

Investigation of the Drying Effect on Physiochemical Properties of Coffee Beans by Using Solar Kiln Experimental Setup



Addisu Terfa Tadesse

A Thesis Submitted to Department of Mechanical Engineering,
College of Mechanical, Chemical and Materials Engineering

Presented in Partial Fulfillment of the Requirement for the Degree of Master of
Science in Thermal Engineering

Office of Graduate studies

Adama Science and Technology University

**June, 2025
Adama, Ethiopia**

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Advisor: Dr. Dawit Gudeta Gunjo (Ph.D)

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I hereby declare that this Master Thesis entitled “**Investigation of the Drying Effect on Physiochemical Properties of Coffee Beans by Using Solar Kiln Experimental Setup**” is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

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Acronyms and abbreviation

OSD	open sun drying	EMC	Equilibrium moisture content
DSD	Direct solar dryer	FT-NIR	Fourier transform near infrared
NC	Natural convection	S-EHD	Solar electric hybrid dryer
FC	Forced convection	DPSAH	double pass solar air heater
LHS	Latent heat storage	TES	Thermal Energy Storage
SAH	solar air heater	HTF	Heat Transfer Fluid
FPC	Flat plate collector	PCM	Phase change material
UV	ultraviolet	IDSD	Indirect solar dryer
MC	moisture content	SHS	sensible heat storage
CGAs	Chlorogenic Acids	VOCs	Volatile Organic Compounds
RH	Relative humidity		

Greek symbol and their description			
α	absorptivity	σ	Boltzmann constant
δ	declination	θ	Angle of incidence
ρ	density	μ	dynamic viscosity
β	tilt angle	ε	emissivity
ω	hour angle	ν	kinematic viscosity
φ	latitude	η	efficiency
γ_s	solar azimuth angle	γ	surface azimuth an
ω_s	sunrise and sunset angle	θ_z	Zenith angle

Nomenclature

ρ_c	density of glass cover
δ_g	thickness of glass
CP_g	Specific heat of cover material
CP_a	Specific heat of air
T_g	temperature glass cover
T_f	mean temperature of fluid inside SAH
T_p	mean plate temperature
T_a	ambient temperature
T_{db}	dry bulb temperature
α_g	absorptance glass cover
$h_{c,fg}$	Convective heat transfer between the cover and fluid(air)
$h_{c,fa}$	Convective heat transfer between the floor cover and the air
$h_{c,p-a}$	Convective heat transfer between the product and the air
$h_{r,p-c}$	Radiative heat transfer between the product and the cover
$h_{r,pg}$	Radiative heat transfer between the plate and glass cover
$h_{r,gs}$	Radiative heat transfer between the cover and the sky
$h_{c,ga}$	Convective heat transfer between the cover and the ambient
m_a	mass of air
Q_u	Useful heat collected by the collector
H_d	Monthly average daily diffuse radiation on horizontal surface
H	Monthly average daily global radiation on horizontal surface
H_o	Monthly average daily extraterrestrial radiation on horizontal surface

I	Monthly average hourly global radiation
I_t	Total hourly irradiance on a tilted surface
I_d	Monthly average hourly diffuse radiation
R_b	Beam radiation factor
ρ_g	Diffuse reflectance of ground
h_{fg}	Latent heat of vaporization
m_{air}	Mass flow rate of air
m_w	Amount of water removed from a wet product
m_i	Initial moisture content
m_f	Final moisture content

Abstract

This study combines thermal performance modeling, biochemical quality assessment, and a farmer-centered design approach to enhance solar coffee drying, a crucial yet neglected field in postharvest technology. Conventional open sun drying is plagued by contamination, rewetting, and microbial growth, ultimately reducing the quality of coffee. In response to these issues, an active solar kiln dryer was designed and constructed from cheap and locally sourced materials. The experimentation investigates the effects of solar kiln drying on the physicochemical properties of green coffee beans including moisture loss, nutrient retention, and biochemical composition. Numerical analysis of heat and mass transfer during drying were likewise analyzed for performance. Proper drying, the study stresses, is key to preserving coffee quality that directly affects market value, demand, and consumer acceptability.

The findings indicate that the solar kiln dryer saves drying time by 42% and have an overall system efficiency of 8.7%, while at the same time causing a significant amount of energy saving relative to traditional approaches. Moreover, the system preserves high coffee bean quality through the reduction of faults and safeguarding essential biochemical traits. By providing protection against risks like non-uniform drying, infestation by pests, and rain-induced damage, the proposed drying equipment presents an eco-friendly and economically sound option for small-scale farmers. An underlying feasibility analysis demonstrates that the solar drying process improves product quality while reducing postharvest loss, making it an ecologically benign alternative to traditional methods. This study offers a sustainable and feasible approach to the enhancement of coffee drying practices, achieving better quality results with possible application in analogous agro-climatic zones.

Keywords: drying effect, solar kiln, coffee beans, bioactive, moisture content

CHAPTER ONE

Introduction

1.1. Background of Study

Drying is a complex phenomenon involving simultaneous heat and mass transfer under transient conditions, coupled with rate-dependent physical and chemical changes that influence both product quality and heat-mass transfer dynamics(Desa et al., 2024). The choice of drying method can significantly modify the physiochemical characteristics of coffee, including its bioactive compounds(Moon et al., 2024). Drying significantly impacts the physical properties of products, altering their structure, texture, and overall composition(Moon et al., 2024). The impact of moisture removal on a material, influencing its physical, chemical, and structural properties(Pittia et al., 2006)(Science, 2018). When moisture is removed some of the following occur, materials shrink and thus density and porosity are affected. In foods, it leads to wrinkling and texture modification. Decreased moisture content reduces the possibility of microbial activity and chemical reactions and thereby increases shelf life(Yao et al., 2022). As water content decreases, the ability of the material to retain heat is reduced, altering its thermal conductivity. Dehydration may result in color change as a result of alteration of concentration of pigments and surface texture. Further, reduction in levels of moisture significantly affects the mechanical properties of materials so that they become more susceptible to brittleness and cracking. In the case of agricultural commodities, i.e., fruits and vegetables, drying will lead to wrinkling and color change because of increased concentration of pigments and degradation of some compounds.

During drying, several physical changes may take place, including shrinkage, puffing, crystallization, and glass transitions(Of, n.d.). Simultaneously, numerous chemical and biochemical reactions some desirable and some damaging can occur, influencing the color, texture, aroma, and other quality characteristics of the product(Of, n.d.)(Nasrin et al., 2021). The basic principle of drying is the evaporation of water from the wet material with the application of external thermal energy.

The drying process involves two simultaneous steps: heat transfer to the product and mass transfer as moisture moves from the interior to the surface of the product (Tiwari, 2016). The weight decrease of the dried product from the drier was measured, and the latent heat of evaporation was multiplied to calculate the energy needed to turn water from liquid to vapor.

One of the most important phases in the making of coffee is drying. The coffee bean must be dried in order to stop microbiological growth and increase the coffee's shelf life(Eduardo et al., 2021). Because every coffee producer has certain product qualities they want to attain, maintaining coffee properties during the drying process is crucial. To reduce the drying time, regulated drying techniques have been created and implemented in industries up to this point.

Overall, drying is a critical process that affects the physical properties and chemical compositions of materials in various ways. Understanding these effects is essential for optimizing drying techniques to achieve the desired quality and functionality in different applications.

Solar drying represents an improved version of the conventional sun drying method and has been successfully applied to various agricultural products(Paola et al., 2023). It is an innovative and eco-friendly technique that utilizes solar energy to remove moisture from various agricultural products and wood(Yao et al., 2022). Widely employed in agricultural, food processing, and industrial sectors, this method offers an energy-efficient solution for product preservation while significantly reducing conventional energy consumption. Solar drying systems can be categorized into three main type: direct, indirect, and mixed-mode(Maryam Al Baloushi, 2020). The direct method exposes materials to sunlight, offering simplicity and cost-effectiveness but remaining vulnerable to weather fluctuations. Indirect systems employ solar collectors to heat air, which is then directed through a drying chamber, allowing for more controlled drying conditions(Ennissioui et al., 2023). The mixed-mode approach combines both techniques to optimize drying efficiency while preserving product quality(Ekka et al., 2020). A major benefit of solar drying lies in its sustainable nature, decreasing dependence on fossil fuels and minimizing carbon emissions(Muhshin et al., 2022). The method also excels in maintaining nutritional value in food products by avoiding overheating, making it particularly suitable for drying fruits, vegetables, grains, and spices. Its applications extend beyond food preservation to industrial uses such as timber drying, textile processing, and agricultural waste treatment. While solar drying presents certain challenges like weather dependence and relatively slower drying speeds compared to conventional methods, ongoing technological improvements in solar collector design and hybrid system integration are progressively enhancing its performance and reliability.

Solar drying of agricultural products is a crucial aspect of product handling and processing(Yao et al., 2022). Solar kiln is the simplest and safest way to dry wood and agricultural product quickly. Over

the years, various dryer designs have been critically evaluated. Solar dryers were first utilized for non-agricultural goods before being expanded to dry agricultural goods(Tiwari, 2016). Solar dryer technology is a practical and affordable way to reduce harvest loss and improve product quality(Sintie & Aduye, 2020).

1.1.1. Coffee

Coffee's ability to provide flavor, aroma, and favorable physiological and psychological effects makes it one of the most well-liked and extensively consumed hot beverages in the world.(Beshah et al., 2013). Arabica and Robusta coffee make up 75 and 25 percent of global coffee production, respectively, making coffee the second most traded commodity in the world after oil (Mehari et al., 2016). During the 2020–21 crop year, about 166 million 60 kg bags of coffee were consumed worldwide. about the past several years, the amount consumed has increased at a pace of 1.3% to 4.4% annually(Hu et al., 2023). Over 125 million people throughout the world depend on coffee for their livelihoods(Hassen et al., 2021).

Coffee's history dates back to the tenth century, and there are several myths about its usage. Over 1,000 years ago, a goatherd in the southwest highlands of Ethiopia collected a few red berries from some young, green trees growing there in the wild and tried them to determine whether they had flavor and whether they made the customers feel happy(Chauhan et al., 2015). The coffee plant, Coffee Arabica, originated in Ethiopia and is now grown all over the world. Coffee cultivation in Ethiopia began thousands of years ago in the jungles of Kaffa, Illubabor, Wollega, Bale, and other areas due to natural forces(Chauhan et al., 2015). Coffee arabica developed in these woodlands before spreading to other parts of the world to become the progenitor of coffee plantations as they exist today. Arabica coffee is more expensive than Robusta and produces better-tasting beverages(Mehari et al., 2016). Depending on soil and weather conditions, Ethiopia produces between 400,000 and 550,000 metric tons of coffee annually, making it the world's fifth-largest producer(Girma Adugna, 2021). About 17% of the world market for coffee comes from this nation.

It is vital to the cultural and socio-economic life of Ethiopians and contributes 34% of the country's foreign exchange, half of GDP, 90% of exports, 85% of total employments in the country and providing livelihoods for an estimated 15 million people involved in some aspect of coffee production(Amamo, 2014). Ethiopia produces four varieties of coffee: forest coffee, semi-forest coffee, garden coffee, and plantation coffee. These four types make up 10%, 35%, 50%, and 5% of

Ethiopia's total coffee output, respectively (Girma Adugna, 2021). Within the producing regions, around 35% of the overall production is consumed. In Ethiopia, coffee ceremonies are deeply ingrained in the culture. A coffee ceremony opens important events (Chauhan et al., 2015).

1.2. Problem of Statement

In today's coffee industry, quality has become a decisive economic factor, directly influencing price, consumer demand, and market competitiveness. However, postharvest drying, one of the most important coffee processing phases, remains a challenge, particularly for smallholder farmers that employ the traditional open sun drying. This method subjects coffee beans to various risks, including dust, insect, and microbial contamination; uneven drying with attendant mold growth; and instant rewetting by rain, all of which lower quality and reduce shelf life (Abdissa et al., 2023). Moreover, open sun drying is time-consuming and labor-intensive, often failing to reach the optimum 12% moisture level required to arrest spoilage (Ghosh, 2014). While solar drying technologies such as cabinet and tunnel dryers have been explored for other products, there has been minimal scientific research on their application to coffee beans, with few studies on drying efficiency, biochemical quality preservation, or adaptability to different climatic conditions. Solar dryers in the present are generally developed for single conditions without consideration for long-term performance or scalability, leaving a void in farmer-appropriate, practical solutions (Beshah et al., 2013). Also, unfavorable drying conditions may cause nutrient loss and flavor degradation, which further reduce market value (Ameyu et al., 2017), (Nasrin et al., 2021). To surmount these issues, there is an urgent need for an optimized solar kiln drying system that is capable of guaranteeing uniform moisture removal, preserving the physicochemical properties of coffee, and reducing postharvest losses. This project seeks to improve coffee quality, farmer profitability, and promote sustainable farming practice among the coffee-producing areas through the creation of a cost-effective and efficient solar drying innovation.

1.3. Objective of the Study

1.3.1. General Objective

The objective of the study is Investigating Drying Effect on Physiochemical Properties of Coffee Beans by Using Solar Kiln Experimental Setup.

1.3.2. Specific Objective

- ✓ Studying analytically and numerically the heat and mass transfer performance of solar kiln
- ✓ Improving the solar drying kiln's drying efficiency while preserving the beans' physical and biochemical properties.
- ✓ Manufacturing prototype and conducting experimentation for identifying the energy required to dry coffee beans to the desired moisture content.
- ✓ Minimizing the possibility of contamination by the use of controlled, enclosed drying conditions.
- ✓ Conducting comparative analysis on bioactive and physical property of sun drying and solar kiln drying.
- ✓ Offering smallholder farmers scalable options by substituting sustainable solar thermal technology for ground-level drying.

1.4. Significance of Study

The physiochemical properties of coffee determine its quality. Understanding these properties helps optimize processing and drying method ensuring a consistent and enjoyable coffee experience. Postharvest processing methods significantly impact all key quality parameters of raw coffee beans (Ameyu et al., 2017). This project expects to represents a significant improvement over traditional open sun drying, which is commonly used to preserve coffee beans and other agricultural products. By drying in a closed environment with higher internal temperatures, this system reduces the potential for crop damage from animals, birds, and unexpected rain, which often lead to decreased product quantity and quality. It is anticipated that the upgraded system will provide premium coffee beans that can be shipped to both domestic and foreign markets, bringing in a sizable sum of money. It also cuts down on the amount of space needed, labor effort, and processing time. To guarantee the best outcomes, trials will also be conducted to assess the most popular coffee drying technology.

1.5. Expected Outcome

This thesis is expected to produce high-quality coffee beans for end users, generating fair income and raising community awareness about the significance of solar kiln drying. A nutritive and physical property analysis will also be conducted to compare open sun drying and kiln drying, evaluating the most suitable method for coffee drying.

1.6. Scope of the Study

It is anticipated that this research will yield premium coffee beans for final consumers, creating equitable revenue and increasing public knowledge of the value of solar kiln drying. In order to compare open sun drying with kiln drying, a nutritional and physical property analysis will also be carried out, assessing the best technique for drying coffee.

1.7. Organization of the study

This research was divided into five chapters. In the first chapter, the thesis is introduced, along with the drying system background, problem description, general and particular objectives, importance, scope, and organization of the study. Chapter Two presents a related literature review covering the classifications of solar dryers and solar air heaters, as well as the physical properties and chemical composition of green coffee beans. A summary of the examined literature and a list of current research gaps that this study attempts to fill are included in the chapter's conclusion. The third chapter covers the thesis work's approach, which includes data gathering techniques, estimations of materials and equipment, solar radiation, theoretical analysis of the sun dryer, and the construction and size of the solar kiln system. Chapter 4 presents the experimentally observed key parameters of the drying systems investigated in the study. A comprehensive comparative analysis was conducted to evaluate the effects of different drying methods on both the physical and chemical properties of green coffee beans. The performance of each drying system was systematically assessed based on multiple quality indicators, including moisture removal rate, energy efficiency, and the preservation of essential bean characteristics. Last chapter concluding synthesizes key findings from the study, evaluating the impact of different drying systems on coffee bean quality and processing efficiency and insights aim implementing drying techniques that enhance coffee quality, sustainability, and market competitiveness.

CHAPTER TWO

LITERATURE REVIEW

2.1. Overview

This chapter presents an extensive review of the pertinent literature on the impact of drying on coffee beans and drying equipment involved. It discusses the developments and optimization procedures employed to improve the efficiency of coffee drying processes, paying particular attention to the design and operation of more efficient drying equipment. Moreover, the chapter examines the inherent relationship between different drying techniques such as traditional sun-drying, mechanical drying, and hybrid technology and the quality attributes of the dried coffee beans comprising sensory profile, chemical composition, and physical properties. Also, it discusses the use of numerical modeling approaches to simulate and solve the coupled heat and mass transfer equations that describe the drying kinetics. This approach gives more insight into the physical mechanisms involved and allows the prediction and optimization of drying behavior under various conditions.

2.2. Basic principle of solar drying system

A solar drying system is a sustainable method for drying agricultural products, food, or other materials using solar energy. Solar drying is one of the green technologies to preserve agricultural products by reducing their moisture content to a level that prevents the growth of microorganisms and other biochemical processes (Abdissa et al., 2023). It harnesses sunlight to remove moisture from materials, making them easier to preserve, transport, and store. Solar drying and forced convection of hot air (mechanical drying) are traditionally used for the drying process of coffee beans. Solar kiln with transparent cover is design to transmit largest practical percentage of incident solar energy into kiln. The sun radiant energy (light) hits the dark interior and heats the kiln. As kiln heats up the fan circulates warm air through the material stack on drying chamber. The moving air picks up moisture from wet material and is vented out the back. Solar drying system is an eco-friendly alternative to conventional drying methods, which typically rely on electricity or fossil fuels.

