0.33[d]
Open sun	4cm	36.7±0.33[c]
	6cm	47.0±0.00[a]
	2cm	25.3±0.33[f]
Zone 1	4cm	28.3±0.33[e]
	6cm	39.3±0.33[b]
	2cm	20.7±0.33[g]
Zone 2	4cm	21.0±0.00[g]
	6cm	32.0±0.00[d]
	2cm	14.0±0.00[i]
Zone 3	4cm	17.3±0.33[h]
	6cm	28.3±0.33[e]
CV%		1.35

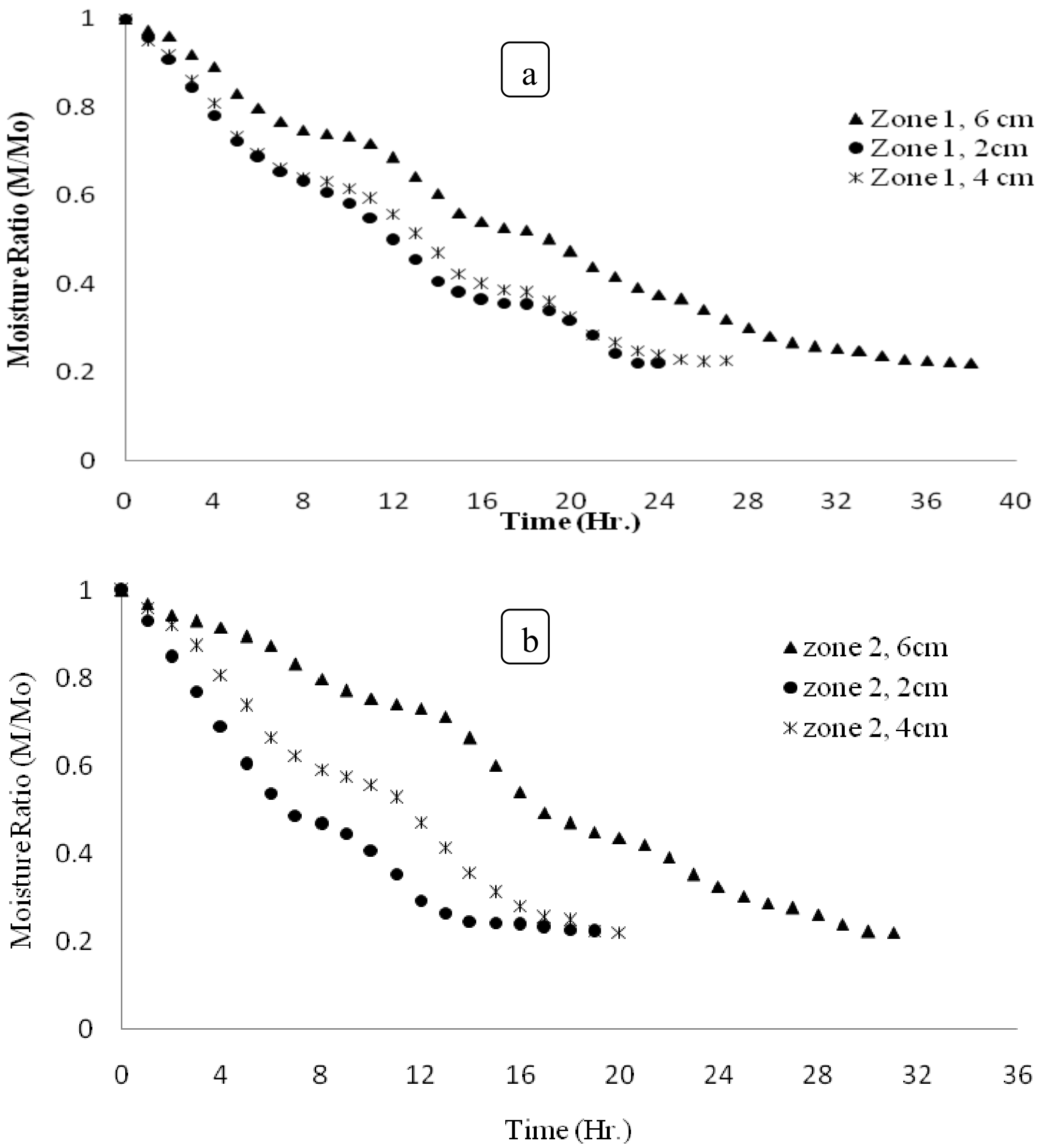
4.2.2 Drying kinetics of the parchment coffee

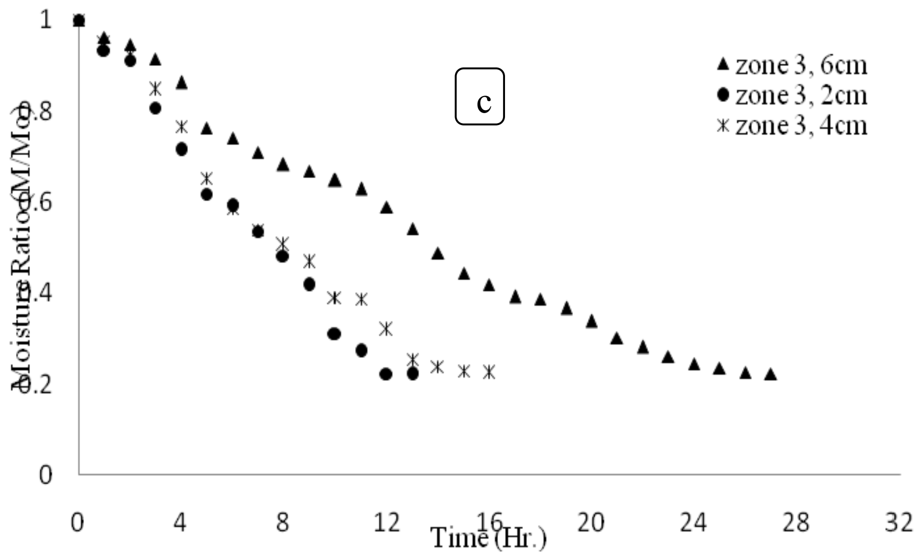
4.2.2.1 Effect of drying layers thickness on drying kinetics of parchment coffee at constant drier zone

During the drying of coffee beans at three different drier zones with open sun condition , there was a reduction of moisture content from 108.3% to 13% dry basis for different layer thickness. The drying curve of each treatment at a constant dryer zone with different layer thicknesses are described in Figure 3.

The moisture ratio curve for all thickness under all drier zone and open sun condition showed a similar pattern, thus as the drying thickness increased the moisture removal decreased. This indicates the influence of drying thickness on the drying characteristics of parchment coffee.

In all zones, drying characterized by a higher rate of moisture removal rate at the initial drying period, but, as drying proceeds, there was a gradual reduction in moisture removal rate. In all zones, as layer thickness increased the physical barrier to the moisture removal also increases, which result in extended moisture removal process as observed in the moisture ratio curve (Figure 3). The long moisture ratio curve observed for the parchment coffee dried at a thickness of 6 cm under all drier zones. This is because the moisture migration is complicated as moisture removed from the interior part of the product. Results in this work are in agreement with the works of Menya and Komakech, (2013), who indicated a higher moisture removal rate for the coffee dried at lower loading density. However, the less significant difference observed between layer thickness 2 and 4 in drier zone one (Figure 3a) and three (Figure 3c) as compared with drier zone two (Figure 3b) and open sun ((Figure 3d) conditions. This might be because of below and above optimum drying environment conditions in zone one and three respectively as compared to zone two.


a
Zone 1, 6 cm
Zone 1, 2cm
Zone 1, 4 cm
Moisture Ratio (M/Mo)
Time (Hr.)
b
zone 2, 6cm
zone 2, 2cm
zone 2, 4cm
Moisture Ratio (M/Mo)
Time (Hr.)



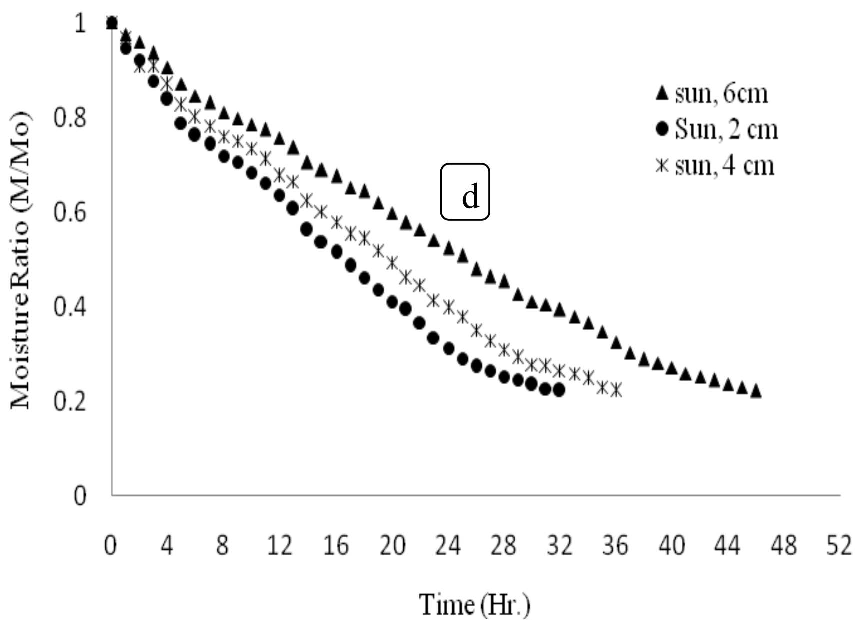
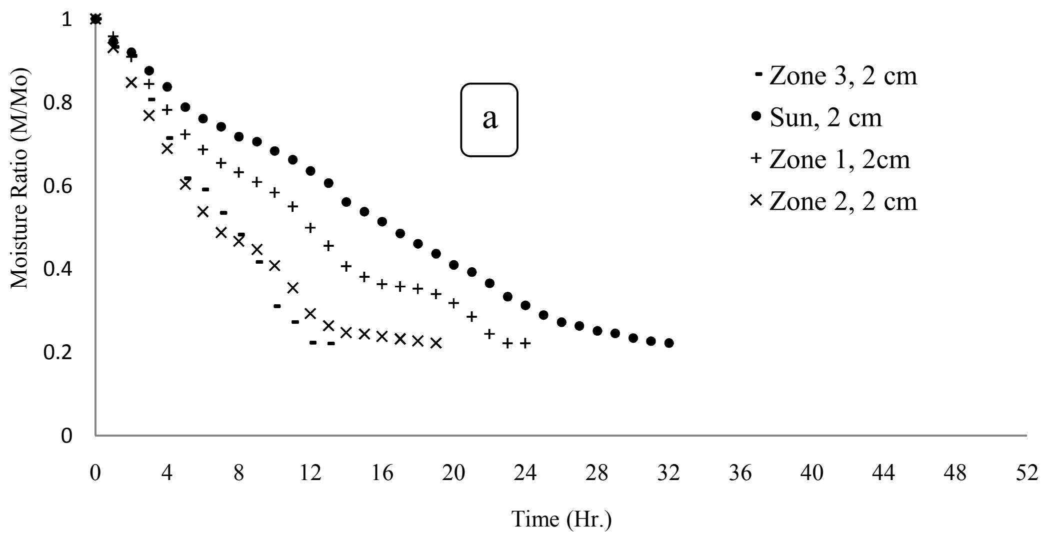