A drying system removes moisture from a material, usually by the application of heat and controlled air circulation. The goal is to reduce the moisture content of the material to a level that prevents spoilage or degradation, while preserving quality and minimizing energy consumption.

The working principle of a drying system involves the interaction between heat, mass transfer, and airflow, which results in the evaporation of moisture from the material to be dried.

Heat Transfer: Heat is applied to the material being dried to increase its temperature. This can be done through direct heat sources (e.g., sunlight, heated air) or indirect heat sources (e.g., radiators, electric heating). The applied heat raises the temperature of the material, which increases the kinetic energy of the water molecules, causing them to evaporate. As the material's temperature rises, the water or moisture contained within the material transitions from a liquid to a vapor (evaporation). This phase change occurs at the surface of the material first, and then moves inward as more moisture from within the material moves toward the surface.

Mass Transfer: moisture evaporates from the surface of the material, more water molecules migrate from the interior of the material to the surface, where they can then evaporate. This is a process of mass transfer driven by the difference in moisture content between the inside of the material and its surface.

Moisture Exhaust: The moist air that is carrying the evaporated water is vented out of the drying chamber or environment to avoid saturation, which would slow or stop the drying process. Effective exhaust mechanisms (forced ventilation) are necessary to maintain a low relative humidity around the material. This moist air must be continuously replaced with fresh, dry air to maintain the drying process.

Control Mechanisms: In advanced drying systems, temperature, humidity, and airflow are carefully controlled to achieve consistent and efficient drying. Sensors and automation can be used to monitor moisture levels and regulate the drying process.

By using various drying layer thicknesses that are more appropriate for a certain drier zone and by defining and implementing a particular drying kinetic model for improved quality and safety, regional variations in drying rates may be balanced.

2.3. Classification of drying system

Several key considerations must be evaluated to ensure optimal performance and product quality(El-sebaili & Shalaby, 2012). Energy efficiency is crucial because drying is an energy-intensive process; renewable-based systems energy or use heat recovery systems, such as heat pumps, that can significantly reduce operational costs. Maintenance of bean quality is another factor of prime concern, as improper drying can lead to deficiencies, flavor deterioration, or non-uniform moisture content. Systems must allow precise control over temperature, humidity, and airflow to prevent overheat or drying out, which can cause damage the subtle flavor and aroma of the beans. Besides, the production scale influences the decision, with small-scale farms being benefited by less complicated systems like solar or batch dryers, while industrial operations require large-capacity automatic systems such as conveyor or fluidized bed dryers. Beginning investment and operating costs must be affordable, and environmental issues must be given priority, favoring structures that minimize carbon emissions or use renewable energy sources. Lastly, the conditions in the location of processing can render a preference for hybrid over fully Mechanical systems are considered more suitable. The technology utilized for drying green coffee beans is crucial for sustaining quality, preventing spoilage, and consistency in storing and roasting. They classified under 2 types; natural drying process and controlled drying system(Yao et al., 2022).

1. Natural Drying Method

- *open sun drying* (OSD): the crop is spread in a thin layer on the ground and exposed directly to solar radiation, wind and other ambient conditions(El-sebaili & Shalaby, 2012).
- *Raised Beds*: Beans are placed on mesh or perforated surfaces elevated above the ground to improve airflow and uniform drying.

2. Controlled Drying System

In order to ensure consistent drying and preserve bean quality, controlled drying systems for green coffee beans are made to offer exact control over temperature, humidity, and airflow. These systems can be categorized according to the kind of control they offer and their technological approach.

a) Solar drying systems

- Direct mode: The direct method exposes materials to sunlight, offering simplicity and cost-effectiveness but remaining vulnerable to weather fluctuations(Maryam Al Baloushi, 2020).
- Indirect mode: Indirect systems employ solar collectors to heat air, which is then directed through a drying chamber, allowing for more controlled drying conditions(Ennissioui et al., 2023).
- Mixed mode: The mixed-mode approach combines both techniques to optimize drying efficiency while preserving product quality(Ekka et al., 2020).

b) Mechanical Drying Methods

- *Rotary Dryers*: Coffee is loaded into a rotating drum, where hot air is passed through to dry the beans. Faster and more uniform drying than sun drying. High energy consumption, initial setup cost.
- *Conveyor Dryers*: Beans move on a conveyor belt through a drying chamber with controlled heat and airflow. Continuous process, good for large-scale operations. Requires maintenance and energy efficiency optimization.
- *Fluidized Bed Dryers*: Hot air is forced upward through a bed of beans, causing them to "float" and dry uniformly. High drying speed and uniformity. Initial cost and complexity.

c) Advanced Technologies

- *Heat Pump Dryers*: Uses a heat pump system to generate hot air while recycling energy, allowing precise control of temperature and humidity. Highly energy-efficient, environmentally friendly, maintains bean quality. Expensive initial investment.
- *Infrared (IR) Drying*: Infrared heaters directly transfer energy to the beans, quickly evaporating moisture. Faster and more uniform drying with reduced microbial contamination. It requires fine control to prevent overheating.
- *Microwave-Assisted Drying*: Combines hot air drying with microwave energy for faster internal moisture evaporation. It reduces drying time and energy use.
- *Vacuum Drying*: Beans are dried under low pressure, reducing the boiling point of water for gentle drying. Maintains flavor and aroma better than high-temperature methods and high equipment cost, more suited for specialty coffee.

d) Hybrid Systems

- **Combination of Solar and Mechanical Drying:** Solar energy is used during the day, while mechanical systems (like heat pumps) take over during the night or cloudy weather. Balances cost and efficiency, more sustainable.

2.4. Factor Affecting Solar Drying System

several factors affect solar dryer performance, and several research examine these elements in an effort to increase the drying efficiency of solar dryers (Zhu et al., 2024). Several factors affect the efficiency and effectiveness of a solar drying system (Ugwu et al., 2015). The performance of a solar air heater (SAH) is influenced by a combination of environmental, design, operational, and material factors. These factors influence how quickly and uniformly materials are dried and how well the system performs under different environmental and operational conditions. Some factors are controllable (like design and materials) while others are not (like ambient temperature and weather). Understanding these factors is critical for optimizing efficiency and output.

1. Environmental Factors

The intensity of sunlight directly affects heat gain. Then, ambient temperature, since the heater's efficiency depends on the temperature difference (Helwa et al., 2007). Lower ambient temperatures increase the temperature gradient between the absorber and air, enhancing heat transfer. Wind speed could affect convective losses. High wind increases convective heat losses from the collector surface, reducing efficiency. Geographic location and seasonal variations also play a role in sunlight availability.

2. Design Factors

Design factors include the absorber plate's material and coatings. If the plate has a selective coating, it absorbs more heat. Surface coatings (selective coatings like black chrome) to maximize solar absorption and minimize radiative losses. The geometry of the absorber, like fins or roughness, increase turbulence and heat transfer area to enhance heat transfer (El-sebaili & Shalaby, 2012). Glazing type, number of layers, and material transparency (e.g., glass vs. polycarbonate) and anti-reflective coatings impact transparency and insulation. Insulation on the sides and back prevents heat loss. Airflow configuration such as single vs. double pass, duct geometry (length, width, shape) and airflow path (serpentine, baffled) affects how much heat is transferred. Thermal storage integration,

like phase change materials (PCMs) or rock beds to store excess heat for later use(Embale & Gunjo, 2023).

(Zhu et al., 2024)studied Influencing Factors Used for Performance Evaluation of Solar Dryers. They investigate the variables affecting the assessment of solar dryer performance. Under identical climatic circumstances, the drying behavior of solar dryers with a single pass and those with two passes was studied. Whereas the double-pass collector's immediate efficiency peaks at about 60%, the single-pass collector's reaches at a peak of 56%. According to the collector performance curves, the double-pass collector performs more steadily.

3. Operational Factors

Airflow rate is crucial. Too high might not let air absorb enough heat, too low reduces efficiency. Inlet air temperature; if it's already warm, the heater can't add much more. System tilt and orientation relative to the sun affect how much radiation is captured(Helwa et al., 2007). The tracking system, whether fixed or movable, also matters. Maintenance aspects like dust on the glazing or corrosion can degrade performance over time.

4. Material Properties

Material properties are important too. Thermal conductivity of the absorber material determines how well heat is transferred. Emissivity of the absorber surface affects how much heat is radiated back. Durability of materials against weathering and corrosion ensures long-term efficiency. Cost of materials might influence design choices, balancing performance and affordability.

5. Other Factors

Other factors could include humidity, as moist air has different thermal properties(Helwa et al., 2007). Shading from nearby objects can reduce irradiance. System aging and component degradation over time. Control systems, like automated fans or dampers, optimize airflow dynamically. Hybrid systems combining with PV panels or heat recovery systems also impact performance.

Comparison of factors like temperature, moisture control, exposure, and drying uniformity of open sun drying and solar kiln drying.

Parameter	Open Sun Drying	Solar Kiln Drying
Temperature	Uncontrolled (ambient, fluctuates with weather)	Controlled (higher, stable temperatures)
Humidity	Dependent on ambient humidity	Reduced humidity (enclosed system)
UV Exposure	Direct UV exposure	Filtered/Reduced UV exposure (glazing)
Drying Time	Longer (3–7 days)	Shorter (2–4 days)
Contamination risk	High (dust, pests, microbes)	Low (enclosed, protected environment)

Table 2.1 comparison of factor affecting drying method

2.5. Performance Enhancement Technique of drying system

Enhancing solar dryer performance requires a holistic approach, often combining multiple techniques. To enhance the performance of solar kiln dryer, a multifaceted approach combining material science, design optimization, and system integration is essential(El-sebaili & Shalaby, 2012). Scholars have discovered that a diversity of techniques and methods might be employed to improve the performance. One key method is the counter-flow air passage design, where air first travels above the absorber plate (between the glass cover and absorber) before being redirected below the absorber plate, allowing extended heat absorption and improved energy extraction. Additionally, insulation at the back minimizes heat loss, while the glass cover traps solar radiation, creating a greenhouse effect that raises the absorber's temperature. Using a variety of performance enhancement strategies, several experimental and theoretical investigations have been carried out to enhance the efficiency of double-pass solar air heaters (DPSAHs). These include the use of packed bed materials (PBMs) for improving thermal storage and heat transfer, extended surfaces for augmenting the heat exchange area, and corrugated or grooved absorbing surfaces for enhancing turbulence and boosting energy absorption. Further, introducing barriers in the flow channel has been explored to break laminar airflow and stimulate better mixing and enhanced convective heat transfer. Such changes are aimed at enhancing

thermal efficiency, reducing heat loss, and maximizing system performance in general to make DPSAHs more valuable in solar energy application.

(Kalash et al., 2020) conducted “Thermal Performance Improvement of Double Pass Solar Air Heater”. In the experiments, 10 metal tubes were used to create three double pass solar air heaters. The bottom base and sidewalls were insulated with 25 mm thick aluminum glass wool. There were three types of configurations used in the experiments. The findings indicated that both the temperature and the solar flux levels increased as time went on from morning but began to decrease at noon. At the same time, the energy stored followed a steady increase throughout the day and fell at night. The research also noted that air velocity in the collector created vortices in the process.

Furthermore, selective coatings on the absorber plate improve solar absorption while reducing re-radiation losses. These combined techniques significantly boost the DPSAH’s efficiency compared to conventional single-pass systems, making it a highly effective solution for solar drying and space heating applications.

Among them some of them discussed below.

A) Double Pass

The thermal efficiency of a conventional solar air heater (SAH) is generally low due to the poor convective heat transfer between the heat-collecting surface and the working fluid. Enhancing this convective heat transfer is crucial for improving the overall thermal performance of the system. To address this limitation, the double-pass concept was introduced as an effective method to reduce top heat losses to the environment and increase heat transfer. In a double-pass SAH arrangement, the air initially flows beneath the absorber plate, where it extracts heat from the plate’s underside. It then reverses direction and flows above the absorber plate, further absorbing heat. This configuration not only increases the surface area for heat exchange but also enhances the convective heat transfer coefficient, leading to improved thermal efficiency of the solar air heating system. In a double-pass design, air passes on both sides of the absorber plate, removing heat from both surfaces of the latter before flowing in opposite directions along the plate. A Double-Pass Solar Air Heater (DPSAH) performance is highly reliant on different combinations of design, which assume very significant roles in its heating performance. According to the direction of airflow, DPSAHs are divided into three main types: parallel flow, counter-flow, and recycling (or circular) flow systems. Research shows that

double-pass configurations are 10–15% more efficient compared to single-pass solar air heaters (SPSAHs), which renders them a better choice for improving thermal energy extraction.

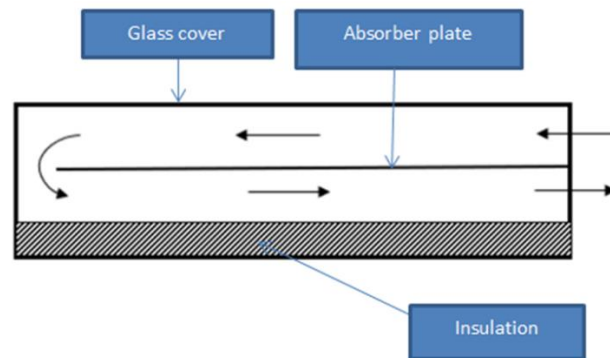


Figure 2. 1 Conventional double-pass SAH

a) Parallel Flow Double pass SAH

A solar thermal device called a Parallel Flow Double Pass Solar Air Heater (DPSAH) uses two distinct air streams to improve heat transmission inside the collector. This design delivers better thermal efficiency and greater air temperatures than single-pass variants. Superior energy economy, high output temperatures, and low maintenance needs are some of the key benefits. The system does, however, have several disadvantages, including a bigger spatial footprint than single-pass options, higher initial installation costs, and more structural complexity that results in lengthier setup times. Notwithstanding these drawbacks, its improved functionality makes it a desirable option for applications needing effective solar heating.

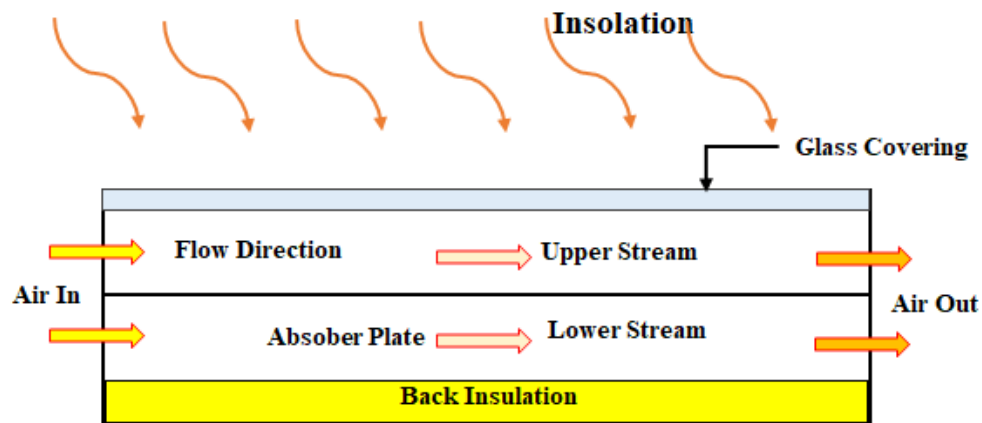


Figure 2.1 Parallel-flow, double-pass SAH(Singh et al., 2022)

(Singh et al., 2022) Reviewed Double Pass Solar Air Heater. The study's primary goal was to familiarize the researcher with the various strategies employed to increase DPSAH's efficacy. Along with discussing classification and the heat transfer mechanism's operating principle, the study also discovered untapped areas for further research, made recommendations, and voiced worry about the best types of DPSAH and their specified criteria. To improve understanding, the results of the several approaches that have been used thus far are thoroughly examined and discussed. Concerns, difficulties, and chances for the future are also covered.

Counter Flow Double Pass SAH

A double-pass counter-flow solar air heater (DPCFSAH) is an air heating system that utilizes solar energy to warm air. It consists of three main components: a solar collector, a fan, and a heat exchanger. The solar collector absorbs sunlight and converts it into thermal energy, which heats the air as it circulates through the fan and heat exchanger. The heated air is then redirected back into the solar collector, allowing the system to reuse the thermal energy efficiently.

One of the key benefits of DPCFSAH is its high efficiency, as the air passes through the heat exchanger twice, maximizing heat transfer and delivering more warmth. Additionally, this system is cost-effective since the solar collector is the primary component requiring purchase, reducing overall expenses. However, counter-flow solar air heaters also have some limitations. Their performance depends heavily on solar energy availability, requiring direct sunlight to operate effectively. Furthermore, regular maintenance is necessary to ensure the fan and heat exchanger function optimally, which can be a drawback for some users.

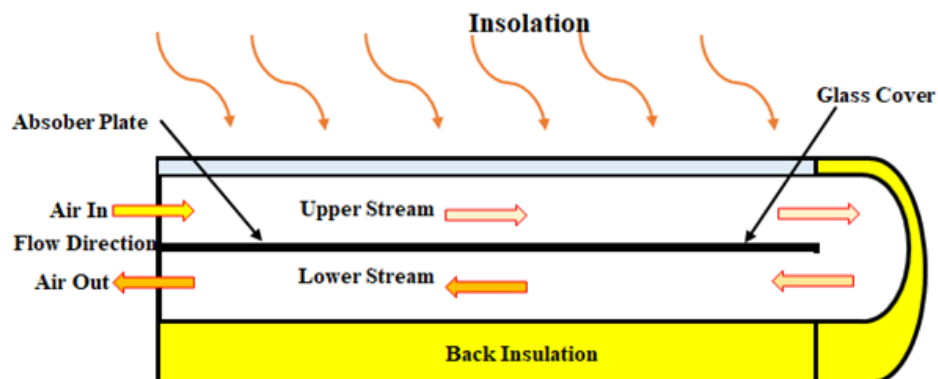


Figure 2.2 schematic of counter flow double pass SAH (Singh et al., 2022)

(Abdu.Y.,2021) carried out an investigation of the experimental performance of a double pass solar air heater with baffles for drying red chilies. The mass of evaporated moisture from 5 kg of red chili was 3.94 kg as the moisture content decreased from an initial value of 81% to 11.7% in wet basis. At an average drying air temperature of 55 °C, the latent heat evaporation of water was computed and found to be 2.371 MJ/kg. 9.342 MJ of heat were needed to evaporate 3.94 kg of moisture. Over the course of the drying process, 106.7 MJ of energy were added to the drying system. It was discovered that the dryer's specific energy consumption for drying red chilies was 7.52 kWh per kilogram of moisture. It was discovered that the drying system's total efficiency was 8.75%.

b) Recycle Flow Double Pass SAH

Recycle Flow Double Pass SAH is a type of solar air heater that uses the double-pass effect to capture and retain more of the sun's energy (Singh et al., 2022). Two sets of fins are used in this kind of solar air heater, and their arrangement optimizes the quantity of solar energy that is captured. The arrangement of the fins allows the sun's energy to heat the air as it travels through the first set before it passes through the second set and is heated once more. The heater's efficiency is raised by this air recycling operation (Singh et al., 2022). A double-pass recycled flow solar air heater (DPRFSAH) offers several advantages over single-pass systems, including higher efficiency and better performance in cold climates. The double-pass design minimizes energy loss caused by convective heat transfer, enhancing overall thermal efficiency. Moreover, this type of solar air heater is relatively simple to install and maintain. However, it also has some drawbacks, such as requiring more space due to its dual-pass structure and being more costly than single-pass models. In a DPRFSAH, a portion of the heated exhaust air is recirculated into the intake channel, where it mixes with fresh incoming air using a blower, further improving energy utilization.

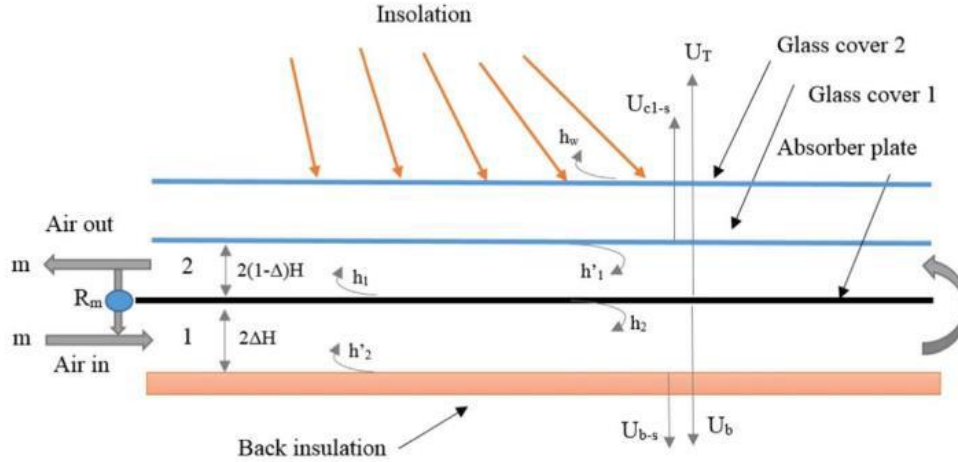


Figure 2. 3 Double-pass SAH with recycle operation (Singh et al., 2022)

S

c) Multi-Pass Solar Air Heater

This type of solar air heater design distinguishes itself from traditional systems by employing a multi-pass airflow mechanism to enhance thermal efficiency. When operating at moderate temperatures or under windy conditions, the system typically incorporates dual or additional glass covers to minimize convective and radiative heat losses from the collector. However, the glass layers also attenuate incoming solar radiation through partial absorption and reflection, slightly reducing the total energy reaching the absorber surface.

B) Extended surfaces

Extended surfaces mounted on the absorber plate perform two functions concurrently: they both disturb the airflow to enhance turbulence and function as fins to increase the effective surface area for heat transfer. Numerous studies have explored different types of extended surfaces such as baffles, fins, and corrugated absorber plates for their effectiveness in improving thermal performance. These modifications aim to intensify convective heat transfer by disrupting the thermal boundary layer and increasing the contact area between the heated surface and the working fluid.

(Mishra et al., 2013) An experiment was conducted to gather data on heat transfer and flow friction in an air heater duct featuring delta-shaped obstacles on the absorber surface, with a duct aspect ratio of 6:1. The absorber plate was exposed to an 800 W/m^2 constant heat flow. The study was conducted over a range of Reynolds numbers (Re) from 2100 to 30,000. The relative obstacle height (e/H) varied

between 0.25 and 0.75, the relative longitudinal pitch (Pl/e) between 1.5 and 5.5, the relative transverse pitch (Pt/b) between 1 and roughly $7/3$, and the angle of incidence (α) between 30° and 90° . The findings indicated that the use of obstacles in a double-flow collector significantly enhances its performance compared to a system without such features.

C) Thermal energy storage (TES)

Thermal Energy Storage (TES) is an innovative technology that captures and retains thermal energy by heating, melting, or vaporizing a storage medium, enabling the stored energy to be used later for heating, cooling, or electricity generation. The system works by reversing the process—cooling, solidifying, or condensing the medium—to release the stored energy when required. Among the most efficient TES methods is the use of Phase Change Materials (PCMs), which absorb and release significant energy during phase transitions, such as melting and solidifying. In solar applications, excess daytime heat can be stored by melting PCMs, with the energy later recovered at night as the material resolidifies, ensuring a steady thermal supply even without sunlight. Current research aims to enhance storage materials, boost heat transfer efficiency, and lower costs to promote TES as a more viable and sustainable energy management solution.

(Sajawal et al., 2019) examined the thermal performance of a double-pass solar air heater integrated with phase change materials (PCM) enclosed in finned metallic tubes to enhance energy storage and heat transfer rates. Experimental tests were conducted to analyze the PCM's charging (heat absorption) and discharging (heat release) behaviors. The research evaluated the air heater under three distinct configurations. The first configuration operated without any PCM, serving as a baseline for comparison with the PCM-enhanced setups. The ideal configuration for the best heater performance was found to be the third one, which has RT44HC and RT18HC in the upper and lower passes, respectively.

(Tadele, 2020) conducted “Experimental Investigation of PCM Integrated Solar Dryer for Fish Drying”. The developed solar drying system integrates four key components: a solar air heater, a shell-and-tube latent heat storage (LHS) unit containing paraffin wax, a drying chamber, and a blower. Ambient air first enters the solar air heater, where it is warmed by absorbed solar radiation. This heated air then circulates through the tube side of the LHS unit positioned between the heater and drying chamber. Performance testing demonstrated the system's effectiveness by removing 3.57 kg of

moisture from 5 kg of fresh fish, achieving a moisture reduction from 75% to 12.5% (wet basis). The system operated with an overall efficiency of 9.4%.

Nanofluid

In recent years, significant advancements in nanotechnology have greatly enhanced the ability to produce ultrafine particles, leading to the development of an innovative class of solid-liquid mixtures known as nanofluids. These advanced fluids consist of a base liquid such as water, oil, or ethylene glycol containing a small concentration of uniformly dispersed nanoparticles (typically less than 100 nm in size) made of metals, oxides, or carbon-based materials. Due to their unique thermophysical properties, nanofluids exhibit superior thermal conductivity and enhanced heat transfer characteristics compared to conventional fluids. Nanofluids is in solar air heaters, used as a heat transfer medium to enhance the absorption and dissipation of thermal energy, leading to better performance in solar thermal systems.

Further research is ongoing to optimize nanoparticle concentration, stability, and cost-effectiveness to maximize the benefits of nanofluids in renewable energy applications.

2.6. Physiochemical Property of Green Coffee Bean

The quality of the dried product will be affected by the drying process in terms of its form, color, texture, fragrance, rupture, and nutritional content. It covers the drying process as well as important elements like drying temperature and dehydration capability. The tissue of the dried items, which differs according on the kind of crop or food product, was altered by the drying technique utilized. By lowering the moisture content (to 10–12%) and water activity (A_w), the drying process has a major effect on the physicochemical characteristics of green coffee beans. This inhibits microbial development and stabilizes storage. While incorrect drying can result in brittleness, mold, or fermentation, appropriate drying preserves the color, hardness, and integrity of beans. Chemically, drying affects volatile chemicals, sugar metabolism, Maillard reactions, and the stability of organic acids, all of which have an impact on roast development and cup quality. While mechanical drying guarantees uniformity but can result in heat damage if temperatures rise beyond 40 to 45°C, sun drying protects delicate tastes but runs the risk of uneven drying. High-quality roasted coffee is ensured by appropriate drying, which is gradual, homogeneous, and regulated. In contrast, poor drying results in faults like fermented, moldy, or baked tastes. The solar dryer results in a better texture quality of the dried product(Pagukuman & Ibrahim, 2022).

2.6.1. Chemical composition of green coffee bean

The chemical composition of coffee beans is complex, comprising a wide variety of compounds that contribute to their flavor, aroma, and nutritional value (Gichimu et al., 2014). They are composed mainly of carbohydrates (accounting for 60% of the total weight of raw coffee beans), including polysaccharides like cellulose and hemicellulose, and small amounts of simple sugars like sucrose (Saud & Salamatullah, 2021). Lipids, primarily in the form of triglycerides, phospholipids, and unsaponifiable matter, make up about 10-15% of the bean. Proteins and free amino acids contribute to the bean's nutritional content.

One of the most notable compounds in green coffee is chlorogenic acid ($C_{16}H_{18}O_9$), a powerful antioxidant that constitutes about 6-12% of the bean's dry weight and plays a role in its characteristic acidity and bitterness (Kulapichitr et al., n.d.). Chlorogenic acid contains antibacterial, antifungal, antiviral, and antioxidant activities that enhance the human immune system. Green coffee beans also contain alkaloids, mainly caffeine and trigonelline, which influence their stimulant properties and flavor profile. Caffeine has been perhaps the most widely known compound and is the most investigated component of coffee. Caffeine ($C_8H_{10}N_4O_2$) or 1,3,7-trimethylxanthine is a chemical compound that contributes to the strength, body, astringency, and bitterness of coffee (Gichimu et al., 2014) (Shofinita et al., 2024). Caffeine can boost the immunological system, improve human performance, and stimulate the central nervous system. They also include trace metals and minerals including potassium and magnesium, along with trace amounts of volatile chemicals that add to the scent. Approximately one thousand volatile chemicals, both aroma-active and non-aroma-active, have been identified by research to date in coffee (Shofinita et al., 2024).

(Eshetu et al., 2022) investigated the impact of drying and processing techniques on the biochemical makeup of coffee (*Coffea arabica* L.) cultivars in the Jimma Zone in southwest Ethiopia. The purpose of the study is to assess how the biochemical makeup of different coffee varieties is impacted by various drying and processing techniques. Biochemical components were measured using a prediction model based on Fourier Transform-NIR spectroscopy. The findings revealed that at both study locations, the interaction between coffee variety, processing method, and drying technique had a significant impact on most of the biochemical properties of green coffee beans. Notably, across both sites, all coffee varieties processed using the full-wash method and dried artificially exhibited higher caffeine content.

(Gichimu et al., 2014) Assessment on “Biochemical Composition Within *Coffea arabica* cv. Ruiru 11 and Its Relationship with Cup Quality”. The analysis reveals distinct biochemical differences between coffee varieties: Robusta beans contain approximately 2.2% caffeine - significantly higher than Arabica's average of 1.2% (range: 0.6-1.9%). Regarding chlorogenic acids (CGA), measurements show Arabica beans typically contain 4-8.4% CGA (dry basis), while Robusta demonstrates higher concentrations at 7-14.4%. Hybrid varieties exhibit intermediate CGA levels between these two main species. Trigonelline comprises about 1.1% of the chemical composition of the green coffee of *C. Arabica*. The lipid content of green Arabica coffee beans averages 15%. Caffeine content was ranging from 1.01% to 1.54%.

Longer drying times combined with high drying temperatures and high relative humidity can lead to cell rupture, deterioration of the dried crops' quality, and breakdown of their volatile components. (Pagukuman & Ibrahim, 2022).

Comparison of open sun drying and solar kiln drying in terms of their effects on the chemical composition of green coffee beans.

Parameter	Open Sun Drying	Solar Kiln Drying
Sucrose	Uneven drying causes localized fermentation reduce sugar up to ~ 15% (6.2%)	Uniform drying minimizes fermentation, retaining ~ 95% of sugars. (7.8%)
Chlorogenic Acids	Degrades CGAs by ~15–20% 72 mg/g (dry basis)	preserve CGAs better, retaining ~85–90% of original content. (85 mg/g)
Lipid Oxidation	Reduce lipid stability	Preserve lipid content
Caffeine	Slight reduction (~2–5%) due to prolonged heat stress	Minimal loss (~1–2%) due to optimized drying time
Ochratoxin A	5.2 µg/kg	<1 µg/kg
Volatile Organic Compounds (VOCs)	UV exposure and oxidation degrade VOCs	Reduced UV and airflow control preserves VOCs.

Table 2.2. Comparison of drying method effects on the biochemical composition of coffee beans.

2.6.2 Physical property of green coffee bean

Green coffee beans exhibit distinct physical properties that play a crucial role in their processing and quality assessment(Eduardo et al., 2021). They are typically small, dense, and oval-shaped, with a smooth, firm surface and a characteristic central groove. The beans have a greenish or bluish-green color, which varies depending on the variety and growing conditions, and can serve as an indicator of freshness and quality. Drying is a critical post-harvest process that significantly impacts the quality and physical properties of green coffee beans(Eduardo et al., 2021). Proper drying reduces the moisture content of the beans to an optimal level (generally around 10-12%), maintain their structural integrity during storage and transport(Agrarias, 2023). Insufficient drying can leave beans prone to mold growth, fermentation, and spoilage, which compromises their flavor and market value. Conversely, over-drying can lead to brittleness and cracking of the beans, reducing their weight and causing mechanical damage(Pagukuman & Ibrahim, 2022). Furthermore, uneven drying where some beans retain higher moisture levels can result in inconsistent roasting performance and flavor profiles. Green coffee beans are hard and resistant to breakage, making them suitable for handling and roasting. They have a high density, which influences the roasting process and the final coffee flavor. The physical properties of green coffee beans, such as size, shape, and texture, are also important for sorting and grading, ensuring consistency in quality and performance during roasting.

(Shofinita et al., 2024) reviewed coffee extract drying techniques and how they affect the physicochemical properties of the extracts. The review assesses the effects of several drying methods, including spray-drying, freeze-drying, and spray-freeze-drying, on the physicochemical characteristics of coffee, including its morphology, particle size, moisture content, bulk density, and bioactive ingredient retention. The findings indicate that spray-drying outperformed the other methods, yielding coffee with better physical properties and higher bulk density. Moreover, spray-dried coffee showed lower moisture levels, attributed to the high-temperature gas used during the drying process.

(Eduardo et al., 2021) Studied Determination and modeling of physical and aerodynamic properties of coffee beans (*Coffea arabica*) during the drying process. The study analyzed key physical and aerodynamic characteristics of coffee, such as terminal velocity and drag coefficient (both measured and calculated), at different moisture levels. The findings revealed that these properties underwent notable variations as the coffee's moisture content reduced throughout the drying process. Notably,

there was a 32% reduction in unit-specific mass and a 20% volumetric contraction. Additionally, terminal velocity decreased by 28%, suggesting that coffee beans could be effectively separated using gravimetric methods at different moisture content levels.

(Ameyu et al., 2017) conducted research on the effects of harvesting and postharvest processing techniques on the raw quality characteristics of green Arabica coffee beans grown in Hararghe, Ethiopia's eastern region. The impact of various harvesting and postharvest handling methods on the intrinsic qualitative attributes of Hararghe coffee was investigated in this study. The findings showed that every aspect of the coffee beans' raw quality was significantly impacted by the harvesting technique. Similarly, postharvest processing methods showed a substantial impact on quality parameters, though with some variations: for unwashed coffee, all quality traits were significantly affected except odor, while in washed coffee, every measured quality parameter showed significant changes. These findings highlight the critical role of both harvesting practices and postprocessing methods in determining the final quality profile of Hararghe coffee.

(Shekata et al., n.d.) investigated the properties of a vertical mixed flow dryer used in the drying of coffee beans. When coffee beans are dried utilizing a vertical mixed flow pattern with slanted trays, hot air may come into direct contact with each bean. Both the mass transfer coefficient and the convective heat transfer coefficient are improved by this technique. An increased convective heat transfer coefficient facilitates efficient heat flow. During the initial stages of drying, the rate of water reduction is relatively high, but as the process continues, the rate of moisture removal gradually decreases.

(Yuwana et al., 2021), Coffee Beans Drying Trials Utilizing the Hybrid Solar Dryer. The researchers carried out two comparative drying experiments: one using solar energy (with open sun drying as control) and the other using biomass energy via wood combustion. Results showed that the wood-fired drying system experienced far greater temperatures and lower humidity inside the drying chamber compared to ambient, 15.82°C above ambient temperature and 53.43% lower relative humidity.