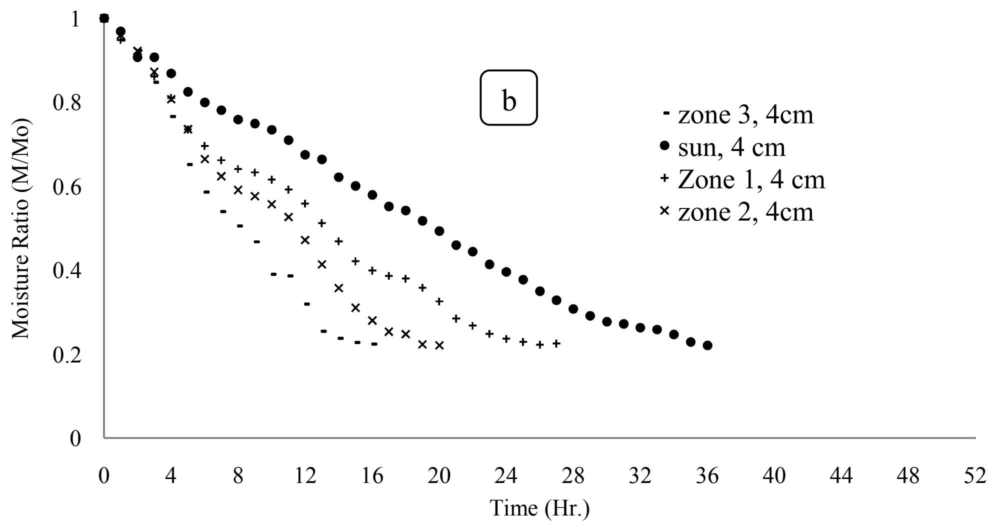
Figure 3 : Drying behavior of coffee parchment due to variation of drying layer thickness in the same zone of solar tunnel drier (a-c) and open sun (d) conditions

4.2.2.2 Effect of dryer zones on drying kinetics of parchment coffee at a constant layer thickness

Figure (4 (a-c)) shows the effect of solar tunnel dryer zones on moisture removal characteristics of parchment coffee. As shown in the figures, there is a variation in the moisture removal rate for the parchment coffee dried at a similar thickness under different dryer zones and open sun conditions. Accordingly, among the dryer zones and open sun drying conditions at the same thickness, coffee dried under zone three characterized by a faster rate of drying for all layer thicknesses as compared to others. This might be associated with relative higher drying medium temperature with lower relative humidity. Both are driving forces to create a bigger vapor pressure difference between the product and the drying medium. As indicated in Figure 4a, when the layer thickness kept 2 cm in all zones, more or less no significant differences observed on the rate of drying between zone 2 and 3. This might be due to enough vapor pressure difference of drying medium at zone two which could maintain the same drying rate at zone three. However, when the drying layer thickness increased to 4 cm a noticeable difference in the rate of drying observed as zone three,> zone two> zone one > open sun (Figure 4b). When layer thickness increased to 6 cm (figure 4c), no noticeable difference in the rate of drying between zone one and two. This might be due to higher-layer density (6 cm) which contributes to the release of enough moisture, which could be beyond the vapour pressure difference in zone two. However, in all cases (figure 4a-c), the rate of moisture removal of open sun drying was slower than all zones in solar tunnel drier. This shows that a relatively fast drying time could be achieved by applying tunnel solar drier for better results and safety.

This result was explained well by (Prachayawarakorn *et al*., 2008), that the higher capability of removing moisture at high temperatures can possibly be explained by the acceleration produced through the movement of water molecules at higher temperatures which took part in a more rapid decrease of the moisture content


a
Zone 3, 2 cm
Sun, 2 cm
Zone 1, 2cm
Zone 2, 2 cm
Moisture Ratio (M/Mo)
Time (Hr.)
0
0.2
0.4
0.6
0.8
1
0
4
8
12
16
20
24
28
32
36
40
44
48
52


b
zone 3, 4cm
sun, 4 cm
Zone 1, 4 cm
zone 2, 4cm
Moisture Ratio (M/Mo)
Time (Hr.)
0
0.2
0.4
0.6
0.8
1
0
4
8
12
16
20
24
28
32
36
40
44
48
52

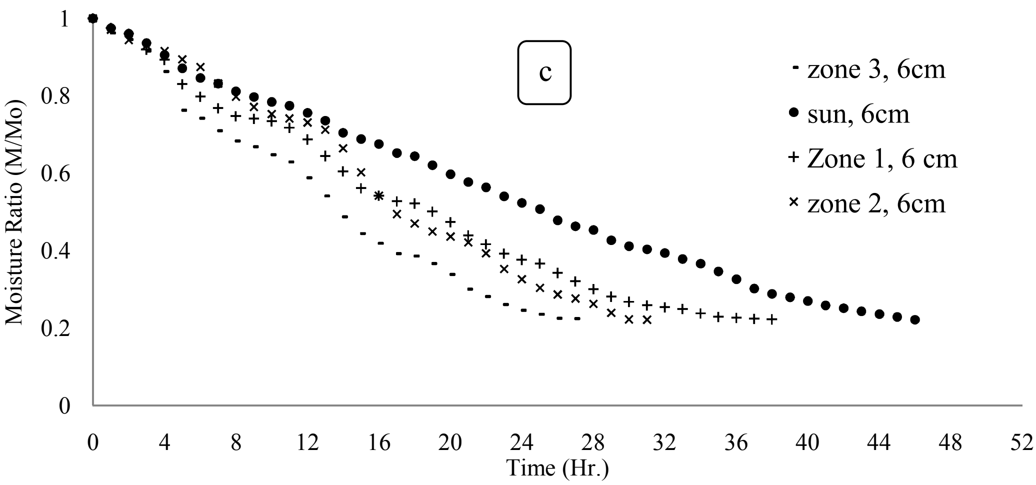


Figure 4: Drying behavior of coffee parchment due to variation of drier zones and open sun at constant drying layer thickness (a-c)

4.2.3 Evaluation and selection of drying kinetics models

As indicated in Table (3), a model described by lower RMSE and Chi-square as well as higher R^2 values best describe the drying kinetics of parchment coffee at the different drier zone and layer thicknesses. Under zone one condition, for 2 and 4 cm drying thicknesses Verma model best describes the drying characteristics. However, at layer thickness of 6 cm the best model is Modified Midilli (Table 3) in the same zone. In zone two for 2 cm better described by Two terms model but for 4 and 6 cm layer thicknesses Modified Midilli's kinetics model still bets. Similarly, in zone three, for all thicknesses Modified Midilli model best described the drying characteristics of the parchments. For open sun drying for 2 cm layer thickness the Modified model but for, 4 and 6 cm layer thicknesses the Diffusion approach model was best-fited models (Table 3). But in most cases Modified Midilli model best described the drying behavior of the samples for most drying layer thickness except open sun drying. These results are different from the findings of Corrêa *et al*. (2006) where Page and Verma's models were found best models to represent drying behaviour of coffee berry drying during convective drying at 45^{o}C. However, the present study is in agreement with the works Phitakwinai *et al*., (2019) who reported that Modified-Midilli model is a powerful model in predicting the drying behavior of parchment coffee within the drying air temperature range of 50–70°C.