(Debele & Science, 2020) performed “Experimental and Numerical Performance Investigation of Solar Air Heater for Drying Agricultural Products and Space Heating for Brooding of Chicken”. The study recorded the maximum daily energy collection by the solar air heater (SAH) for different configurations in March as follows: conventional SAH (1249.991 kJ/day), finned absorber (1451.881

kJ/day), Gypsum thermal storage (2020.621 kJ/day), reflector-assisted (4217.50 kJ/day), and combined effect (7721.589 kJ/day). Conversely, the minimum energy collection occurred in July, with values of 790.039 kJ/day (conventional), 943.115 kJ/day (finned absorber), 1231.490 kJ/day (Gypsum storage), 2486.887 kJ/day (reflector-assisted), and 4883.041 kJ/day (combined configuration).

(Dussán, E.D., 2023) studied Design and performance of a solar dryer for processing of coffee beans in Colombia. The goal of the study was to develop a complete set of tools for comprehending, modeling, forecasting, and managing the drying process of coffee in three distinct scenarios: mixed, forced, and natural convection. When the grain moisture content fell below 12% (wb), the drying time computation was terminated. When compared to the process specifications, which call for 21 hours of drying, the rectangular-shaped dryer's grain moisture content of 11.87% (wb) after 21.3 hours of drying at 50°C is reasonable and correct. The circular dryer takes 23.6 and 28.5 hours, respectively, to obtain 11.97% (wb) moisture content when drying at 45°C and 40°C.

(Nasrin et al., 2021), studied Drying Characteristics and Nutritive Analysis of Coffee Beans Under Different Drying Methods. For coffee beans, the effects of three drying techniques—open sun drying, solar drying, and solar-electrical hybrid drying (S-EHD)—were determined. Weight loss, drying rate, and the nutritional value of dried coffee beans are among the parameters that were noted. Three distinct drying techniques—OSD, SD, and S-EHD—were used in the coffee bean drying experiment. Coffee beans were dried to achieve the following equilibrium moisture contents: 10.60-13.61% (w.b.), 14.98%-16.23%, and 6.47%-8.83%.

(Abdissa et al., 2023) completed the study Harmonizing Drying Time, Layer Thickness, and Drier Zones for Drying Kinetics: Quality and Safety of Wet-Processed Parchment Coffee (*Coffea arabica* L.) Dried in Solar Tunnels. They even out differences in drying time and moisture content throughout the long tunnel solar drier, and by applying varying layer thicknesses in different zones, beans may have more comparable drying times and moisture contents. The results indicated that, with the exception of titratable acidity and sensory qualities, dryer zones substantially ($p < 0.05$) interacted with layer thickness for the majority of the tested parameters.

(Javier et al., 2020) carried out research A comparison of drying coffee beans in a traditional oven versus a microwave. Twenty coffee bean drying tests were performed; half used electromagnetic radiation in a microwave cavity and the other half used thermal radiation from an electric oven. Samples of coffee beans with, without, and with parchment were used in the studies. The diffusion

coefficient was 22 times greater for materials dried in the microwave cavity than for samples dried with heat radiation, according to the results. Additionally, samples dried in the conventional oven exhibited uniform temperatures, unlike those exposed to microwave radiation, which showed temperature variations.

2.7. Literature Summary and Gap

The study of drying effects on coffee beans' physical and chemical composition is the main focus of the body of literature. They look at how the drying process affects the dried coffee bean's quality. The characteristics of dried coffee beans can be characterized by a number of factors, including their sugar level, volatile chemical profile, fatty acid composition, and bioactive components. It is evident that the drying process has a significant impact on coffee bean quality. Another important conclusion that can be made from this data is that, as compared to continuous convective drying, the intermittent nature of solar drying produces higher quality. The numerical solution to the heat and mass transport during the drying process is the subject of some publications. In order to counteract the latent heat during evaporation, the drying process uses a significant quantity of energy. Therefore, in order to create an energy-efficient dryer, the drying process must be optimized. This covers the range and research of agricultural product solar kiln dryers. Numerous studies are experimental investigation drying characteristics, temperature profile, fluid flow pattern, and moisture profile during solar drying of various agricultural product. Preservation and drying effects on quality of dried products are also studied. Also, economic feasibility and environmental impacts are assessed in details. Those studies have achieved desirable variations in performance and efficiency within the respective areas of focus.

Research gap

Studies on the effectiveness of solar drying methods for coffee drying, particularly thermal performance and quality preservation, are somewhat limited, despite the fact that their use has grown in Ethiopia. Previous studies on solar dryers such as solar tunnel dryers for parchment coffee and solar cabinet dryers for vegetable and fruit drying have been limited, with the majority of studies focusing on specific types of dryers, local climatic conditions, or short-term performance without examining long-term efficiency. Moreover, most of the studies just focused on either thermal efficiency or physicochemical quality parameters separately from one another, without delineating a clear connection between drying conditions such as temperature, airflow, and humidity and the final coffee quality, such as parameters of flavor profile, acidity, and moisture content. Moreover, generalized

numerical models that can forecast dryer performance in the various agro-climatic regions of Ethiopia are not available. Hence, a holistic study that will compare various solar dryer designs, incorporate thermal and quality tests, predictive model development for wider application, and examine economic and environmental benefits is required. This research would enhance solar drying process optimization for Ethiopian coffee for energy efficiency and high-quality products, as well as for sustainable agro-processing.

CHAPTER THREE

Methodology

3.1. Method

The experiment was conducted from April 25 to April 28, 2025. The study was aimed at quantifying the influence of coffee drying methods on coffee (Coffee Arabica) quality at ASTU, Adama, Ethiopia. The collected samples were dried using two different methods: open sun drying (OSD) and solar drying in a kiln. For both methods, the samples were spread in a thin layer on a metal grid tray and dried until a constant mass was achieved. Throughout the drying process, ambient temperature, drying air temperature, relative humidity inside the drying chamber, and sample weight were measured at one-hour intervals. Once drying was complete, a sample of the dried coffee beans was collected and sent for sensory evaluation.

This study involves several key steps from beginning to end. The study employs both theoretical analysis and experimental investigation. The theoretical method is based on governing equations to analyze each system component and drying kinetics, while a review of relevant literature provides insight into the background and other influencing factors. The experimental approach tests the system's performance, with a kiln prototype manufacture after completing the sizing and material selection for each component. Solar radiation intensity for Adama city is estimated using empirical formulas and weather data gathered from the National Meteorological Agency (NMA), Adama branch. Each system configuration is modeled for numerical analysis, and Microsoft Excel is used for calculations. The investigation was focused on the drying process of coffee beans (*Coffea Arabica*) in a solar kiln dryer, for this purpose an examination was carried out of the operating conditions such as: drying air temperature, air volumetric flow, air mass flow and relative humidity, the measurement of these parameters made it possible to evaluate the quality problem of the final product. This study was conducted a literature review on the drying process of coffee beans and experimentally investigate the effects of different drying methods on the physicochemical properties of coffee beans and evaluate performance of drying system. By utilizing a solar kiln dryer experimental setup, drying parameters and kiln performance will be analyzed to evaluate a suitable drying system. Wet-processed coffee beans will be dried using both open sun drying and a solar kiln for comparative analysis. The interior conditions of the solar kiln (temperature, relative humidity, and air velocity) as well as the coffee bean weight loss will be monitored and controlled throughout the drying process across different sections.

The initial moisture content of the coffee is about 55-62% and after drying the final moisture content should be around 12% (w.b) and the drying should be even and homogenized to obtain the good quality of green coffee bean. The samples were processed using two different drying methods: solar kiln drying and open sun drying. To distinguish between the two, the samples were labeled as SD (solar kiln drying) and OSD (open sun drying), respectively. Sensory tests were conducted to evaluate the quality of the green coffee bean samples. Various basic physical properties, including moisture content, density, hardness, color, and size, were assessed alongside the analysis of bioactive compounds. Final moisture content will assess through oven drying method and bioactive chemical compositions were quantified using FT-NIR spectrometer prediction model. The results from the analysis were interpreted to precise data set for comparative analysis. Drying kinetics will be modeled through empirical and theoretical approaches to predict the drying behavior accurately. A comparative analysis will be conducted between sun drying and solar drying to evaluate their effectiveness. Finally, the results will be thoroughly discussed, and conclusions will be drawn based on the findings.

3.1.1. Sample Preparation

To ensure consistent processing, only fully ripe red coffee cherries were selectively handpicked during peak harvest season. The parchment coffee was separated from the pulp by processing each cherry separately using a mechanical pulper. To eliminate faulty floaters, the parchment coffee was flotation tested in water as soon as it was pulped. For drying comparison, the washed parchment coffee was divided for processing under two conditions: (1) on wire-mesh trays in a controlled kiln chamber, and (2) through traditional open-air drying. This methodology allowed for systematic quality evaluation of different post-harvest treatments.

3.2. Materials and Equipment

The performance of a solar kiln relies heavily on its design and the careful integration of various components that work together to optimize the drying process. Constructing an effective solar kiln requires thoughtful integration of these components to create a system that efficiently captures and uses solar energy for drying. Choosing and implementing each component correctly ensures the kiln's optimal performance, energy efficiency, and durability. The primary components of a solar kiln, along with their functions and considerations, are carefully evaluated.

The system components, measuring equipment, and materials required for constructing the experimental prototype and evaluating the system parameters were procured from local markets in Adama and Addis Ababa, Ethiopia. The selection criteria for the materials to be used in the experimental setup were based on local availability, economic feasibility, and suitability for the purpose. Easily available and low-cost materials were emphasized to ensure feasibility and reproducibility, as well as to meet the technical requirements of the experiment.

The main materials used are presented below with their uses.

- Rectangular Iron: used as a support framework for the upgraded solar collector and in the building of the solar kiln.
- Transparent Glass: used to transmit largest practical percentage of incident solar energy into kiln.
- Sheet metal: used for construction of chamber casing and walls
- Black paint: used to paint absorber plates to increase absorbance of absorber plate.
- Insulator: used for covering system components to reduce thermal heat loss and enhancing the kiln's efficiency.
- Fan: used to circulate air across kiln chamber.
- Wire mesh: used for stacking and organizing the materials to be dried.
- Doors and Access Points: allows for loading and unloading materials, as well as maintenance access. Typically, they made from the same materials as the structural frame and Proper seals to prevent unwanted heat loss or air infiltration. They must be easy to open and close while maintaining environmental controls.

No.	Components	Specification	Property
	Transparent cover	Glass	High thermal conductivity and can withstand wind loads, dust storms, and rainfall
2	Sheet metal(absorber)	Galvanized Iron	High thermal conductivity, high radiation absorptivity, and resistant to corrosion
3	Insulation	Thermo foam	Low thermal conductivity, affordable, and effective
4	Casing (wood)	Local	Affordable and easy to construct

	Drying chamber	Metal grid	Good air distribution through chamber
6	Paints	Black	Good absorptivity
7	polyethylene sheet	Black(4m ²)	Good absorptivity and prevent air leakage
8	Supportive frame	Steal bar and angle iron	Resistant to corrosion with good strength to withstand the system

Table3.1 specification of solar kiln components

3.2.1. Measuring Instruments

Two single channel calibrated thermocouple thermometers were used to measure the temperature during the studies. To measure the temperature in the drying chamber and collector, thermocouple wires were affixed to various parts of the prototype. The samples are weighed using a digital balance with an accuracy of ± 0.01 g. The digital weight balance and thermocouple thermometer are photographed in Fig. 3.1.



Figure 3.1 measuring instruments a) thermocouple thermometer b) digital mass balance

3.3. Research design

This study adopts a combined theoretical and experimental methodology to analyze the performance of a solar dryer system. The theoretical approach involves the application of governing equations to model the thermal and aerodynamic behavior of key components, such as the solar air heater and drying chamber. Energy balance equations, heat transfer principles (including convection and radiation losses), and psychrometric relations for moisture removal were used to predict system performance under various operating conditions.

A working prototype was built for the experimental investigation after careful component size and material selection to maximize effectiveness, longevity, and cost. The system's double-pass solar air heater was carefully tested under practical conditions, with monitored parameters such as temperature and airflow velocity. To ensure reliability, the experimental results were validated against previous studies to benchmark performance.

Beyond assessing the dryer's thermal efficiency, this study also investigates the drying effects on the physicochemical properties of agricultural products, such as moisture content, color retention, nutrient composition, and shelf-life stability. By analyzing these factors, the research provides insights into how solar drying influences product quality, ensuring that the system not only performs efficiently but also preserves the desired characteristics of the dried produce.

This integrated approach enhances the reliability and reproducibility of the research by providing a thorough assessment of both the solar dryer's operational performance and its influence on green bean quality. The methodology concurrently evaluates the system's thermal efficiency and functional parameters while assessing the drying process's effects on key product characteristics—such as nutritional value, texture, color preservation, and shelf life. By combining these technical and quality-focused analyses, the study offers a holistic view of the technology's efficacy, bridging engineering performance with agricultural preservation needs. The robust validation framework, which pairs theoretical modeling with experimental testing, further strengthens the practical applicability of the results for real-world solar drying applications.

3.3.1. Solar kiln sizing

Manufacturing a solar kiln is relatively straightforward and inexpensive. The most crucial element in regulating how much heat the kiln can get from sunlight is the roof's slope. The ideal angle for a solar kiln's roof is generally equal to the latitude of the location, plus or minus 15 degrees depending on the

season(Arvind & Shyam, n.d.). For winter season the angle should be the latitude plus 15 degrees. In case of my work glass cover tilts at an angle of 24° ($8.5+15$) south facing for optimum solar energy collection.

the principal design requirements of the kiln drying system are generally determined by a set of basic factors: (1) the desired rate of moisture evaporation from the treated item, (2) the amount of thermal energy to be supplied for effective dehydration, (3) the air mass and circulation conditions needed, including both rate of mass flow and volumetric airflow, (4) the optimum outlet temperature range of the drying chamber, and (5) the size requirements of all system components. These parameters must be accurately computed to yield effective drying performance, with utmost consideration given to the thermodynamic equilibrium among heat input, air flow, and moisture evacuation rates. The design process typically entails computations of the heat transfer coefficients, the psychrometric air properties, as well as residence time required to achieve desired product moisture content with a sacrifice of energy efficiency.

Initial Parameter	Values and expectations
moisture content(initial)	62 %
Anticipated moisture content	12 %
Sample weight	6 kg
Average solar radiation (during experiment)	658 W/m ²
Average ambient temperature(9:00-16:00)	29 °C
Average relative humidity	35%
Desired drying temperature	50°C
Tilt angle	24° (latitude+15)

Table 3.2 initial assumption and standards

This thesis focuses on a double-pass solar air heater (DPSAH) designed for drying applications, utilizing a counter-flow air pass configuration to enhance thermal efficiency. Unlike conventional solar air heaters, this design allows for greater heat extraction, improving performance by 10–15% without additional costs (Arvind & Shyam, n.d.). By optimizing airflow pathways, the DPSAH effectively captures and retains more thermal energy, making it a cost-effective and high-performance solution for solar drying applications.

The system comprises a glass cover, absorber plate, and back insulation, structurally similar to a parallel-flow design. However, in this setup, air first flows between the absorber plate and the glass cover before being redirected beneath the absorber plate. This counter-flow arrangement maximizes heat absorption by ensuring prolonged contact between the air and heated surfaces, significantly boosting overall efficiency compared to traditional single-pass systems.

3.4. Analysis and estimation of solar radiation intensity

Determining the entire amount of solar energy incident on the solar collector is crucial for assessing the effectiveness and performance of the solar drying system, and this requires precise data on solar radiation intensity. The establishment of solar radiation intensity from available metrological data is an important input to the energy and mass balance models employed in the design and assessment of the solar kiln system.

In the present research, the intensity of solar radiation was approximated based on local meteorological data for proper modeling and analysis. Adama, Ethiopia, is located at a geographical coordinate of approximately 8.514477°N latitude and 39.269257°E longitude. The experimental setup, however, was done at a nearby location, which is approximately 8.5625°N latitude and 39.29°E longitude. Since the locations are very close to each other, it is asserted that the climatic and solar radiation conditions are effectively equal for the intended purpose of this research. Figures 3.1 and 3.2 illustrate the ten years data of temperature variation and sunshine hour taken from meteorology for Adama City from 2015 to 2024.

3.4.1. Estimation of Hourly Variation of Atmospheric Temperature

In order to precisely predict the thermal and energy dynamics of the solar drying system, a mathematical description of both daytime and nighttime circumstances was developed. These explanations are crucial for modeling the changes in ambient temperature, solar radiation, and heat transfer activities that take place over the course of a day.

The hourly variation of atmospheric temperature was estimated using the sin-exponential model developed by Parton and Logan (1981). This model characterizes the diurnal temperature cycle through two distinct phases: a sinusoidal function to simulate daytime warming and an exponential decay function to represent nighttime cooling. The model operates under two fundamental assumptions - first, that maximum temperatures occur during daylight hours prior to sunset, and

second, that minimum temperatures are reached in the early morning. By utilizing only daily maximum and minimum temperature data as inputs, this approach effectively captures the asymmetric nature of diurnal temperature fluctuations, providing reliable hourly temperature estimates. The model's ability to represent the characteristic daytime warming and nighttime cooling patterns makes it particularly useful for various agricultural and environmental applications requiring detailed thermal data (Tadele, 2020).

The mathematical description for the daytime and nighttime were expressed:

For daylight hours

$$T(h) = (T_{max} - T_{min}) \sin \left(\frac{\pi m}{Y+2a} \right) + T_{min} \text{-----Eq-----3.1}$$

For night-time hours

$$T(h) = (T_{sunset} - T_{min}) \exp \left(-\frac{bn}{z} \right) + T_{min} \text{-----Eq----3.2}$$

Where

$T(h)$ = temperature throughout the day or at any time.

m = hours from the time the temperature reaches its lowest point to sunset

n = number of hours from sunset to when the temperature is at its lowest

Y = length of the day and z = length of the night

a = lag coefficient for T_{max} = 1.8h and b = night time temperature coefficient = 2.2h

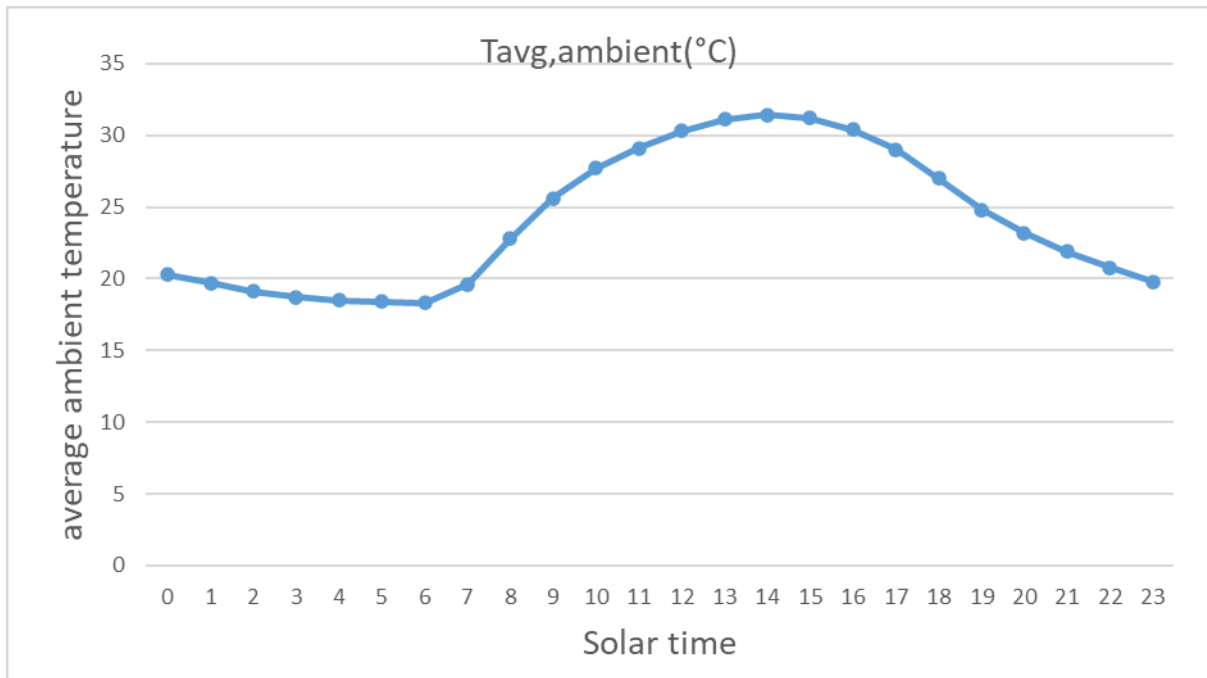


Figure 3.2 Average hourly variation of ambient temperature of Adama

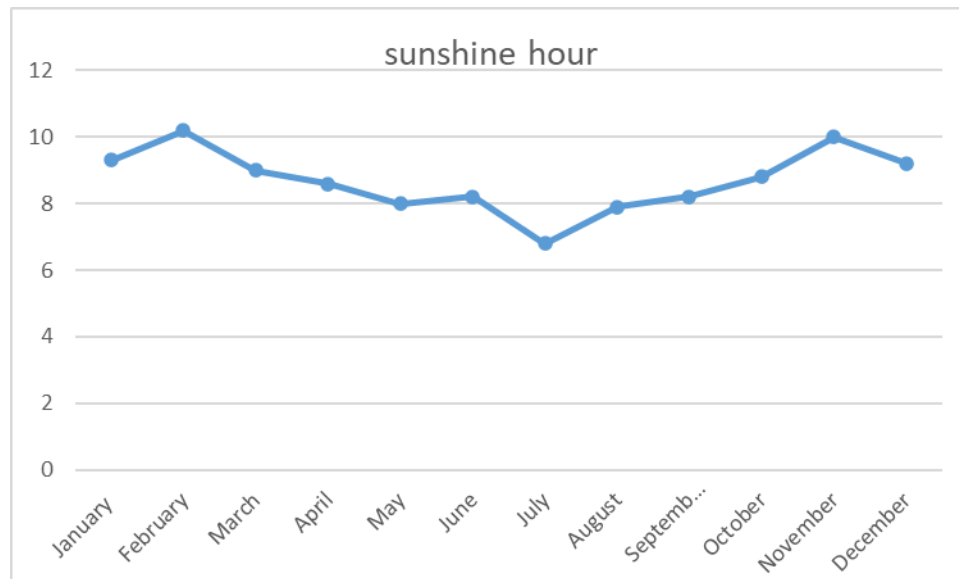


Figure 3.3 Monthly average sunshine hour of Adama

3.4.2. Estimation Solar Radiation

The Angstrom (1924) correlation represents the pioneering method for estimating monthly average daily global solar radiation. This model establishes a linear relationship between three key parameters:

(1) the measured monthly average daily radiation, (2) the theoretical clear-sky radiation for the location, and (3) the observed fraction of possible sunshine hours. The original Angstrom regression equation achieved a remarkable estimation accuracy of $\pm 10\%$, demonstrating its reliability for solar radiation prediction. By correlating actual radiation data with sunshine duration records, this approach provides a practical solution for locations with limited radiation measurements. The model's simplicity and effectiveness have made it the foundation for numerous subsequent radiation estimation techniques in solar energy applications (Deceased & Beckman, n.d.).

Monthly average daily extraterrestrial radiation on horizontal surface (H_0) can be termed as;

$$H_0 = \left(\frac{24 \cdot 3600 \cdot I_{sc}}{\pi} \right) \left(1 + 0.033 \cos \left(\frac{360 \cdot n}{365} \right) \right) \left(\cos \varphi \cos \delta \sin \omega_s + \frac{\pi \cdot \omega_s}{180} \sin \varphi \sin \delta \right) \text{-----Eq---3.3}$$

$$\delta = 23.45 \sin \left(360 \frac{284 + n}{365} \right)$$

$$\omega_s = \cos^{-1}(-\tan \varphi \tan \delta)$$

Where $I_{sc} = 1367 \text{ W/m}^2$ and $\pi = 3.14$

φ = latitude angle(8.56)

ω_s = sunset hour angle

δ = declination angle

Estimating Monthly average daily global radiation on horizontal surface (H) given by

$$H = H_0 \left(a + b \frac{n_s}{N_s} \right) \text{-----Eq.....3.4}$$

$$a = -0.11 + 0.235 \cos \varphi + 0.323 \frac{n_s}{N_s}$$

$$b = 1.449 - 0.533 \cos \varphi - 0.694 \frac{n_s}{N_s}$$

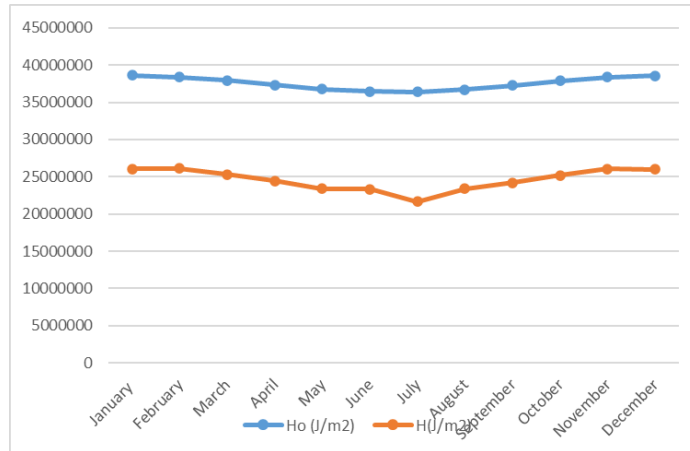


Figure 3.4 Monthly average daily Extraterrestrial and Global radiation on horizontal surface

3.4.3. Estimation of Monthly Average Daily Diffuse and Beam Radiations

The monthly average number of bright sunshine hours (n) and the monthly average global solar radiation (Hg) on a horizontal surface may be used to determine the monthly average daily diffuse solar radiation (Hd) on a horizontal surface (Deceased & Beckman, n.d.).

$$\overline{H}_d = \overline{H} \left(0.931 - 0.814 \frac{n_s}{N_s} \right) \text{-----Eq.....3.5.}$$

$$\overline{H}_b = \overline{H} - \overline{H}_d$$

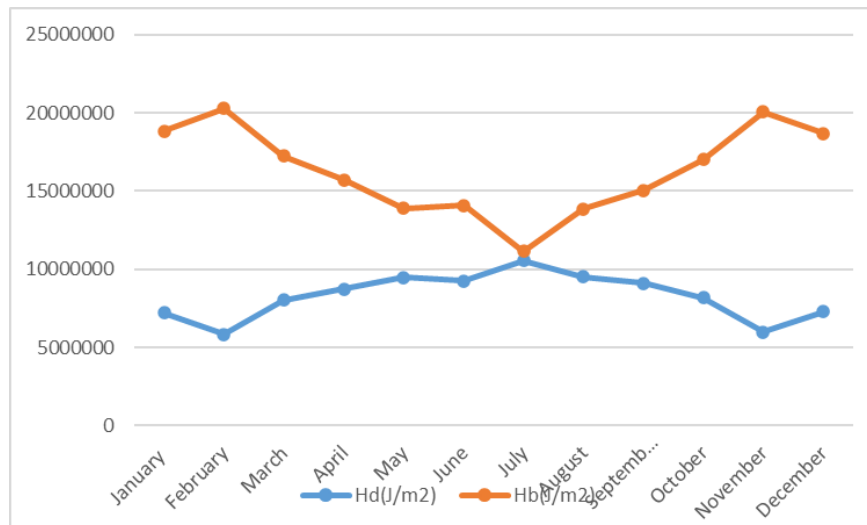


Figure 3.5 Monthly mean Daily Beam and Diffuse Radiations

Prediction of monthly average hourly global and diffuse radiation on horizontal surface;

The monthly average global radiation (H) on a horizontal surface may be used to calculate the monthly average hourly global radiation (I) on the same surface.

$$I = H \left(\frac{\pi}{24} \right) (a + b \cos \omega) \left(\frac{\cos \omega - \cos \omega_s}{\sin \omega_s - \left(\frac{\pi \omega_s}{180} \right) \cos \omega_s} \right) \text{-----Eq.....3.6.}$$

$$a = 0.409 + 0.5016 \sin(\omega_s - 60)$$

$$b = 0.6609 - 0.4767 \sin(\omega_s - 60)$$

From the monthly average daily diffuse radiation (H_d) on a horizontal surface, one may calculate the monthly average hourly diffuse radiation (I_d) on the same surface.

$$I_d = H_d \left(\frac{\pi}{24} \right) \left(\frac{\cos \omega - \cos \omega_s}{\sin \omega_s - \left(\frac{\pi \omega_s}{180} \right) \cos \omega_s} \right) \text{-----Eq.....3.7.}$$

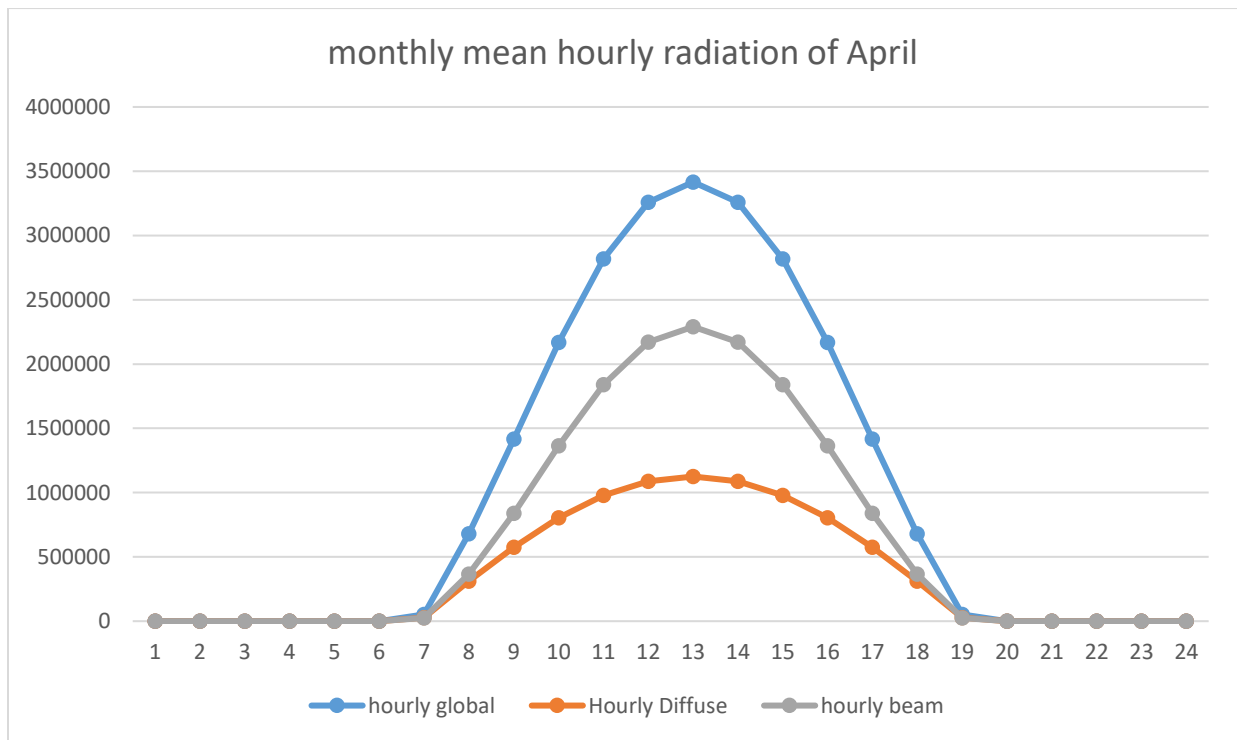


Figure 3.6 Monthly mean hourly radiation on horizontal surface

3.4.4. Estimation of Radiation on sloped surfaces

The total of the beam, diffuse, and reflected solar radiation from multiple surfaces (from a horizontal surface and surfaces around it) is the incidence solar radiation on an inclined (tilted) surface (Arvind & Shyam, n.d.). Consequently, the global, beam, diffuse, and total reflected radiation to the tilted surface may be used to represent the total incident solar radiation on a surface slanted at an angle β ;

$$I_T = I_b R_b + I_d \left(\frac{1+\cos\beta}{2} \right) + I \rho_g \left(\frac{1-\cos\beta}{2} \right) \text{-----Eq.....3.8.}$$

Where; I_T - is total hourly irradiance on a tilted surface (W/m²)

I_b - is beam hourly irradiance on a horizontal surface (W/m²)

I_d - is diffused hourly irradiance on a horizontal surface (W/m²)

β - is tilt angle (24°)

ρ_g - diffuse reflectance of ground. The value is 0.2 for ordinary ground (Arvind & Shyam, n.d.)

R_b - The ratio of incident beam radiation on a slanted surface to that on a level surface is known as the beam radiation factor. for location found in northern hemisphere using artificial latitude.

$$R_b = \frac{\cos(\varphi-\beta) \cos \delta \cos \omega + \sin(\varphi-\beta) \sin \delta}{\cos \varphi \cos \delta \cos \omega + \sin \varphi \sin \delta} \text{-----3.9}$$

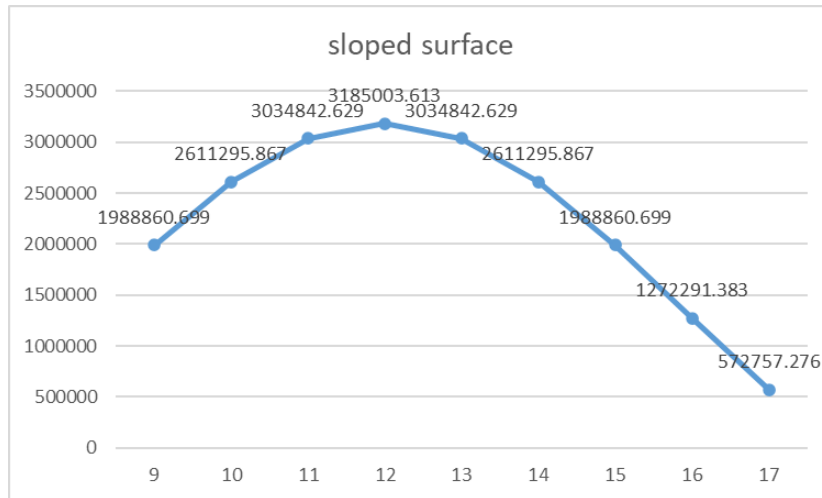


Figure 3.7 inclined (tilted) surface($\beta=24$) Incident solar radiation

3.5. Assessment Method of Physiochemical Property of Green Coffee Bean

3.5.1. Assessment method of bioactive composition of green coffee bean

Green coffee beans are a complex matrix of chemical compounds that significantly influence the final cup quality after roasting and brewing. They are primarily composed of carbohydrates, lipids, proteins, alkaloids, chlorogenic acids, water, and minerals. Green coffee beans possess a complex chemical composition that forms the basis for their distinctive flavors and aromas when roasted. Carbohydrates constitute 50-60% of the bean's dry weight, primarily as structural polysaccharides like cellulose and hemicellulose that also contribute to aroma development during roasting. The lipid fraction (10-17%) includes triglycerides, diterpenes (cafestol and kahweol), and unsaponifiable compounds that are crucial for flavor retention and crema formation in the final brew. Proteins and free amino acids (8-12%) serve as precursors for flavor development through Maillard and Strecker reactions during the roasting process. The beans contain 1-2% caffeine, an alkaloid responsible for coffee's characteristic bitterness and stimulating properties. Chlorogenic acids (6-12%), a group of phenolic compounds, act as important antioxidants while contributing to acidity, bitterness, and astringency. Minor components include trigonelline, which transforms into aromatic pyridines during roasting, and essential minerals like potassium, magnesium, and calcium that influence both bean metabolism and brewing characteristics. This intricate combination of chemical constituents ultimately creates the rich sensory profile of roasted coffee.