Table 3 : Values of RMSE, χ^2 and R^2 involved in the tested models

		Open Sun		
	Models	**RMSE**	**Chi-squared**	$\mathbf{R^2}$
2cm	**M.Midilli**	**0.043351**	**0.000200**	**0.988631**
	Diffusion approach	0.026620	0.000754	0.979546
	Verma	0.020862	0.000463	0.984803
	Henderson and Pabis	0.025289	0.000681	0.977829
	Newton	0.026621	0.000731	0.979546
	Modified Page	0.026621	0.000754	0.979546
	Two term model	0.025289	0.000703	0.977829
4cm	M.Midilli	0.016820259	0.000307885	0.992515
	Diffusion approach	**0.014578775**	**0.000224686**	**0.992541**
	Verma	0.021198447	0.000475053	0.986121
	Henderson and Pabis	0.027280603	0.000786759	0.973906
	Newton	0.029749475	0.000909615	0.976673
	Modified Page	0.022165570	0.000935604	0.976673
	Two term model	0.027280603	0.000809899	0.973905
6cm	M.Midilli	0.022489114	0.001000000	0.992582
	Diffusion approach	**0.010121138**	**0.000106990**	**0.996315**
	Verma	0.023799508	0.000591591	0.987310
	Henderson and Pabis	0.026971272	0.000759781	0.974822
	Newton	0.031852647	0.001036647	0.978937
	Modified Page	0.031852647	0.001059684	0.978937
	Two term model	0.026971272	0.000777048	0.974822

	Zone 1			
	Models	**RMSE**	**Chi-squared**	**R^2**
2 cm	M. Midilli	0.030259	0.000995	0.980000
	Diffusion approach	0.017956	0.000350	0.990000
	Verma	**0.017548**	**0.000335**	**0.988691**
	Henderson and Pabis	0.018163	0.000359	0.987904
	Newton	0.018789	0.000368	0.988142
	Modified Page	0.018789	0.000384	0.988142
	Two term model	0.018163	0.000359	0.987904
4cm	M.Midilli	0.02861307	0.00088169	0.981212
	Diffusion approach	0.02135366	0.00049105	0.983924
	Verma	**0.01929644**	**0.00040099**	**0.986772**
	Henderson and Pabis	0.02159166	0.00050206	0.983612
	Newton	0.02216557	0.00050951	0.984135
	Modified Page	0.02216557	0.00052911	0.984135
	Two term model	0.02277343	0.00058086	0.981797
6cm	**M.Midilli**	**0.025641464**	**0.000693024**	**0.991145**
	Diffusion approach	0.084907291	0.007598937	0.863403
	Verma	0.081542966	0.007008674	0.970236
	Henderson and Pabis	0.029649253	0.000926596	0.984041
	Newton	0.028976099	0.000861709	0.984765
	Modified Page	0.028976099	0.000884999	0.984765
	Two term model	0.023345219	0.000590416	0.982419

Zone 2				
	Models	**RMSE**	**Chi-squared**	**R^2**
2 cm	M.Midilli	0.0389628	0.0016867	0.973091
	Diffusion approach	0.0246533	0.0006753	0.980642
	Verma	0.0220360	0.0005400	0.985220
	Henderson and Pabis	0.0246490	0.0006750	0.980680
	Newton	0.0246610	0.0006400	0.980549
	Modified Page	0.0259950	0.0006760	0.980549
	Two term model	**0.0190790**	**0.0004280**	**0.988112**
4m	**M.Midilli**	**0.022523694**	**0.000560719**	**0.983981**
	Diffusion approach	0.028443573	0.000894199	0.974765
	Verma*et al*	0.032475171	0.001165651	0.978472
	Henderson and Pabis	0.034278588	0.001175022	0.967216
	Newton	0.039283389	0.001620344	0.971667
	Modified Page	0.039283389	0.001705625	0.971667
	Two term model	0.032605441	0.001240301	0.967216
6cm	**M.Midilli**	**6.23761E-05**	**0.001871284**	**0.977793**
	Diffusion approach	0.060173881	0.003862289	0.975087
	Verma *et al*	0.066905433	0.004774759	0.954885
	Henderson and Pabis	0.051517238	0.002830961	0.922812
	Newton	0.073634450	0.005596937	0.941415
	Modified Page	0.063779923	0.004339071	0.935961
	Two term model	0.051517238	0.002928580	0.922813

Zone 3				
	Models	**RMSE**	**Chi-squared**	**R^2**
2cm	**M.Midilli**	**0.02681582**	**0.0008389**	**0.983345**
	Diffusion approach	0.03220624	0.0012101	0.970062
	Verma*et al*	0.04666326	0.0025403	0.953703
	Henderson and Pabis	0.04203172	0.0020611	0.949828
	Newton	0.18987744	0.0027731	0.957630
	Modified Page	0.05074688	0.0030044	0.957630
	Two term model	0.04203172	0.0022484	0.949828
4cm	**M.Midilli**	**0.020796**	**0.000490**	**0.988002**
	Diffusion approach	0.021991	0.000548	0.985872
	Verma*et al*	0.035421	0.001422	0.979519
	Henderson and Pabis	0.031357	0.001114	0.971734
	Newton	0.041086	0.001794	0.975562
	Modified Page	0.041086	0.001913	0.975562
	Two term model	0.038588	0.001808	0.974780
6cm	**M.Midilli**	**0.0197301**	**0.0004192**	**0.987261**
	Diffusion approach	0.0247928	0.0006619	0.980119
	Verma*et al*	0.0266044	0.0007622	0.984450
	Henderson and Pabis	0.0276268	0.0008219	0.975538
	Newton	0.0337741	0.0011829	0.978843
	Modified Page	0.0337741	0.0012284	0.978843
	Two term model	0.0276268	0.0008548	0.975538

The plot of the observed data and the predicted data of the modified-Midilli model for zone three conditions is shown in Figure 5 which shows a very close agreement between measured and predicted values using the model.

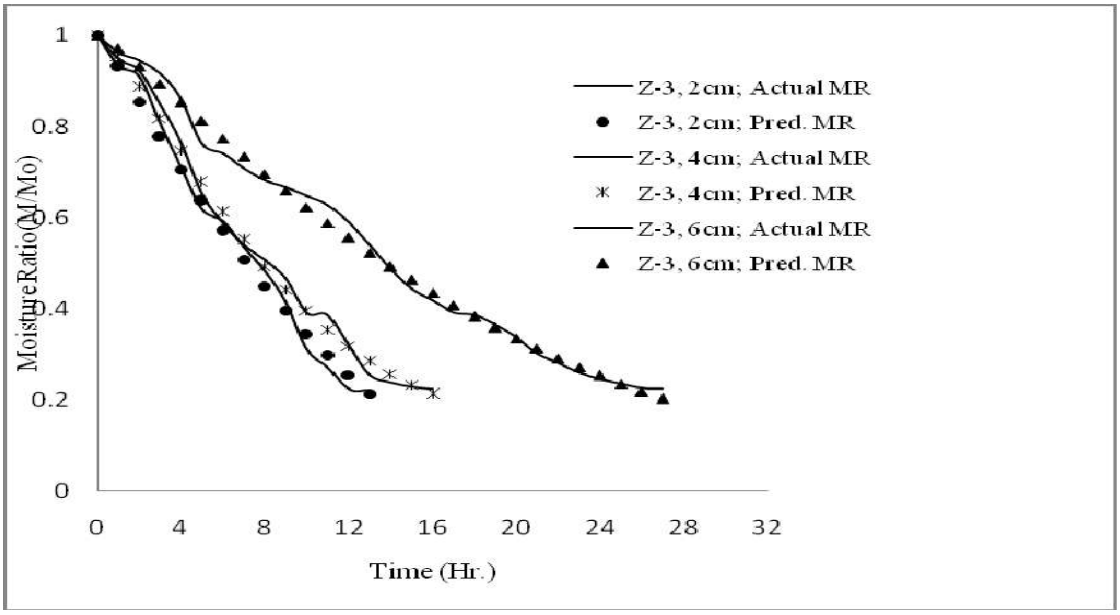


Figure 5 : Predicted versus measured moisture ratio value according to the modified- Midilli model in Zone 3 drying conditions

4.2.4 Effective diffusivity of parchment coffee

Table (4) shows the values of effective diffusivity for different zones and layer thicknesses. The effective diffusivity for parchment coffee was between (1.2 to 5.0X10^{-6} m^2/s). The highest diffusivity value was observed for zone three, followed by zone two, zone one and open sun, respectively, as expected from the above discussed data. This showed that diffusivity is directly proportional to the level of drying medium temperature and RH which were the highest and lowest at zone 3. Tesfaye *et al.* (2013), reported an effective diffusivity coefficients value between 1.88x 10^{-06} and 2.26x10^{-06} m^2/s for parchment coffee dried under solar tunnel drier at different temperature (30^{0}C, 40^{0}C and 50^{0}C) which is in close agreement with our result. However, Corrêa *et al*., (2010) studied the drying kinetics of coffee fruits at temperatures between 35°C and 55°C and they reported effective diffusivity coefficients between values 2.99 × 10^{-11} and 5.98 × 10^{-11} m^2/s during convective drying of coffee at 45^{o}C. Varadharaju *et al*., (2001) reported moisture diffusivity of coffee cherry within the range of 8.78–10.00 × 10^{-10} m^2/s for drying of 40^{0}C, 50^{0}C and 60^{0}C, Hernandez-Diaz *et al*. (2008) reported within the range of 4.63– 10.75 × 10^{-10} m^2/s with average value of 7.17 ×10^{-10} m^2/s.

The values in all the above three cassses by far lower than our results. The variation might be associated with other drying conditions and variety differences.

On the other hand the effect of layer thickness is also observed, with the smallest thickness the highest diffusivity and vice versa in all zones. Diffusivity value is reciprocal when the thickness is concerned. This might be because the greater thickness would possibly create a physical barrier that hinders the diffusion movement of the water molecules, resulting in lower effective diffusivity value. Results in this work are aslo in agreement with the works of Tesfaye *et al.* (2013), who indicated that effective diffusivity decreased with increased drying density while studying the drying characteristics of parchment coffee dried under solar tunnel drier at different temperature (30^0C, 40^0C and 50^0C). and found out effective diffusivity coefficients between 1.88x 10^{-06} and 2.26x10^{-06}.

Table 4 : Effective Diffusivity of the parchment coffee dried under different drying zones with different thicknesses

Drying zones	Layer thickness	Diffusivity
Open sun	2 cm	1.57E-06
	4 cm	1.68E-06
	6 cm	1.2E-06
Zone 1	2 cm	2.8E-06
	4 cm	2.51E-06
	6 cm	2.15E-06
Zone 2	2 cm	3.48E-06
	4 cm	4.12E-06
	6 cm	1.98E-06
Zone 3	2 cm	5.03E-06
	4 cm	2.44E-06
	6 cm	1.89E-06

4.3 Influence of drying zones and layer thickness on physicochemical properties

4.3.1 pH

The acidity of coffee associated with pH recognized as one of the sensory quality attributes of coffee brew. pH value in coffee has been identified as one of the major drivers for flavor differences in different coffees (Lowor *et al*., 2007). As a result, changes in the pH can lead to changes in flavor, body, aroma as well as the acidity of brewed coffee.