Green coffee beans are rich in bioactive components, which are compounds that contribute to their health benefits and sensory qualities. Understanding and assessing these components is crucial for evaluating the potential health effects and quality of the beans. Key bioactive compounds and their common methods of assessment:

Evaluating the bioactive components of green coffee beans including chlorogenic acids (CGAs), caffeine, lipids, and antioxidants demands precise analytical methods for accurate quantification and characterization. Fourier-transform near-infrared (FT-NIR) spectroscopy serves as an advanced, non-destructive tool for this purpose, capable of analyzing CGAs, caffeine, and other phenolic compounds. The technique works by detecting near-infrared light absorption caused by molecular vibrations in chemical bonds (e.g., O-H, C-H, N-H). The resulting FT-NIR spectrum plots transmittance against wavenumber, with distinct absorption peaks corresponding to functional groups of bioactive

compounds. By matching these spectral signatures to known references, researchers can qualitatively and quantitatively determine the concentrations of key phytochemicals in green coffee.

3.5.2. Assessment method of physical property of green coffee bean

Determining the physical properties of green coffee beans is a crucial aspect of evaluating their quality, processing potential, and market value. Properties such as moisture content, size, density, color, weight, and hardness are measured using specific tools and techniques to ensure consistency and optimal performance during roasting and brewing. The key physical properties typically measured, along with the corresponding methods for determinations are:

Moisture content valuation

Moisture content, for instance, is assessed with the oven-drying method to ensure it falls within the ideal range of 10 –12%, which prevents spoilage and ensures proper roasting. ISO 6673 is an international standard that specifies a method for determining the loss in mass of green coffee at 105°C. It's a method for determining moisture content in green coffee, applicable to both decaffeinated and non-decaffeinated types. Moisture content was determined using the oven drying method by drying the sample at 105°C for 16 hours, followed by measuring the initial and final mass to calculate moisture loss. The percent moisture content of the coffee bean was calculated using Equation.

$$MC(w. b) = \frac{m_i - m_d}{m_i} * 100 \text{-----} 3.10.$$

where, m_i is the initial mass of the dried product,

m_d is the mass of the fully dried product (oven dried).

Density approximation

Bean density is a critical physical property used to assess the quality of green coffee beans, as it reflects growing conditions, drying method, bean structure, and potential flavor development. Denser beans are usually higher quality because they have more nutrients and develop better flavors during roasting. Density might be measured by looking at bean hardness or using a flotation test where denser beans sink. Density is calculated by measuring the mass per unit volume, which is critical for predicting how beans will behave during roasting. The density of green coffee beans is evaluated using a combination

of methods that assess both bulk density (mass including air gaps) and true density (mass of the solid bean material). These methods help determine bean quality, roast behavior, and flavor potential.

Bulk density is the mass of a material per unit volume, including the space between particles (interstitial voids). For green coffee beans, it indicates how much space a given weight of beans occupies, which is important for storage, packaging, and transport. Bulk density was determined using the volume displacement method, where a fixed-volume cylinder was filled with green coffee beans (Campus, 2022), and the mass per unit volume was calculated.

$$\text{Bulk density} = \frac{\text{bean weight}}{\text{occupied volume}} \text{-----} 3.11.$$

True density refers to the mass of the solid material per unit volume, excluding any pores or air spaces between or within the particles. It reflects the actual compactness of the bean material itself. Indicates internal structure; relevant for roasting. The true density of green coffee beans was determined using the liquid displacement method, in which the beans were placed in a graduated cylinder and the volume of liquid displaced was measured (Campus, 2022).

$$\text{True density} = \frac{\text{bean weight}}{\text{displaced volume}} \text{-----} 3.12.$$

The presence of microscopic air pockets within the bean's cellular structure plays a crucial role in determining coffee quality, shelf life, and behavior during storage and transportation. Porosity measures the proportion of void (empty) spaces within a bulk material. For green coffee beans, it indicates how much of the total volume is made up of air spaces between and within the beans. This affects drying, roasting, and packaging behavior. Green bean porosity of sample was determined by using difference of true density and bulk density (Campus, 2022).

$$\text{porosity} = \frac{\text{true density} - \text{bulk density}}{\text{true density}} * 100 \text{-----} 3.13.$$

The color of green coffee beans provides valuable insights into their freshness, processing method, storage conditions, and potential cup quality. High-quality green beans are typically a consistent green color, maybe with some bluish or greyish tones. Color, an indicator of freshness and processing quality, is visually inspected or measured with colorimeters.

The size and shape of beans are determined through sieving, where beans are separated by screen sizes to grade them for uniformity, a key factor in even roasting. Bean size and shape uniformity is important

aspects for quality indicator. Beans are often graded by size using screens, and uniform size ensures even roasting. Irregular shapes might roast unevenly. So, size consistency is a physical property linked to quality.

Hardness is a significant physical property of green coffee beans that has a direct correlation with their production conditions, processing, and final cup quality. Hardness is the green coffee beans' resistance to alterations, fractures, or breaches. This constitutes a significant physical characteristic that affects the roasting process, grinding behavior, and general bean quality. Green coffee hardness evaluation beans were conducted using a texture analyzer or penetrometer that measures the force required to break or pierce the bean, which indicates its mechanical resistance. The drying method employed greatly affected the hardness of green coffee beans. A comparison of hardness characteristic testing of solar-dried and open sun-dried beans shows large variations. Textural differences, which are directly due to their respective drying methods. Solar-dried beans were found to have a greater average breaking force compared to sun-dried beans, suggesting enhanced structural strength and a better capacity to withstand mechanical stress. This can facilitate improved handling during the processing stage and a more even roasting profile. The fracture patterns observed in solar-dried and open sun-dried coffee beans reveal significant differences in structural integrity and quality retention. Solar drying samples normally have more uniform and controlled cracks, due to the controlled air flow and temperature in the solar drying system, enabling a gradual moisture migration. In contrast, open sun-dried samples exhibit irregular, often severe fracturing characterized by profound, random cracks and surface deterioration. These architectural flaws are brought about by uncontrolled environmental factors such as daytime temperature variation and direct ultraviolet radiation and uneven airflow which generates non-uniform moisture gradients and causes quick, differential shrinkage. The improved fracture properties of products dried by sun improve quality parameters: improved visual appeal for marketability, improved rehydration capacity due to maintained porosity, and improved mechanical toughness in handling and storage.

Surface physical quality of open sun-dried and solar-dried beans exhibit marked differences that greatly affect their quality and marketability. Solar-dried products generally have a more even and pleasing surface appearance, with consistent color retention, minimal browning, and reduced surface defects. This better appearance is due to the controlled drying environment, whose temperature (45-60°C) and air supply are always ideal, thus avoiding high temperature and oxidative damage. The

controlled atmosphere also restricts case hardening, leading to smoother surfaces with fewer cracks and wrinkles. Open sun-dried products, on the other hand, have irregular and degraded surface features, such as prominent discoloration, irregular texture, and visible evidence of erosion. Exposure to direct sunlight and fluctuating environmental conditions leads to photo-oxidation, resulting in faded or darkened areas, particularly in products with high pigment content. Additionally, the lack of controlled airflow and protection from dust and insects contributes to surface contamination and physical damage, further fading the product's visual appeal.

3.6. Sizing of solar air heater

This study employs a double-pass solar air heater (DPSAH) for drying applications, chosen for its enhanced thermal performance over conventional single-pass systems. The dual-flow configuration significantly reduces top heat loss coefficients while only marginally increasing costs compared to standard solar collectors. In the DPSAH design, air follows a two-stage heating process: initially flowing through the upper channel between the transparent glazing and absorber plate, then reversing direction through the lower channel beneath the absorber. This counter-current arrangement improves heat transfer efficiency by extending the air's exposure to heated surfaces and minimizing thermal losses. The system's improved energy recovery capability makes it particularly suitable for sustained drying operations where consistent thermal output is required.

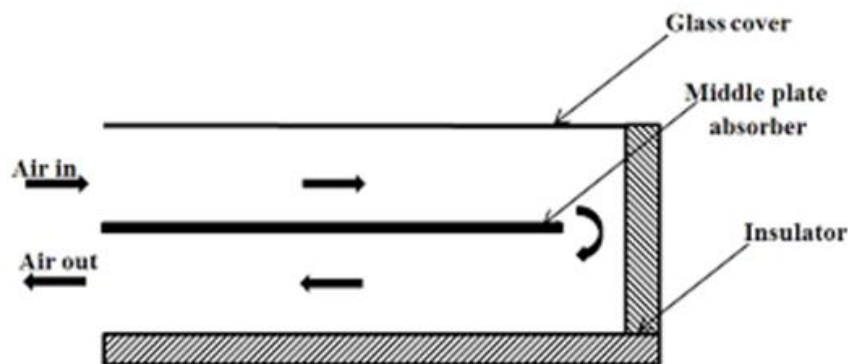


Figure 3.8 Schematic diagram of double pass counter flow SAH

Number of simplifying assumptions can be made to lay the foundations without obscuring the basic physical situation.

- performance of the system is evaluated under steady-state conditions.
- Heat flow through a cover is one dimensional.

- The temperature differential over the clear cover is regarded as insignificant.
- The covers are opaque to heat (infrared radiation).
- One-dimensional heat transmission is thought to occur through the rear insulation.
- Shading of the collector absorber plate is negligible

Heat received by the collector (Q_c): The equation provides the total amount of solar energy that falls on the collection.

$$Q_c = I_t A_c \text{-----} 3.14$$

Where $I(t)$, is solar radiation intensity and A_c is collector area.

Useful heat collected by the collector (Q_u): the rate of thermal energy at the absorber plate calculated by;

$$\dot{Q}_u = A_c [(\tau\alpha)I(t) - U_l(T_p - T_a)] \text{-----} 3.15$$

Where τ is transmittivity, α is absorptivity and U_l is overall heat transfer coefficient.

a). Steady-State Analysis for Forced convection.

Through a number of processes, energy is moved from the absorber plate to the surroundings. Initially, heat is lost through the back loss coefficient, U_b to the surrounding air at ambient temperature, T_a . At the same time, the convective heat transfer coefficient h_c transfers energy to the working fluid at temperature, T_f . Additionally, a linearized radiation heat transfer coefficient, h_r is used to describe the radiation of heat to the bottom surface of the cover glass. A series of energy balancing equations applied to the cover glass control this energy transfer processes, guaranteeing a thorough examination of the system's thermal performance.

Energy balances on the cover yield the following equations:

$$U_t(T_a - T_c) + h_1(T_f - T_c) + hr(T_p - T_c) = 0 \text{-----} 3.16$$

Energy balances on the plate yield the following equations:

$$\tau\alpha I(t) + U_b(T_a - T_p) + h_2(T_f - T_p) + hr(T_c - T_p) = 0 \text{-----} 3.17$$

The rate at which heat energy moves from the glass cover and absorber plate to the working fluid will be computed as;

$$q_u = h_1(T_c - T_f) + h_2(T_p - T_f) \text{-----} 3.18$$

Solving equation 3.16 & 3.17 for $T_p - T_f$ and $T_c - T_f$.

$$T_p - T_f = \frac{S(U_t + hr + h_1) - (T_f - T_a)(U_t h_r + U_t U_b + U_b h_r + U_b h_1)}{(U_t + hr + h_1)(U_b + h_2 + hr) - h_r^2}$$

$$T_c - T_f = \frac{(S * h_r) - (T_f - T_a)(U_t h_2 + U_t U_b + U_b h_r + U_t h_r)}{(U_t + hr + h_1)(U_b + h_2 + hr) - h_r^2}$$

Substituting these two equations into equation 3.18 and arranging gives;

$$q_u = F'[S - U_l(T_f - T_a)] \text{-----} 3.19$$

Where F' is collector efficiency factor, U_l is overall heat transfer coefficient and h_r radiation heat transfer coefficient.

$$F' = \frac{h_r h_1 + U_t h_2 + h_2 hr + h_1 h_2}{(U_t + hr + h_1)(U_b + h_2 + hr) - h_r^2} \text{-----} 3.20$$

$$U_l = \frac{((U_b + U_t)(h_r h_1 + h_2 h_r + h_1 h_2) + U_b U_t (h_1 + h_2))}{h_r h_1 + U_t h_2 + h_2 hr + h_1 h_2} \text{-----} 3.21$$

$$h_r = \frac{\sigma(T_p^2 + T_c^2)(T_p + T_c)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_c} - 1}$$

$$Re = \frac{\rho v D_h}{\mu}$$

$$FR = \frac{\dot{m} C_p}{A_c U_l} \left[1 - \frac{\frac{S}{U_l} - (T_{fo} - T_a)}{\frac{S}{U_l} - (T_{fi} - T_a)} \right] \text{-----} 3.22$$

$$FR = \frac{\dot{m} C_p}{A_c U_l} \left[1 - \exp\left(-\frac{A_c U_l F'}{\dot{m} C_p}\right) \right] \text{-----} 3.23$$

Where FR , collector heat removal F'' factor and collector flow factor

$$F'' = \frac{FR}{F'} = \frac{\dot{m}C_p}{A_c U_l F'} [1 - \exp(-\frac{A_c U_l F'}{\dot{m}C_p})] \text{-----} 3.24$$

$$T_{fm} = T_{fi} + \frac{q_u}{F_R U_l} (1 - F'') \text{-----} 3.25$$

$$T_{pm} = T_{fi} + \frac{q_u}{F_R U_l} (1 - F_R) \text{-----} 3.26$$

Where T_{fm} is mean fluid temperature and T_{pm} is mean plate temperature

b). Unsteady state Analysis for Forced convection

Mass Balance

Change in air moisture across the kiln = moisture leaving product - change in moisture in air within kiln.

$$V_o W_o - V_i W_i = -V_s \frac{\partial MC}{\partial t} - V_a \frac{\partial W_o}{\partial t} \text{-----} (3.27)$$

Energy Balance of the Collector Glass Cover

$$\rho_g \delta_g C P_g \frac{\partial T_g}{\partial t} = \alpha_g I_G + h_{c,fg}(T_f - T_g) + h_{r,pq}(T_p - T_g) - h_{r,gs}(T_g - T_{sky}) - h_{c,ga}(T_g - T_a) \text{---} (3.28)$$

The equilibrium of air energy between the absorber and the glass cover

$$\rho_a \delta_a C P_a \frac{\partial T_f}{\partial t} = h_{c,pf}(T_p - T_f) + h_{c,fg}(T_f - T_g) - \left(U_f * \rho f * (A_{gap,cs} / A_{gap,sa}) \right) * C P_f * (T_f - T_{db,in}) \text{-----} 3.29$$

Energy Balance of the Absorber Plate

$$\rho_p \delta_p C P_p \frac{\partial T_p}{\partial t} = (\tau_g \alpha_p) e I_G - h_{r,pq}(T_p - T_g) - h_{c,pf}(T_p - T_f) - h_{c,pi}(T_p - T_{db,in}) - h_{r,pL}(T_p - T_L) \text{-----} 3.30$$

Energy Balance of the green coffee bean

$$M_L C P_L \frac{\partial T_L}{\partial t} = A_v h_{c,iL}(T_{db,in} - T_L) + A_g h_{r,pL}(T_p - T_L) - \left(M_L \left(\frac{A_v}{A_g} \right) \left(\frac{\partial MC}{\partial t} \right) * L_v \right) \text{-----} (3.31)$$

Energy Balance of the Flowing Air Inside the Kiln

The airflow in the kiln serves two main purposes: acting as a heat carrier and as a medium to absorb the moisture that evaporates during drying. Proper air circulation is crucial to remove the moist air surrounding the coffee cherries and replace it with warmer, drier air. Therefore, selecting the appropriate air velocity is essential to efficiently replace the moist air while maintaining the coffee's quality and minimizing energy consumption by the fan. The drying air velocity significantly influences the drying rate. The mass transfer coefficient is primarily affected by the air velocity, meaning that higher velocities lead to a more rapid moisture loss, with the drying air quickly reaching a high moisture content, compared to lower air velocities.

$$M_a C P_a \frac{\partial T_{db,in}}{\partial t} = A_p h_{c,pi} (T_p - T_{db,in}) - A_v h_{c,Li} (T_{db,in} - T_L) + P_f + M_a C P_a (T_f - T_{db,in}) - [(m_{out} C P_a T_{db,in}) - (m_{in} C P_{amb} T_{db,amb})] \text{-----} (3.32)$$

Conversely, the energy generated from the dryer collector will be computed using the Equation.

$$Q_u = m_a C_{pa} (T_0 - T_a) \text{-----} 3.33$$

A solar collector's efficiency (η_c) can be defined as the ratio of its usable energy gain to its incident solar energy and expressed as

$$\eta_c = \frac{Q_u}{Q_c} = \frac{m_a C_{pa} (T_0 - T_a)}{I_t A_c} \text{-----} 3.34$$

3.7. Statistical analysis of experimental data

When comparing drying models for green coffee beans under varying temperatures, statistical metrics quantitatively assess model performance. Statistical measurements are used to evaluate and compare thin-layer drying models. Statistical measures including the coefficient of determination (R^2), root mean square error (RMSE), and chi-square statistic (χ^2) are essential for assessing model performance when comparing various drying models for green coffee beans under various temperature settings. A model is considered to have achieved goodness of fit if its R^2 value is high and lower for the remaining two. The moisture ratio (MR) variation explained by the model is measured by R^2 , which has a range of 0 to 1. A value nearer 1 indicates a better match. R^2 is helpful for comparing models on the same dataset, although it is sensitive to outliers and can be deceptive for nonlinear connections. However, RMSE provides a straightforward measure of prediction accuracy by quantifying the average variance between observed and anticipated MR values. A more accurate model is shown by a lower RMSE, which makes it especially useful for applications like

industrial coffee processing where reducing drying errors is crucial. Since RMSE is scale-dependent, it should only be compared within the same research, in contrast to R^2 .

Coefficient of Determination calculated by

$$R^2 = 1 - \frac{\sum_{i=1}^N (MR_{exp} - MR_{pr})^2}{\sum_{i=1}^N (MR_{exp} - \overline{MR_{exp}})^2} \text{-----} 3.35$$

Where MR_{exp} indicates the experimental dimensionless moisture ratio, MR_{pr} the model dimensionless moisture ratio, $\overline{MR_{exp}}$ is mean experimental moisture ratio and N is stands for number of observations.

Root Mean Square Error (RMSE) given by;

$$RMSE = [\sum_{i=1}^N \frac{1}{N} (MR_{exp} - MR_{pr})^2]^{0.5} \text{-----} 3.36$$

By weighing errors according to their variance, the chi-square statistic (χ^2) provides further information and is perfect for datasets with substantial variation in prediction errors across temperature ranges. A better fit is indicated by a lower χ^2 value, particularly when working with heterogeneous data. Although χ^2 is a reliable way to evaluate goodness-of-fit, its proper application necessitates duplicated data or an estimate of variance. When combined, these indicators offer a thorough framework for assessing the model.

Chi-Square Statistic (χ^2) calculated by

$$\chi^2 = \sum_{i=1}^n \frac{(MR_{exp} - MR_{pr})^2}{(N-n)} \text{-----} 3.37$$

Where n is constants of the thin-layer models

3.8. Drying Model

The primary processes of drying include capillary action in granular and porous grains as a result of surface forces, surface diffusion on the pore surfaces, and liquid or vapor diffusion as a result of variations in moisture concentrations. When wet green coffee bean dries, two fundamental and simultaneous processes occur:

- a) Heat is transferred to evaporate liquid from the product.
- b) Internal moisture movement within the product and surface water vapor movement brought on by external air temperature, humidity, pressure, and mass flow rate both contribute to mass transfer. The kinetics of this process vary significantly among different substances, with the most pronounced differences observed between hygroscopic and non-hygroscopic materials. Non-hygroscopic substances can theoretically be dried to absolute zero moisture content, as they lack strong moisture-binding capacity. In contrast, hygroscopic materials retain residual moisture even after extensive drying due to chemically bound water molecules and capillary-held moisture within their porous structure. This inherent property distinction critically impacts drying protocols and final product characteristics for different material types.

Accurate drying models must be created in order to optimize the drying process, especially when drying products are subjected to temperature variations. These models mathematically describe the intricate kinetics of moisture removal, which are controlled by simultaneous mass and heat transport processes inside the porous bean structure. Effective modeling for green coffee beans, which normally begin with a wet foundation of 45–60% moisture content, must take into consideration the coffee beans' distinct cellular structure and the temperature-dependent behavior of water diffusion. Thin-layer drying has been employed in a variety of dryer types and is frequently used to ascertain the drying kinetics of crops (Phitakwinai et al., 2019). A layer is referred to be a "thin layer" if its product thickness is low enough to imply that the air qualities are uniform throughout. The thin layer drying process is occasionally used to describe the drying of individual particles or grains of material that are fully exposed to the drying air.

Three types of thin-layer drying equations may be distinguished: theoretical, semi-theoretical, and empirical models (Inyang et al., 2018). From empirical models such as the Page and Modified Page equations to more physically based diffusion models derived from Fick's law; a variety of modeling

techniques have been used. Recent developments have concentrated on creating adaptive models that can manage changing environmental conditions and dynamic temperature profiles. These models offer the coffee industry useful tools to increase energy efficiency and product consistency while preserving the final product's delicate flavor characteristics.

1) Modified Page Model

$$MR = \frac{MC_t - MC_e}{MC_i - MC_e} = \exp(-k \cdot t)^n \text{-----} 3.38$$

$$k = k_0 \cdot \exp\left(-\frac{E_a}{RT}\right) \text{ Arrhenius relationship for drying constant}$$

$$n = a + b \cdot T$$

Where; MR is moisture ratio, k is drying constant (m^{-1}), t is drying time, n is dimensionless empirical constant, MC_t , MC_e , MC_i are moisture content at any time, equilibrium and initial, respectively.

2) Diffusion-Controlled (Fick's Law) Model

$$MR = A \cdot \exp(-k \cdot t) \text{-----} 3.39$$

The Arrhenius equation determines the activation energy, or the lowest threshold amount of energy that water must absorb in order to evaporate.

$$k = D_0 \cdot \exp(-E_a/RT)$$

(Effective diffusivity $D_{\text{eff}} \propto k$).

3) Henderson and Pabis Model

$$MR = a \cdot \exp(-k \cdot t) \text{-----} 3.40$$

$$k = k_0 \cdot \exp\left(-\frac{E_a}{RT}\right) \text{ and } a = f(T)$$

$$4) \text{ Logarithmic Model } MR = a \cdot \exp(-k \cdot t) + c \text{-----} 3.41$$

Parameters a, k, c fitted as functions of T.

Model	Accuracy	Temperature Flexibility	Ease of Use
Modified Page	Very good 4	Excellent 5	Good 3
Fick's Diffusion	Good 3	Very good 4	Poor 2
Henderson & Pabis	Good 3	Good 3	Very good 4
Logarithmic	Very good 4	Very good 4	Good 3

Table 3.3 Model Selection Guidelines

The thermodynamic properties, that is, ΔH , ΔS , and ΔG were computed using Equation's (Öztekin et al., 2022).

$$\Delta H = E_a - RT_a \text{-----} 3.42$$

$$\Delta S = R(\ln D_0 - \ln \frac{k_b}{h_p} - \ln T_a) \text{-----} 3.43$$

$$\Delta G = \Delta H - \Delta ST_a \text{-----} 3.44$$

where ΔH , ΔS , ΔG , k_b , and h_p are the variation in enthalpy (kJ/mol), the variation in entropy (kJ/mol K), the variation in Gibbs-free energy (kJ/mol), k_b is the Boltzmann's constant (1.38×10^{-23} J/K), and h_p is the Planck's constant (6.626×10^{-34} J/s), respectively.

Coffee's equilibrium moisture content (EMC) is a crucial factor that determines whether the beans will become more or less wet under particular temperature and relative humidity circumstances. This equilibrium state occurs when the water vapor pressure of the surrounding environment equals the vapor pressure within the coffee beans (Of, n.d.). The appropriate relative humidity of the air at that temperature is referred to as the equilibrium relative humidity (ERH) when this balance is reached. Notably, the latent heat of vaporization for coffee demonstrates variation depending on its EMC level. Coffee's EMC can be measured through several established analytical methods. These measurements are essential for understanding and controlling coffee's moisture interactions during processing and storage. Various methods can be used to measure the equilibrium moisture content of a hygroscopic material. The Henderson empirical equation may be used to mathematically represent the connection between temperature, relative humidity, and moisture content at equilibrium.

$$1 - RH = EXP(-C * T_{ab} * EMC^n) \text{-----} 3.45$$

$$C = 0.00127486 - (8.3968 * 10^{-6} * T_{db}) + (1.43766 * 10^8 * T_{db}^2) \text{-----} 3.46$$

$$n = -0.983253 + (0.0178613 * T_{db}) - (3.23473 * 10^5 * T_{db}^2) \text{-----} 3.47$$

Amount of water removed from the product, kg

When calculating the mass of water removed from a wet product (mw), the product's original mass and its initial and final moisture content (% w.b.) can be used as;

$$m_w = m_p \left(\frac{MC_i - MC_f}{100} \right) \text{-----Eq--} 3.48$$

Amount of heat energy required to remove moisture from a product, Q_r

The amount of heat required to evaporate moisture from the products to be dried is given by (Embiale & Gunjo, 2023);

$$Q_r = m_w * h_{fg} \text{-----} 3.49$$

Where; m_w mass of moisture removed from product and

h_{fg}- latent heat of evaporation at mean fluid temp.

The latent heat of vaporization can be calculated using the equation given by

$$h_{fg} = cp_w * (597 - 0.56 * T_{f,mean}) \text{-----} 3.50$$

Airflow requirement

Fan capacity of 20 cfm(0.57m³/min) mount to circulate air from solar collector to drying chamber.

The required mass flow rate of air removing moisture from product was calculated from

$$\dot{m}_a = \dot{v}_a * \rho_a \text{-----} 3.51$$

$$\dot{m}_a = \frac{0.57}{60} * 1.2 = 0.0114 kg/s$$

3.9. Experimental Setup and procedure

In this study, an active solar kiln dryer will be constructed using low-cost, locally accessible materials and tested to evaluate its drying efficiency and the quality of the dried product. The solar kiln will consist of a transparent glazing material that will allow light to enter while blocking energy loss, a drying chamber equipped with a metal grid tray, and a wooden casing supported by a metal frame. Measuring instruments will be integrated to track and monitor parameters related to the drying system. Hot air will be generated inside the solar kiln due to the opaque nature of the glass cover and will flow to the lower tray through forced convection, removing moisture from coffee beans spread across the tray rows. The drying chamber will be built from appropriately thick sheet metal, insulated on all sides to prevent heat loss, and designed with an opening to allow ambient airflow.

Manufacturing

The active solar kiln dryer represents an advanced thermal system specifically designed for efficient agricultural product dehydration. The system integrates two primary components: an optimized solar air heater and an insulated drying chamber, working synergistically to maximize energy utilization. The solar air heater employs an innovative double-pass configuration, where ambient air first circulates beneath a blackened absorber plate before reversing direction to flow above it. This countercurrent design enables sequential heating, significantly increasing the air temperature before it enters the drying chamber. The thermally insulated drying chamber minimizes heat losses while maintaining stable operating conditions. Its interior features a vertical rack system with multiple perforated drying trays and strategically placed baffles to ensure uniform laminar airflow across all product layers. A electricity driven axial fan (10W capacity) provides forced convection, maintaining precise temperature circulation throughout the drying process. This integrated configuration demonstrates 25-40% greater thermal efficiency compared to conventional single-pass solar dryers, while the enclosed design protects products from environmental contamination. The system's modular construction allows for adaptation to various agricultural commodities, with airflow velocity and temperature being adjustable based on specific products requirements. The double-pass design significantly improves heat transfer efficiency compared to conventional single-pass systems by extending the air's contact time with heated surfaces and recovering waste heat from the first pass. This integrated assembly demonstrates particular effectiveness for moisture-sensitive crops requiring controlled drying parameters, as it combines the temperature regulation benefits of solar kilns with the

enhanced thermal performance of advanced solar air heating technology, resulting in faster drying times and superior product quality compared to passive solar drying methods.

Construction of the Double Pass counter flow Solar Air Heater (DPCFSAH)

The solar collector, which is intended to effectively absorb solar radiation and transmit thermal energy to circulating air, is the drying system's key heat capture component. Constructed as a rectangular wooden frame measuring 1.5 m in length, 0.75 m in width, and 0.10 m in height, the collector features 20 mm thick plywood walls for structural integrity. The thermal assembly comprises several functional layers: a 0.8 mm thick galvanized iron base plate (1.5 m $\times$ 0.71 m) forms the foundation, topped with a 20 mm foam insulation layer to minimize heat losses. The absorber plate, coated with black polyethylene for maximum solar absorption, works in conjunction with a transparent glass cover that creates an insulating greenhouse effect. This carefully engineered combination of materials and dimensions ensures optimal heat retention and air heating capability for effective drying operations.



Figure 3.9 Manufacturing of double pass solar collector

The absorber plate consists of a 1.35 m $\times$ 0.71 m black-painted steel sheet (1.0 mm thickness) bonded with a black polyethylene sheet for enhanced solar absorption. This assembly is positioned 40 mm above the base plate to create an air channel. For glazing, a 4 mm thick clear glass panel (0.71 m $\times$ 1.46 m) is installed 50 mm above the absorber plate, forming the upper air passage. The complete collector assembly is oriented in a south-facing direction with a 24° tilt angle (calculated as 8.5° + 15° for optimal solar exposure).

Construction of Supporter Structure

The welded metal framework provides structural support for both the wooden collector casing and drying chamber, ensuring rigidity and maintaining the optimal 24° tilt angle for solar exposure. The primary frame (1.5 m × 0.75 m) was fabricated from square metal pipes and angle iron, aligned precisely with the collector's inclination (as illustrated in Figure 4.2). To enhance durability against outdoor conditions, the entire structure was coated with protective varnish.



Figure 3.10 Construction of Supporter frame

Construction of drying chamber (kiln)

The drying chamber is a critical component designed to efficiently dehydrate wet coffee beans using solar thermal energy. Constructed from 2 mm thick plywood, the chamber measures 0.6 m (length) × 1 m (width) × 0.6 m (height) and features a reinforced steel bar and angle iron framework for structural support. The interior walls are lined with a black adhesive sheet to enhance heat absorption from both direct sunlight and the solar collector.

The chamber incorporates four equally spaced drying trays made of fine wire mesh, selected for optimal porosity to balance airflow and minimize pressure drop while maximizing heat transfer efficiency. Each tray is supported by rectangular wooden rails securely fixed to the interior walls. A tightly sealed, hinged plywood door at the front minimizes heat loss, while a secondary access door at the rear facilitates easy loading and unloading of materials. For effective moisture removal, a vent positioned at the base of the front door allows continuous expulsion of humid air.

To ensure uniform drying, the chamber maintain proper spacing between trays for consistent air circulation. Experimental trials are conducted at scheduled intervals to evaluate drying performance under controlled conditions. This design prioritizes thermal efficiency, structural durability, and operational practicality for solar-powered coffee bean dehydration.



Figure 3.11 Construction of drying chamber

This study developed an active solar kiln dryer constructed from low-cost, locally sourced materials. The system comprised two main components: a double-pass solar air heater and an insulated drying chamber. To optimize airflow, an axial fan was installed at the interface between the solar collector and drying chamber.



Figure 3.12 Solar kiln experimental setup unit

Temperature monitoring was achieved through strategically placed thermocouples at the inlet and outlet of the solar air heater and multiple locations within the DPSAH and drying chamber. For performance evaluation, 6 kg of wet-processed coffee beans were loaded into the drying chamber. The system underwent continuous field testing over four consecutive days, during which temperature profiles and moisture content reduction were recorded at regular intervals to assess drying kinetics and thermal performance.

3.10. feasibility study

The technical, financial, environmental, and social viability of a solar drying kiln for coffee bean drying are all thoroughly examined in a feasibility study. The study starts by evaluating the technical elements of the solar drying system, including its materials, construction, and effectiveness in various climates. It assesses the kiln's capacity to sustain ideal airflow and temperatures for efficiently drying crops without sacrificing their quality. In terms of economics, the study looks at the payback period and long-term financial gains for farmers or agribusinesses, as well as the initial investment, operating expenses, and possible savings as compared to conventional drying techniques. By using sustainable solar energy rather than drying systems that rely on fossil fuels, environmental feasibility takes into account the decrease in energy consumption and carbon emissions. The study also looks at the simplicity of usage, social acceptability, and possible effects on nearby populations, especially in rural locations where access to traditional drying methods may be restricted. The feasibility research evaluates these aspects to ascertain whether the solar drying kiln is a workable and sustainable way to enhance post-harvest crop preservation and lower losses.

CHAPTER 4

RESULTS AND DISCUSSIONS

This chapter presents the experimental results of the study based on the impact of drying on the physicochemical properties and performance assessment of a solar kiln dryer. All components of the dryer are examined for their operational aspects, with key findings based on the results thoroughly discussed. Comparative analysis of how various drying processes influence physicochemical properties is also provided.

4.1 Estimation solar radiation intensity

4.1.1 Estimation of hourly solar radiation intensity

The sky was mostly clear during the testing session. The estimated monthly average hourly incident solar radiation on a slanted surface for April, at local time, is shown in Figure 4.1 as a plotted graph and tabular statistics.

Solar time	ω	R_b	I_b	I_d	I	I_t
9	-45	0.88057	1363939	803822.5	2167762	1988861
10	-30	0.897375	1839707	978316.5	2818023	2611296
11	-15	0.905179	2171598	1088008	3259606	3034843
12	0	0.907493	2290593	1125422	3416015	3185004
13	15	0.905179	2171598	1088008	3259606	3034843
14	30	0.897375	1839707	978316.5	2818023	2611296
15	45	0.88057	1363939	803822.5	2167762	1988861
16	60	0.8434	840104.3	576417.5	1416522	1272291
17	75	0.73174	367287.5	311598.8	678886.3	572757.3
Average					2444689.48	2255561.37

Table 4.1 solar radiation on horizontal surface vs sloped surface

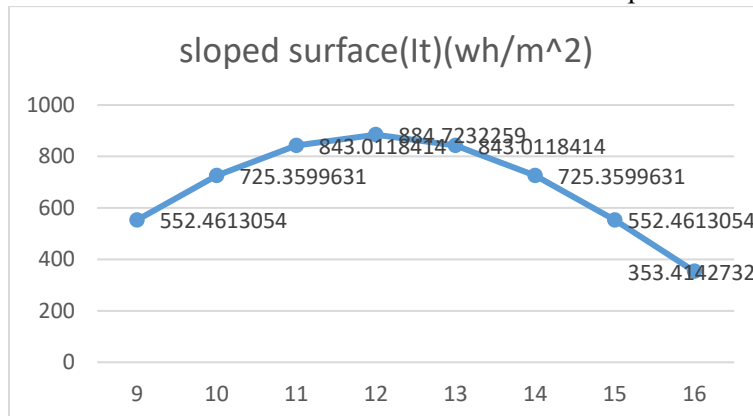


Figure 4.1 variation of average solar radiation intensity of four days with time.