Coffea arabica is considered of good quality when the range of pH is between 4.80 and 5.80 (Petracco, 2001). ANOVA table (Appendix Table 1) shows the significant ($p<0.05$) interaction effects of parameters on pH of coffee. Coffee parchment dried under zone two with the layer thickness of 2 cm resulted in the highest pH (5.9) score, followed by the coffee dried under zone one with a layer thickness of 6 cm (5.7) (Table 5). However, parchment dried in open sun at 6 cm thickness showed the lowest pH value (5.3) which might be associated with the fermentation process during the delayed drying process. The rest of the treatment combinations recorded pH value of (5.6) even though they are statistically different.

The present finding is in agreement with the finding reported with Franca *et al*. (2005) and Butt *et al*.. (2011) who found out pH range of 5.3 to 6.52 and 4.89 to 5.98 for green coffee beans respectively. Similar observation also reported in Ferreira *et al*., 2013), who explains that the reduction in pH associated with fermentation. The acids produced during fermentation such as acetic acid may penetrate the husks of the coffee bean influencing the changes observed for pH.

4.3.2 Titratable Acidity

Titratable acidity value is related to the total concentration of acids in the sample, and it is inversely proportional to coffee quality since high acidity ratings are indicative of low-quality coffee beverages (Franca *et al*., 2004). It is one of the characteristic attributes of coffee sensorial analysis. Its intensity varies predominantly, according to the stage of maturation of the beans, pre-processing and drying.

ANOVA (Appendix Table 1) showed that the interaction effect of drying zones and layer thickness didn't show a significant ($P<0.05$) effect on titratable acidity of the coffee (Table 5).

The highest TA value (2.6) was recorded by the coffee dried under zone three with the layer thickness of 4 cm, zone two 6 cm and open sun 4cm. While the lowest TA value (2.1) was from coffee dried under zone one with a layer thickness of 2 cm, all the TA result was found to be statistically similar.

Under zone, one condition, the lowest (2.1) titratable acidity was recorded for the coffee dried with a thickness of 2 cm, while coffee dried with a thickness of 2 cm and 4 cm resulted in similar (2.5) TA values. Under zone two conditions, the TA value showed an increasing trend with increasing of the thickness (2.2, 2.4 and 2.6) for the thickness of 2 cm, 4 cm and 6 cm respectively. Under zone three, the highest (2.6) TA value is recorded for the coffee dried with a layer thickness of 4 cm. While the lowest (2.4) TA value is recorded for the coffee dried with a layer thickness of 2 cm.

The change in titratable acidity could occur due to the levels of acid present in the coffee beans. The common acids present are; citric, acetic, malic, chlorogenic and quinic acids (Butt *et al*., 2011). Generally under all drying zones, the lowest TA is recorded for the coffee dried with a thickness of 2 cm. Even though statistically similar, zone three showed the highest TA value compared to the other two zones and open sun. This result is in agreement with the findings of Franca et al., (2005) who reported that the TA content for the washed coffee to be between the range of 2 to 4 ml.

4.3.3 Total Soluble Solid

The sugars and acids, together with small amounts of dissolved vitamins and minerals, are commonly referred to as soluble solids (Chope *et al*., 2006; Kader, 2008). Total soluble solids (TSS) are the most important quality parameters used to indicate the sweetness of the coffee brew, which is one of the important quality characteristics of coffee liquor.

ANOVA table (Appendix Table 1) showed that interaction effects of drying zone and layer thickness had a significant ($P<0.05$) effect on the total soluble solid content of the coffee (Table 5). Thus the coffee dried under zone two with a layer thickness of 4 cm resulted in the highest (4.3^{o}Brix) score, followed by the coffee dried under zone two and three with a layer thickness of 2 cm (2.9 ^{o}Brix) each. The lowest total soluble solid content (2.3 ^{o}Brix) was recorded from the coffee dried under the open sun with a layer thickness of 6 cm.

The highest total soluble TSS (2.8^{o}Brix) was from zone one of 6 cm layer thickness, while the coffee dried at 2 cm and 4 cm thicknesses resulted in statistically similar (2.7 ^{o}Brix) . For zone two conditions, the coffee dried at 4 cm layer thickness gave the highest (4.3 ^{o}Brix) TSS value followed by the coffee dried at 2 cm (2.9^{o}Brix) layer thickness. The lowest TSS content (2.6 ^{o}Brix) for zone two conditions recorded for the coffee dried at a layer thickness of 6 cm.

Under zone three, coffee dried at 2 and 6 cm layer thickness of resulted in similar TSS (2.9 ^{o}Brix) value, though statistically different. While the coffee dried at thickness of 4 cm resulted in the lowest (2.8 ^{o}Brix) TSS value compared to the other two thicknesses described. Coffee dried under an open sun with different thicknesses also resulted in different TSS values with the coffee dried at 2 cm showing the highest (2.7 ^{o}Brix) value. The coffee dried at 4 cm and 6 cm scored (2.6 and 2.3 ^{o}Brix) TSS value respectively.

Compared between the zones, zone two showed higher TSS value, and relatively lower TSS value recorded from an open sun drying method. This might happened because the coffees dried at a layer thickness of 2 cm were the fastest to dry both under solar tunnel drier and open sun condition; as a result, reducing the possibility of a loss of soluble components that could happen under extended drying time for the coffee dried with larger thicknesses.

The present result is in agreement with the works of Borem *et al*. (2015) who reported that there is an increase in total sugar and soluble sugar contents during drying of coffee at a temperature of 50-60^{o}C.

4.3.4 Total ether extract

The ether extract content of green Arabica coffee beans averages some 15 %, while Robusta coffees contain much less, namely around 10 % (Speer and Kolling 2001). Coffee oil is composed mainly of triacylglycerols with fatty acids in proportions similar to those found in common edible vegetable oils. These lipid fractions of the beans are extracted into the coffee brew and provide the *crema* emulsion that carries flavor volatiles and fat-soluble vitamins and contributes to perceived texture and mouthfeel of the coffee brew (Oestreich-Janzen, 2010).

ANOVA result (Appendix Table 1) shows that the significantly ($p<0.05$) interaction effects of drying zones and layer thickness on ether extract coffee beans (Table 5). Accordingly, The highest lipid content (15.2) was for open sun 4 cm followed by open sun 2 cm and open sun 6 cm (14.9 and 14.7) respectively. While lowest lipid content (10.9) was reported for treatment zone three with thickness of 2 cm.

Coffee dried at a layer thickness of 4 cm and 6 cm recorded statistically similar results (13.7 and 13.5%) under zone one drying condition. But the coffee dried at a layer thickness of 2 cm resulted in a relatively higher (14.1%) result under the same drying zone. Under zone two drying condition, the three different thicknesses resulted in significantly different (13.7, 13.9 and 13.8%) but statistically similar for the layer thicknesses of 2 cm, 4 cm and 6 cm, respectively.

Coffee dried under zone three showed similar pattern concerning the drying thicknesses; as coffee dried at thicknesses of 4 cm and 6 cm recorded similar result (13.2% each) while the coffee dried at 2 cm showed lower ether extract value (10.9%) than the other two thicknesses dried under the same zone. Coffee dried under open sun recorded higher crude fat value than the three different zones of the solar tunnel drier, with the coffee dried at a layer thickness of 4 cm resulting in the highest (15.2%) crude fat value than the other treatment combinations.

The result obtained in this work also is an agreement with earlier works that reported the ether extract content of green coffee beans to be in the range of 9% to 16% (Clarke and Vitzthum, 2008).

4.3.5 Total Polyphenol Content

Polyphenols are secondary metabolites that plants produce to protect themselves from other pathogenic microorganisms. Polyphenols play great roles in human health by protecting against several diseases related to oxidative stresses and free radical-induced damages (Vladimir-Knezevic et al., 2012). In this study, the amount of total polyphenol content of coffee dried under different drying zones of solar tunnel drier with different thicknesses varied from 39.2 to 53.5 GAE/g among the treatments tested ($p<0.05$). Significant differences in total polyphenols content between coffees were observed, depending on the treatments as shown in (Table 5). The values in the table correspond that the high total phenolic content tends to present a high level of antioxidant activity.

It is noticed that the highest total polyphenols content (53.5GAE/g) was from found in zone two at a layer thickness of 4 cm, but the lowest TPC (39.2GAE/g) in the treatment under zone three with a layer thickness of 6 cm. When drying thicknesses compared, the parchment coffees dried at a layer thickness of 4 cm resulted in higher in TPC. While the coffee dried at thickness of 6 cm gave the lower in TPC under all drying zones.This implies that an increase in layer thickness due to the delay of the drying process might create an opportunity to fermentation condition which could enhance the degradation of polyphenols.

Concerning the drying zones, coffee dried under zone three yielded low TPC in all thicknesses as compared to other drying zones except the considerable effect of zone three on the coffee dried at 4 cm (Table 5). This might be due to the higher drying temperature experienced in the zone during the drying process, leading to a decreased level of polyphenol in the coffee beans. Many research papers presented that the phenolic compounds were the good free radical scavenger (Sendra, 2009). Besides, previous studies showed that coffee bean contained many polyphenolic compounds such as chlorogenic acid, mangiferin and hydroxycinnamic acid esters (Cheong *et al.,* 2013; Moreira *et al.,* 2013) that contribute for TPC but which may degrade under harsh drying condition.

The present work is In agreement with the works of (Mills *et al* ., 2013) who reported that TPC of green coffee ranged up to 65% while studying the influence of drying on CGA content of coffee.

4.3.6 Antioxidant Activities

An antioxidant is a molecule stable enough to donate an electron to a rampaging free radical and neutralize and reduce its capacity to damage. These antioxidants delay cellular damage, mainly through their free radical scavenging property (Halliwell, 1995). The polyphenols content of plants may contribute directly to the antioxidant action (Tosun *et al*., 2009).

The interaction effect of drier zones and layer of drying thickness had a significant ($p<0.05$) effect on DPPH scavenging capacity (Appendix Table 1). The percentage of DPPH free radical scavenging activity of coffee dried under different dryer zones with different drying layer thickness depicted in Figure 6. Under zone one dryer condition, the scavenging activity ranged from 40.5% up to 50.2% which shows better antioxidant activity, which corresponds with polyphenols contents of the coffee. Under zone two conditions, it ranged from 39.7% to 59.2%. The coffee dried under zone two dryer conditions with a thickness of 4 cm resulted in the highest antioxidant activity (59.2%) which shows its potency as a good source of antioxidant. The lowest scavenging activity (38.5%) was obtained from the coffee with a thickness of 6 cm under zone three conditions.

When figure 6 observed, in all zones, including open sun drying, 4 cm layer thickness gave relatively better antioxidant capacity as compared with the other two layer thicknesses. This shows that regardless of drying zones and open sun drying, both fast and slow drying processes associated with 2 and 6 cm layer thicknesses could contribute to the loss of certain antioxidant compounds due to the impact of drying temperature for 2 cm thickness or fermentation for 6 cm thickness.

Yashin *et al* ., (2013) found out that, phenolic compounds in coffee bean are major contributors to their antioxidant capacity. The present work is in agreement with the works of (Farah, 2012) who indicated that arabica coffee beans consist of coffee oils that are sensitive to heat and moist which leads to degradation and decrease in the antioxidant activity.

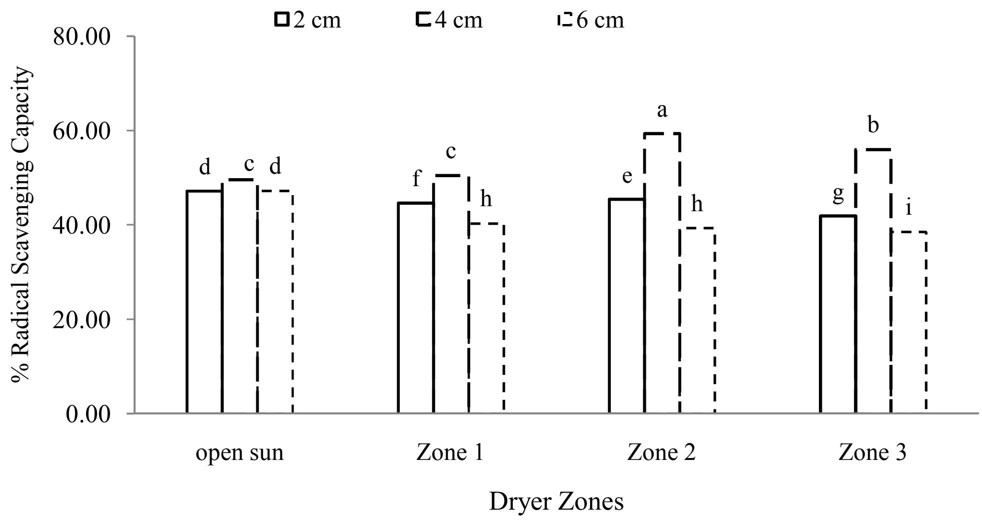


Figure 6: DPPH Radical Scavenging Activity of Coffee dried under different dryer zones with different layer thickness.

The extracts that perform the highest antioxidant activity has the highest concentration of polyphenols (Table 5). This is in agreement with the works of Sultana and Anwar (2008) who reported that, with the increase in the concentration of polyphenols compound or the degree of hydroxylation of polyphenols compounds, DPPH free radical scavenging capacity increases and thus the antioxidant increases.

4.3.7 IC_{50} values

The IC_{50} value for the DPPH scavenging assay calculated for the treatment combinations. Inhibition concentration value, defined as the concentration of antioxidant required for 50% scavenging of DPPH radicals, is a parameter used to measure antioxidant activity. The smaller IC_{50} value corresponds to a higher antioxidant activity of the plant extract (Maisuthisakul *et al.,* 2007). In the present study, lower IC_{50} value (0.8mg/ml) was observed in treatment zone two with a layer thickness of 4cm which indicated its powerful free radical scavenging ability followed by treatment zone three with 4cm (1.6mg/ml). The highest IC_{50} value (6.3 mg/ml) was obtained when the coffee was dried at a thickness of 6 cm under zone three conditions which indicated that its low potential of antioxidant activity.

IC_{50} showed a similar trend with total phenolic content as the highest TPC is related to the highest antioxidant and thus lowest IC_{50} value. Accordingly, under all drying conditions, the lowest IC_{50} value (2.1, 0.8, 1.6 and 2.7) were recorded for the coffee dried at thickness of 4 cm under zone one, two, three and open sun respectively and the highest IC_{50} recorded for the coffee dried at thickness of 6 cm under all drying conditions.

Table 5 : Mean values for the physicochemical property of Parchment coffee dried under different drying zones with different layer thicknesses

Drying Zones	Layer thickness	PH	Titratable Acidity	TSS (°Brix)	Crude Fat (%)	Total Polyphenols (GAE/g)	Antioxidant Capacity (%)	IC 50 (mg/ml)
Open sun	2cm	5.6±0.03^{cde}	2.4±0.01^{a}	2.7±0.02$^{c d e}$	14.9± 0.05^{a}	46.4 ±0.02 ^{e}	47.5 ±0.03^{d}	3.3±0.008 ^{g}
	4cm	5.4±0.02^{f}	2.6±0.01^{a}	2.6±0.00$^{d e}$	15.2±0.03^{a}	48.0 ±0.02 ^{d}	49.6 ±0.02^{c}	2.7±0.035 ^{h}
	6cm	5.3±0.01^{g}	2.4±0.06^{a}	2.3±0.02^{f}	14.7±0.02$^{a b}$	45.9 ±0.00 ^{f}	47.3 ±0.01^{d}	3.3±0.008 ^{g}
Zone 1	2cm	5.6±0.05^{cd}	2.1±0.09^{a}	2.7±0.01$^{d e}$	14.1±0.23$^{b c}$	44.5±0.10 ^{g}	44.3 ±0.03^{f}	4.7±0.144 ^{e}
	4cm	5.6±0.02^{bc}	2.5±0.12^{a}	2.7±0.06$^{d e}$	13.7±0.10$^{c d}$	49.4 ±0.02 ^{c}	50.2 ±0.02^{c}	2.1±0.010^{i}
	6cm	5.7±0.01^{b}	2.5±0.13^{a}	2.8±0.12$^{b c d}$	13.5±0.06$^{c d}$	41.1±0.06^{i}	40.5 ±0.05^{h}	5.8±0.022 ^{c}
Zone 2	2cm	5.9±0.01^{a}	2.2±0.24^{a}	2.9±0.02^{b}	13.7±0.22$^{c d}$	45.9 ±0.04 ^{f}	45.3 ±0.04^{e}	4.2±0.009 ^{f}
	4cm	5.6±0.02^{cde}	2.4±0.09^{a}	4.3±0.11^{a}	13.9±0.12^{cd}	53.5±0.05^{a}	59.2 ±0.04^{a}	0.8±0.010 ^{k}
	6cm	5.5±0.02^{ef}	2.6±0.12^{a}	2.6±0.01^{e}	13.8±0.07^{cd}	40.0±0.01 ^{j}	39.7 ±0.01^{h}	6.1±0.042 ^{b}
Zone 3	2cm	5.6±0.02^{de}	2.4±0.15^{a}	2.9±0.02^{b}	10.9±0.08^{e}	42.5±0.01 ^{h}	41.7 ±0.02^{g}	5.2±0.012 ^{d}
	4cm	5.6±0.01^{cde}	2.6±0.12^{a}	2.8±0.05$^{b c d e}$	13.2±0.10^{d}	50.6±0.01 ^{b}	55.7 ±0.01^{b}	1.6±0.038 ^{j}
	6cm	5.6±0.01^{bcd}	2.5±0.09^{a}	2.9±0.05$^{b c}$	13.2±0.07^{d}	39.2±0.05 ^{k}	38.5 ±0.04^{i}	6.3±0.072 ^{a}
CV%		0.58	7.40	2.46	1.16	1.41	1.63	1.54

4.4 Influence of drying zones and layer thicknesses on sensory property

The cup quality of coffee is a highly complex trait, and depends on physical and sensory qualities, with the coffee variety, climatic conditions during plant growth, processing method, drying, and storage conditions being factors that can affect the coffee quality (Joe *et al*., 2010; Bertrand *et al*., 2012).

ANOVA (Appendix Table 1) for the two-way interactions among drying zones and levels of layer thickness showed no significant difference for the total raw quality of coffee (Table7). Accordingly, coffee dried under zone one with drying thickness of 4 cm, zone three with 4 cm and zone 3 with 6 cm resulted in the highest mean total raw quality score (37.0±0.58, 37.0 ±0.33 and 37.0±0.58) respectively. Although, all the coffee dried under different drying zones and layer thickness showed statistically similar results.

ANOVA for the total cup quality (Table 6) also showed no significant difference ($P<0.05$) for the interaction effect of drying zones and the level of drying thicknesses (Appendix Table 1). Even though there is no significant difference between the treatments, coffee dried under zone two with drying thickness of 2 cm and 4 cm resulted in the highest score (51. 0) among all.

Contrary to this, coffee dried under the open sun with drying thickness of 2cm, 4cm and 6cm, zone three with 2 cm and 6 cm showed the lowest score value (48.0). From this study, it can be seen that drying in open sun resulted in relatively low cup quality when compared to the drying under solar tunnel drier even though they are not significantly different. This could be due to the fact that washed coffees are of high quality resulting in good cup quality and grade in current evaluation criteria. Coffee dried under zone 3 with drying thickness of 2cm and 6cm were also scored lower than other treatments (48.0). This result is in line with the findings of Borem *et al*. (2017) who reported that; the good flavor of coffee grains is achieved when drying air temperatures are kept between 40-60ºC.

The total quality of a coffee is the overall quality of the coffee based on the overall quality attribute results used to determine and evaluate the quality potential of the coffee. Although statistically similar, the highest overall coffee quality recorded for coffee parchment dried under zone 2 with drying layer thickness of 4cm and 2cm (87.3) detected to excellent specialty taste received a "Specialty Grade 1" as per the evaluation of panelists. Also, the coffee dried under zone two with 6cm, zone three with 4cm, zone one with 4cm and 2cm and zone three with 6cm resulted in the mean score of (86.7, 86, 86, 85.7 and 85) respectively and received specialty grade one coffee (Table 6).

On the other hand, the lowest mean total quality point (84.3) recorded from coffee dried in the open sun with the drying layer thickness of 2cm (Table 6) detected to very good specialty taste received a "Specialty Grade 2" classification. The other rest of the treatment combination resulted in the mean score of (84.7) which gave them specialty grade 2 classification. This is in line with the result reported by Anwar (2010), who suggested that the wet processing method resulted in high mean values for good coffee quality. Similarly, FAO (2010) showed that solar-drying could be an economical and effective method in producing high quality coffee if coffee drying under good conditions.

Table 6 : Mean values for Sensory property of Parchment coffee dried under different drying zones with different layer thickness

Drying Zones	Layer Thickness	Total Raw (40%)	Total cup (60%)	Total quality (100%)
Open sun	2cm	36.3±0.33[a]	48.0±0.00[b]	84.3±0.33 [a]
	4cm	36.7±0.33[a]	48.0±0.00[b]	84.7±0.33 [a]
	6cm	36.7±0.33[a]	48.0±0.00[b]	84.7±0.33 [a]
Zone 1	2cm	36.7±0.33[a]	49.0±1.00[ab]	85.7±1.33[a]
	4cm	37.0±0.58[a]	49.0±0.00[b]	86±0.58 [a]
	6cm	36.3±0.33[a]	48.0±1.00[b]	84.3±0.88 [a]
Zone 2	2cm	36.3±0.33[a]	51. 0±0.00[a]	87.3±0.33 [a]
	4cm	36.3±0.33[a]	51.0±0.00[a]	87.3±0.33 [a]
	6cm	36.7±0.33[a]	50.0±1.00[ab]	86.7±1.45 [a]
Zone 3	2cm	36.7±0.67[a]	48.0±0.00[b]	84.7±0.67 [a]
	4cm	37.0 ±0.33[a]	49.0±0.00[b]	86±0.58 [a]
	6cm	37.0±0.58[a]	48.0±1.00[b]	85±1.15 [a]
CV%		1.90	1.18	1.40

4.5 Influence of drier zones and Layer thicknesses on fungal infection

Coffee cherries and beans are subjected to contamination and, consequently, colonization by microorganisms during different phases of processing from harvesting to storage. The contamination of coffee beans by fungi affects both the quality in terms of flavor and aroma of the beverage and presents a safety risk to the final product due to the production of toxic secondary metabolites, the mycotoxins, which can be harmful to consumers at certain concentrations (Vilela *et al*., 2010; Rezende *et al*., 2013). The presence of microorganisms in coffee processing is also an important factor that can affect the final beverage quality as some pectinolytic microorganisms are associated with the degradation of the pulp and mucilage layer producing acids and other metabolic compounds that can diffuse into the coffee beans (Silva *et al*., 2013).

Regarding fungi growth associated with the parchment coffee, a total of 252 fungi were isolated and grouped under *Fusarium, Aspergillus,* and *Penicillium* genera. Accordingly, *Aspergillus* was the dominant 186 (73.81%) followed by *Penicillium* 41(16.27%) and *Fusarium* 25(9.92%). Similarly, different authors detected these fungi from coffee seeds with parchment (Taniwaki *et al*., 2003; Pardo *et al*., 2004).

In connection with each zone, the maximum *Aspergillus* genera (80) were isolated from open sun, followed by Zone one, zone two and zone three (47, 44 and 15 isolates) respectively. For the *penecillium* and *fusarium* genera, the highest (19 and 10) isolates were recorded for the coffee dried under open sun condition, while the lowest was recorded for the coffee dried under zone three (3 and 2) isolates respectively. Moreover from each layer thickness more *Aspergillus* spp. were isolated from 4 cm (33) open sun-dried parchment followed by 6 cm (32) zone two and with the minimum of 1 and 2 fungi genera of *Aspergillus* from zone 3 in 4 cm and zone 2 in 2cm layer thicknesses respectively (Table 7). However, *Pencillium* was not detected in zone two (6cm) and zone three (2cm). Similarly, *Fusarium* not detected in zone two (2 cm and 4 cm), and zone three (2 cm and 6 cm) (Table 7). Considering effects of different treatment combinations on the incidence of the microbes, there was a significant difference ($p<0.005$) was observed between the treatment combinations. Accordingly, the highest mean incidence (93.3%) observed on parchment coffee dried under the open sun with a layer thickness of 6 cm. But the lower mean incidence (4.0%) was on parchment coffee dried under zone three with a layer thickness of 2 cm (Table 7).

The coffee dried under zone two with a layer thickness of 2 cm and zone three with a thickness of 4 cm scored 5.3% and 6.7% respectively which is significantly similar. Similarly, treatment zone 1 with a thickness of 6 cm and open sun with a thickness of 4 cm scored 82.7% and 77.3% respectively which is statistically similar. Layer of drying has shown to have a significant influence on the percentage fungal incidence of the parchment coffee. It is observed that, as layer thickness increased the incidence also increased proportionally under all drying conditions. On the other hand, the fungal incidence decreased with an increase in drying temperature and lower relative humidity from open sun to zone three. Compared to the solar tunnel dryer zones, the highest incidence was observed on the coffee drier in the open sun for all the three layer thicknesses.

Table 7: Influence of drying zones and layer thickness on fungal incidence and infection of the parchment coffee

Drying zones	**Layer thickness**	**Fungal Count**			**Mean Fungal Infection %**
		Aspergillus	**Penicillium**	**Fusarium**	
Sun	**2 cm**	17	3	2	45.3 ± 1.33^{c}
	4 cm	33	4	3	77.3 ± 2.67^{ab}
	6 cm	30	12	5	93.3 ± 1.33^{a}
	Sum	**80**	**19**	**10**	
Zone 1	2 cm	7	2	1	14.7 ± 1.76^{efg}
	4 cm	12	5	2	38.7 ± 2.00^{cd}
	6 cm	28	8	5	82.7 ± 1.33^{ab}
	Sum	**47**	**15**	**8**	
Zone 2	2 cm	2	1	0	5.3 ± 1.33^{fg}
	4 cm	10	3	0	28.0 ± 1.15^{cde}
	6 cm	32	0	5	73.3 ± 1.33^{b}
	Sum	**44**	**4**	**5**	
Zone 3	2 cm	2	0	0	4.0 ± 1.15^{g}
	4 cm	1	1	2	6.7 ± 0.67^{fg}
	6 cm	12	2	0	23.3 ± 0.67^{def}
	Sum	**15**	**3**	**2**	
	Total Sum	**186**	**41**	**25**	
CV%					9.98

In the present study, coffee beans dried under different drying zones with different drying layer thickness showed some contamination at the beginning, but with the variation of drying conditions between solar and open sun as well as among different zones of solar drier variation in terms of incidence was observed for the three identified fungi genera. Initial load of cross-contamination might be the same, but the drying medium condition determines the level of incidence which was observed lower in solar drier than the open sun. Silva *et al*. (2000) reported the occurrence and diversity of these groups of fungi (*Aspergillus*, *Penicillium* and *Fusarium)* on the surface of coffee cherries and beans as natural coffee contaminants from the field to the warehouse conditions.

Even though *Aspergillus* and *Penicillium* were dominant in this study, *Fusarium* was also detected. According to (Pitt and Hocking (1997), *Aspergillus* competes for a substrate with *Fusarium* and *Penicillium*, and its incidence increases in environments with relatively high temperatures and low water activity, which are the ideal conditions found in the final stages of processing and drying.

In the current study, minimizing the drying layer thickness reduces the incidence of fungal contamination besides increasing drying temperature. Therefore, drying temperature and fungi incidence have a reciprocal relationship that is as drying temperature increased fungal load decreased for the same layer of drying thickness. This could be due to lower drying temperature takes longer drying time which could favor for the growth and multiplication of fungi. In line with the present study, Enyan, (2011) reported the fungal load increased with increasing depth of bean kernels and ranged from 57% to about 75% while studying the effect of drying method and depth of robusta coffee.

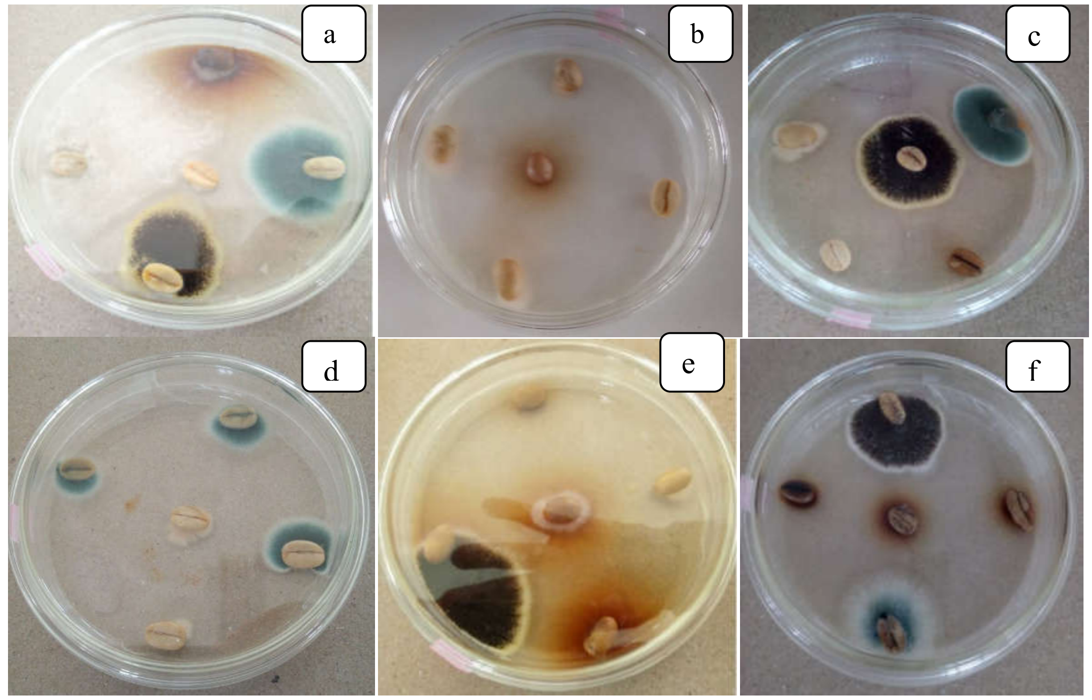


Figure 7: Fungi developed on Parchment coffee after 7 days of incubation on PDA at 25^0C. (a=Open sun, 4cm; b=zone 3,2cm; c=zone 2,6cm; d=zone 1,4cm; e=zone 3,6cm; f=zone 1,6cm)

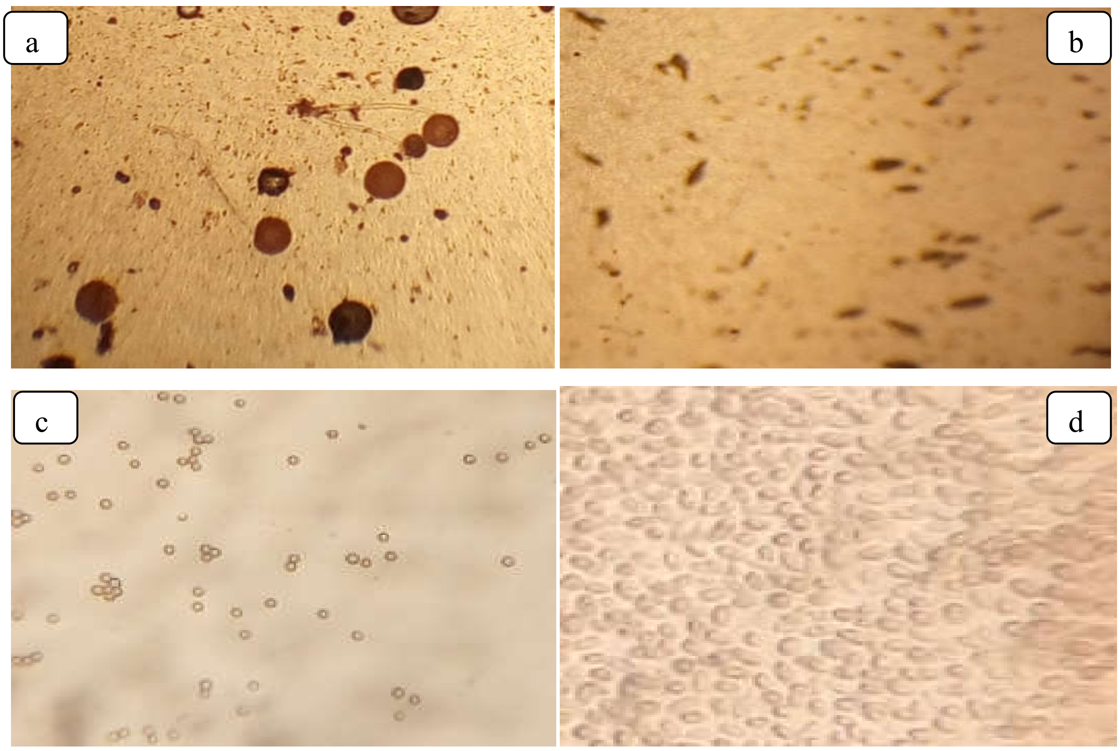


Figure 8: Microscopic view of *Aspergillus* (a) *Fusarium* (b) and *Penicillium* (c,d) Genera

5. SUMMARIES AND CONCLUSION

5.1 Summary

The drying characteristics of parchment coffee studied under solar tunnel conditions as compared with open sun drying. The drying rate was affected by the dryer zone temperature and layer thickness. Increasing dryer temperature, reduction of RH from open sun to zone three with reduction of layer thickness increased the drying rate and decreased the drying time.

Among the thin layer drying models, Modified Midilli was more robust to fit most of drier zones with layer thicknesses as compared with other evaluated models. According to the results, the Modified Midilli model could adequately describe the drying behavior of parchment coffee under the solar tunnel dryer. The second and third selected models are the Verma and Diffusion Approach models, respectively.

Among studied drier zones with layer thickness, parchment coffee dried in zone two at 4 cm layer thickness gave superior results. The difference of drying temperature and RH among drier zones can be compensated by adjusting drying layer thickness in zone one and three. From observed results, it can be said that a layer thickness of 3 or 5 cm could be the best fit in zone one or three for better quality respectively. However, evaluated parameters in all three zones of solar tunnel drier were superior as compared to quality parameters of parchment coffee from open sun drying. The same observed for incidence and infection of the identified fungi genera (*Fusarium, Aspergillus,* and *Penicillium*).

The total quality of a coffee is the overall quality of the coffee-based the overall quality attribute result used to determine and evaluate the quality potential of the coffee. The highest overall coffee quality observed from parchment coffee dried under zone 2 with drying layer thickness of 4cm (87.3) and 2 cm (87.3), specialty coffee quality rate which could be associated with washed coffee grade.

5.2 Conclusion

From this study that it can be concluded that, solar tunnel drying can be a good drying option for coffee drying by preventing quality losses which probably couldn't prevented in case of open sun drying. Among the dryer zones, dryer zone two is likely the best drying zone for best coffee quality but comparative quality grade can be achieved by adjusting drying layer thicknesses at different drier zones. The use of 5-5.5 cm layer thicknes for zone three and from 2.5 to 3 cm for zone one can be a solution to reduce variation in drying rate and other quality parameters for long solar tunnel driers.

6. FUTURE LINE OF WORK

Due to the limitation of resources, facilities, and time in this study, it wasn't possible to address all the required quality parameters like determining the caffeine and chlorogenic acid contents. In addition to this, the study conducted in the partially loaded condition of the big solar tunnel drier. Under fully loaded conditions simulating the actual scenario, the results may not be the same. Therefore, these two critical gaps in this study is recommended to be addressed in the future.

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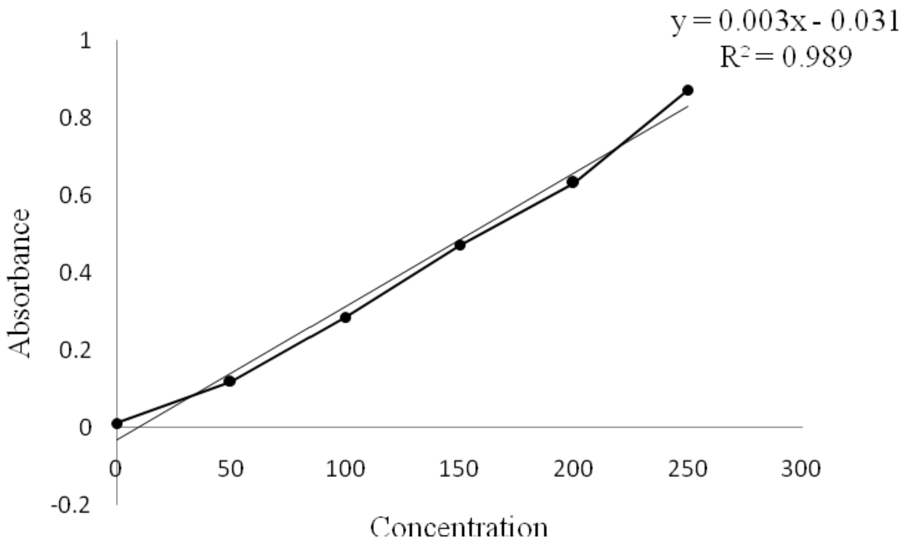
8. APPENDIX



Appendix Figure 1. Standard curve for Gallic acid

Appendix Table 1. Summary of ANOVA Tables

Source	Tested Parameters Along with their P. Values P<0.05 is significant											
	Hours to drying	pH	TA	TSS	Ether Extract	TPC	AOA	IC50	Total Raw Quality	Total Cup Quality	Total Quality Points	Fungal Count
Blocks	0.713	0.779	0.126	0.980	0.166	0.082	0.516	0.947	0.034	0.041	0.063	0.378
Drying zone	0.000	0.000	0.616	0.000	0.000	0.000	0.000	0.000	0.619	0.005	0.010	0.000
Layer thickness	0.000	0.000	0.005	0.000	0.219	0.000	0.000	0.000	0.700	0.904	0.300	0.000
Drying zone*Layer thickness	0.000	0.000	0.264	0.000	0.000	0.000	0.000	0.000	0.933	0.638	0.173	0.000

Appendix Table 2. Constants values for tested kinetic models

samples	Models	RMSE	Chi-squared	R^2	Constants
Zone one 2 cm	M. Midilli	0.030258914	0.000995219	0.97918	b=0.004528 c=1.325143 K=0.031
	Diffusion approach	0.017956	0.00035	0.988164	a=-0.01745 b=1.983394 k=0.031
	Verma	0.017548	0.000335	0.988691	a=1.829585 b=0.045237 k=0.031
	Henderson and Pabis	0.018163	0.000359	0.987904	a=1.012372 b=0.061066
	Newton	0.018789	0.000368	0.988142	a=0.060032
	Modified Page	0.018789	0.000384	0.988142	a=0.070939 b=0.846258
	Two term model	0.018163	0.000359	0.987904	a=0.981371 b=0.061065 d=0.061072 k=0.031
Zone two 2 cm	M.Midilli	0.038962867	0.001686783	0.973091	b=0.011195 c=1.551565 k= 0.04
	Diffusion approach	0.024653301	0.000675317	0.980642	a=-0.00212 b=2.349267 k=0.04
	Verma	0.022036	0.00054	0.98522	a=0.770691 b=0.119136 k=0.04
	Henderson and Pabis	0.024649	0.000675	0.98068	a=1.002002 b=0.093958
	Newton	0.024661	0.00064	0.980549	a=0.0937218
	Modified Page	0.025995	0.000676	0.980549	a=0.126662 b=0.739938
	Two term model	0.019079	0.000428	0.988112	a=0.987167 b=0.112336 d=-0.03991 k=0.04

samples	Models	RMSE	Chi-squared	R^2	Constants
Zone three 2 cm	M.Midilli	0.026815825	0.000838937	0.983345	b=-0.00737 c=1.134109 k= 0.064
	Diffusion approach	0.032206243	0.001210116	0.970062	a=-0.13644 b=1.853563 k=0.064
	Verma	0.046663267	0.002540371	0.953703	a=1.123365 b=0.095149 k=0.064
	Henderson and Pabis	0.04203172	0.00206111	0.949828	a=1.067979 b=0.109569
	Newton	0.1898774	0.002778	0.95763	a=0.10006
	Modified Page	0.0507468	0.003044	0.95763	a=0.1359989 b=0.7405844
	Two term model	0.042031722	0.002248484	0.949828	a=1.003978 b=0.109568 d=0.109569 k=0.064

Sun 2cm	M.Midilli	0.043351721	0.002000621	0.988631	b=-0.00737 c=1 k= 0.0246
	Diffusion approach	0.026620706	0.000754382	0.979546	a=0 b=1.815272 k=0.0246
	Verma	0.020862	0.000463	0.984803	a=1.102501 b=0.050084 k=0.246
	Henderson and Pabis	0.025289	0.000681	0.977829	a=1.021498 b=0.045981
	Newton	0.026621	0.000731	0.979546	a=0.044656
	Modified Page	0.026621	0.000754	0.979546	a=0.09026 b=0.494746
	Two term model	0.025289	0.000703	0.977829	a=0.996899 b=0.045981 d=0.045987

samples	Models	RMSE	Chi-squared	R^2	Constants
Z1 4cm	M.Midilli	0.02861307	0.00088169	0.981212	b=0.00218 c=1.261015 k= 0.03
	Diffusion approach	0.02135366	0.00049105	0.983924	a=-0.01866 b=1.895646 k=0.03
	Verma	0.019296442	0.000400995	0.986772071	a=3.214620942 b=0.036798125 k=0.03
	Henderson and Pabis	0.021591658	0.000502061	0.98361225	a=1.013053 b=0.056454
	Newton	0.0221655	0.0005095	0.98413	a=0.055473
	Modified Page	0.0221655	0.000529	0.98413	a=0.00504 b=11.0071
	Two term model	0.02277343	0.00058086	0.981797	a=1.005654 b=0.055899 d=4.000089 k=0.03

Zone two 4 cm	M.Midilli	0.022523694	0.000560719	0.983981	b=-0.08718 c=1.878376 k= 0.041
	Diffusion approach	0.028443573	0.000894199	0.974765	a=-0.08718 b=1.878376 k=0.041
	Verma	0.032475171	0.001165651	0.978472	a=56.77897 b=0.041419 k=0.041
	Henderson and Pabis	0.034278588	0.00117502	0.967216	a=1.054993 b=0.07405
	Newton	0.039283389	0.00162034	0.971667	a=0.068816
	Modified Page	0.039283389	0.001705625	0.971667	a=0.088236 b=0.779909 k=0.041
	Two term model	0.032605441	0.001240301	0.967216	a=1.013993 b=0.074051 d=0.074052 k=0.041

samples	Models	RMSE	Chi-squared	R^2	Constants
SUN 4 cm	M.Midilli	0.016820259	0.000307885	0.992515	b=-0.00279878 c= 1.12900835 k= 0.021
	Diffusion approach	0.014578775	0.000224686	0.992541	a= 1.5432 b= 0.020587 k= 0.021
	Verma	0.021198447	0.000475053	0.986121	a= 41.13481 b= 0.021342 k= 0.021
	Henderson and Pabis	0.0272806	0.0007867	0.97390	a= 1.030471 b= 0.039423
	Newton	0.0297494	0.0009096	0.9766	a= 0.037789
	Modified Page		0.0009356	0.9766	a= 0.04594 b= 0.822576
	Two term model	0.027280603	0.000809899	0.973905 8	a= 1.010469 b= 0.039423 d= 0.039426 k= 0.021

samples	Models	RMSE	Chi-squared	R^2	Constants
Zone three 4 cm	M.Midilli	0.020796024	0.000490138	0.988002	b=0.003739 c=1.295282 k= 0.052
	Diffusion approach	0.021991	0.000548	0.985872	a=-0.11877 b=1.986781 k=0.052
	Verma	0.035421	0.001422	0.979519	a=4.911416 b=0.058617 k=0.052
	Henderson and Pabis	0.031357	0.001114	0.971734	a=1.066304 b=0.09727
	Newton	0.041086	0.001794	0.975562	a=0.089325
	Modified Page	0.041086	0.001913	0.975562	a=0.044663 b=2
	Two term model	0.038588	0.001808	0.97478	a=1.046884 b=0.09495 d=4.721559 k=0.052

samples	Models	RMSE	Chi-squared	R^2	Constants
Zone one 6cm	M.Midilli	0.025641464	0.000693024	0.991145	b= 0.00079 c= 1.2 k= 0.021
	Diffusion approach	0.084907291	0.007598937	0.863403	a= 0.69 b= 0.09 k= 0.021
	Verma	0.081542966	0.007008674	0.970236	a= 1 b= 0.05 k= 0.021
	Henderson and Pabis	0.0296492	0.0009265	0.984041	a= 1 b= 0.04
	Newton	0.0289760	0.0008617	0.984765	a= 0.039204
	Modified Page	0.0289760	0.0008849	0.984765	a= 0.036558 b= 1.072371
	Two term model	0.023345219	0.000590416	0.982419	a=1.024433 b= 0.041593 d= 0.041596 k= 0.021

Zone two 6 cm	M.Midilli	6.23761E-05	0.001871284	0.969779328	b= -0.01075 c= 0.904734 k= 0.021
	Diffusion approach	0.060173881	0.003862289	0.975087	a= 39.5469 b= 0.0006 k= 0.021
	Verma	0.066905433	0.004774759	0.954884623	a= 35.5365 b= 0.0214 k= 0.021
	Henderson and Pabis	0.051517	0.002830	0.9228124	a= 1.14446 b= 0.04518
	Newton	0.073634	0.005596	0.9414149	a= 0.0372689
	Modified Page	0.063779	0.004339	0.935961	a= 2.467026 b= 0.016111
	Two term model	0.051517238	0.00292858	0.922813	a= 1.066898 b= 0.045182 d= 0.045184 k= 0.021

samples	Models	RMSE	Chi-squared	R^2	Constants
Zone three 6cm	M.Midilli	0.01973017	0.000419224	0.987261	b=-0.00085 c=1.185364 k=0.03
	Diffusion approach	0.02479286	0.000661969	0.980119	a=-0.07081 b=1.907636 k=0.03
	Verma	0.026604406	0.00076224	0.98445	a=27.35205 b=0.030686 k=0.03
	Henderson and Pabis	0.02762685	0.000821954	0.975538	a=1.049933 b=0.05576
	Newton	0.03377	0.001182	0.9788	a=0.052181
	Modified Page	0.033774	0.001228	0.9788	a=0.051159 b=1.019985
	Two term model	0.02762685	0.000854832	0.975538	a=1.019935 b=0.055769 d=0.055772 k=0.03

Sun 6cm	M.Midilli	0.022489114	0.001	0.992582	b=0.002071068 c=1.299807677 k=0.017
	Diffusion approach	0.010121138	0.00010699	0.996315621	a=1.773326313 b=0.013244608 k=0.017
	Verma	0.023799508	0.000591591	0.98731	a=38.09574946 b=0.017266542 k=0.017
	Henderson and Pabis	0.026971272	0.000759781	0.974822	a=1.04368782 b=0.030669946
	Newton	0.0318526	0.001036	0.97893	a=0.028857849
	Modified Page	0.0318526	0.001059	0.97893	a=0.832320203 b=0.034671571
	Two term model	0.026971272	0.000777048	0.974822	a=1.026688038 b=0.030669924 d=0.030669567 k=0.017

Appendix Figure 2: Field Activities

a) Washing after fermentation ended; b) Picking unwanted materials in the washed coffee;

c) unwanted materials such as broken seeds, parchment removed seeds, foreign materials, burned seeds, seeds with hulls attached, green beans and etc which were discarded;

d) Wet parchment coffee laid on solar tunnel drier; e) solar tunnel drier as seen from outside;

f, g and h) taking samples weight during drying; i) colleagues having fun at break time.

Appendix Figure 3 : Determining physicochemical properties in Postharvest Management Laboratory

Appendix Figure 4 : Analyzing PH of green coffee Using digital PH meter

Appendix Figure 5 : Analysing Sensory property of the coffee by trained panellists at ECX coffee quality Laboratory of Jimma Branch