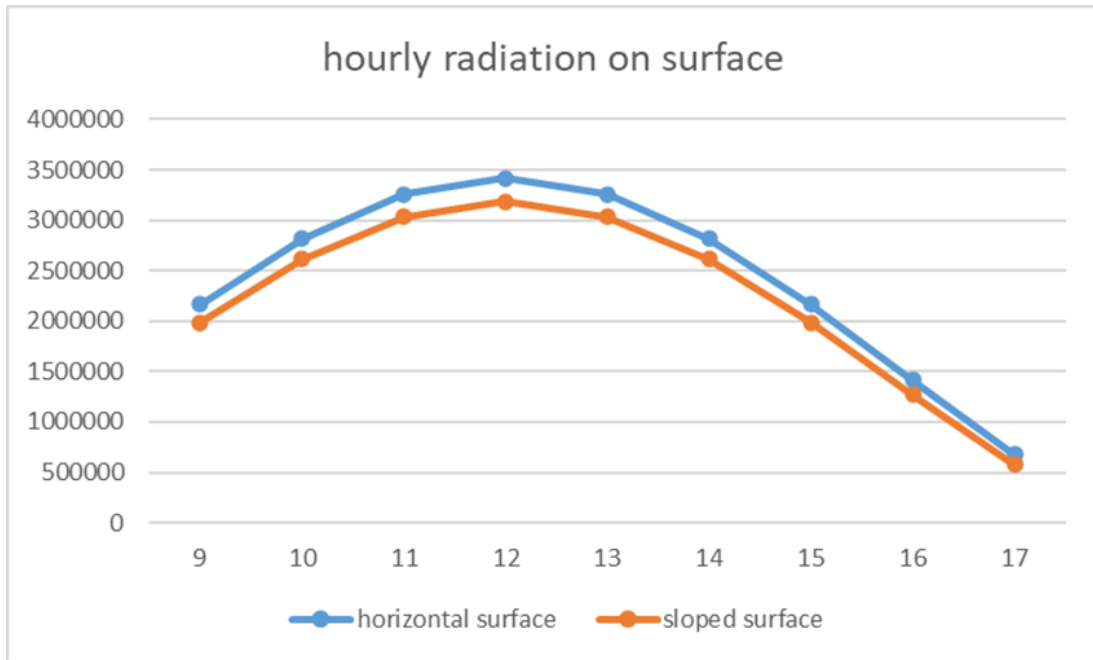


Figure 4.2 comparison of solar radiation on sloped and horizontal surface

4.1.2. Estimation of Hourly Variation of Atmospheric Temperature and humidity

During the experiment, the ambient temperature varied from about 25.1 to 31 °C. It is also observed that the ambient temperature is nearly the same across all the experimental days and conditions.

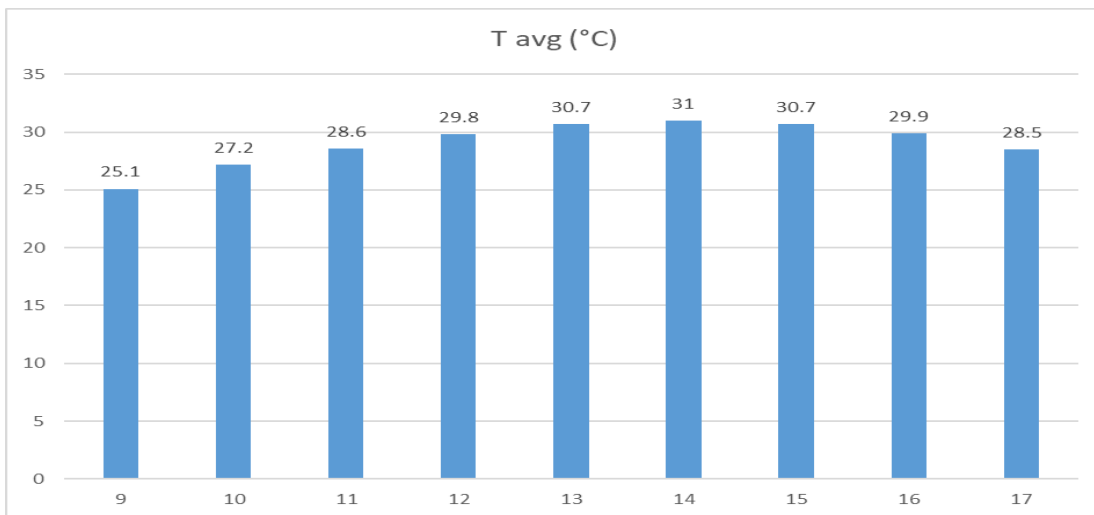


Figure 4.3 Mean hourly variation of ambient temperature of experiments period

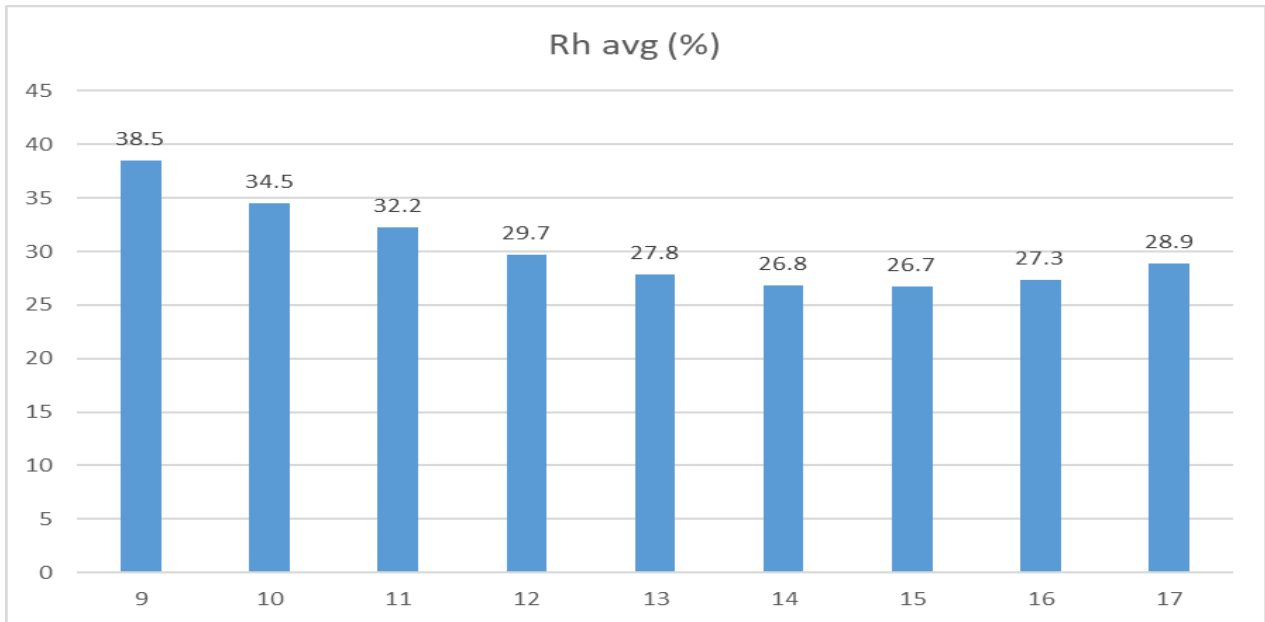


Figure 4.4 hourly variation of relative humidity during experiment

(b) Performance analysis Double pass counter flow solar air heater

Throughout the testing period, important data such as the entrance (ambient) temperature, exit temperature, and mean plate temperature of the collector were collected at one-hour intervals in order to assess the double-pass flat plate solar air heater's effectiveness. These data were crucial for determining the system's overall efficacy and thermal efficiency. Heat transfer properties, energy conversion efficiency, and temperature variations throughout the solar air heater were ascertained by analyzing the data that was gathered. This section presents the findings from these tests and then goes into great depth about how they affect system performance. To offer a thorough grasp of the solar air heater's operating behavior under the specified circumstances, comparisons with theoretical models and related research are also presented.

4.1.3. SAH Outlet and mean plate Temperature Variation

Figure 4.5 illustrates the diurnal temperature variations of the solar collector system over four consecutive days (25-28 April 2025), comparing ambient conditions with mean plate and outlet

temperatures. The data reveals that at a constant mass flow rate of 0.0114 kg/s, the system achieved: Outlet air temperature range: 38°C to 68°C Mean absorber plate temperature range: 48°C to 79°C

Both outlet and plate temperatures exhibited direct correlation with solar irradiance, peaking during maximum insolation periods. The highest recorded outlet temperature (70°C) occurred at 13:00 h on the final test day, while the minimum (36°C) was observed at 09:00 h on the first day. These measurements demonstrate the system's responsive thermal performance to solar flux variations, with plate temperatures consistently exceeding air temperatures due to enhanced solar absorption and thermal inertia.

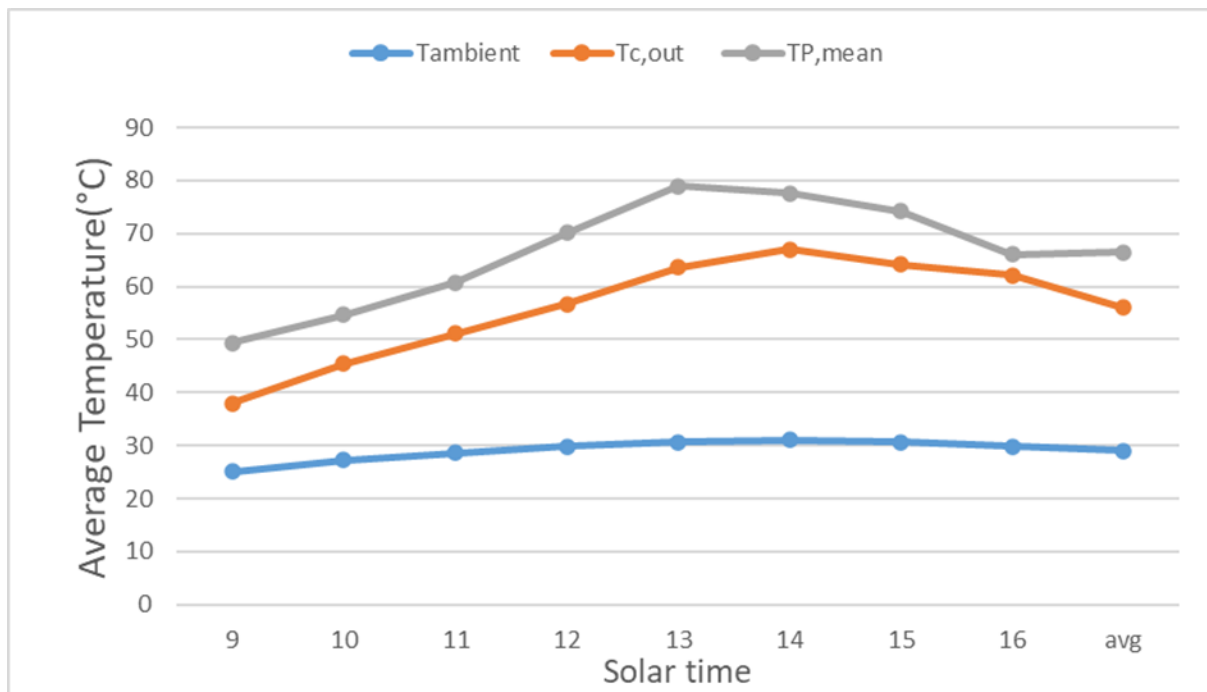


Figure 4.5 average variation of DPSAH Temperature

The temperature profiles of both the outlet collector and the mean plate temperature demonstrate a clear correlation with solar intensity patterns throughout the day. As illustrated in the figure 4.5, the outlet collector temperature shows a steady increase during the morning hours, reaching its peak at approximately 14:00 solar time. This gradual rise directly corresponds with the increasing solar radiation intensity during these daylight hours. Following this peak, a slight but noticeable temperature decline occurs, mirroring the subsequent reduction in available solar energy as the afternoon progresses. Similarly, the mean plate temperature of the collector also follows a similar pattern, slowly rising up to a peak at around 13:00 solar time. The reason that the peak in plate temperature occurs

before the outlet temperature is due to the thermal behavior of the absorbing surface of the collector, which responds more rapidly to solar radiation. The subsequent stabilization and subsequent fall in plate temperature show the reduction in solar intensity towards the later part of the day.

These results depict the immediate dependence of the thermal efficiency of the solar kiln on the presence of solar radiation. The time lag between peak plate temperature (13:00) and peak outlet temperature (14:00) reflects thermal inertia in the system, whereby mechanisms of heat transfer between the absorber plate and circulating air take additional time to stabilize. It is essential to comprehend these thermal dynamics to optimize collector design and operation to achieve peak efficiency during maximum solar hours considering natural decreases in energy input during late afternoon conditions.

The efficiency of solar collector calculated as

$$\eta_c = \frac{Q_u}{Q_c} = \frac{0.0114 * 1.005 * (56 - 29.5)}{2255560/3600 * 1.125} = 43\%$$

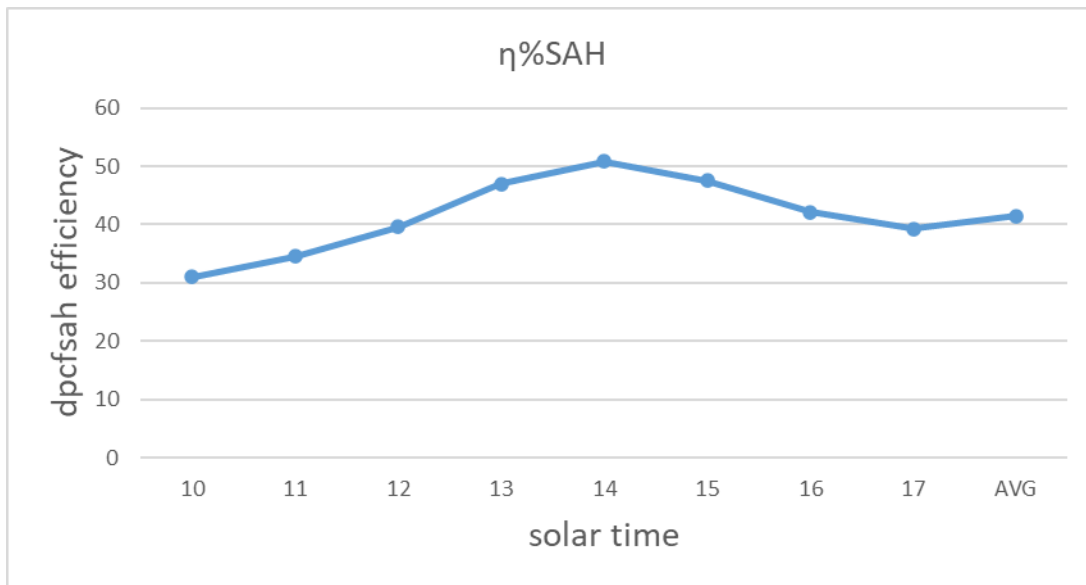


Figure 4.6 efficiency of solar collector (average of four days)

e) Drying Chamber Analysis

The drying chamber was filled with 6 kg of wet, cleaned coffee beans in order to test the dryer's functionality. The wet-washed bean was divided evenly among four trays, and the weights of the beans in each tray were recorded until they achieved a consistent weight in order to assess the product's

moisture loss. The entrance and outflow temperatures of the chamber were measured at one-hour intervals over the four days of the experiment (April 25–28, 2025).

For the four consecutive drying days, Figure 4.6 displays the change in moisture content with drying time. The weight of the bean is measured, and the weight loss during a one-hour period is calculated to ascertain the moisture content of the bean. The green bean's moisture content decreases during the course of 28 hours, from its starting value of 62% (w.b.) to its ending value of 11.7% (w.b.). The bean's moisture content decreases during the course of four consecutive days (28 hours, 7 hours per day) of drying, from 62% (w.b.) to 34% (w.b.), 20.5% (w.b.), 15.2% (w.b.), and 11.7% (w.b.).

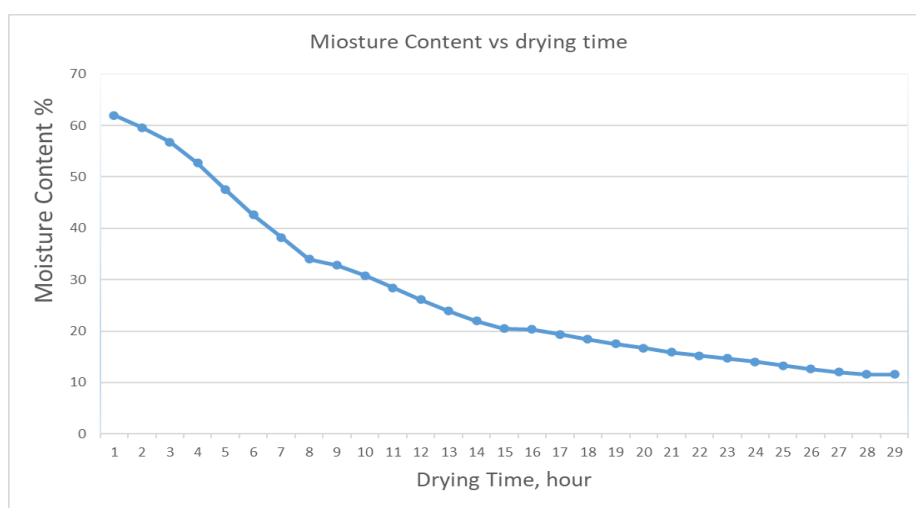


Figure 4.7 variation of moisture content through experiments

It was evident that the first day of the drying process had the fastest rate of moisture removal, which progressively decreased as the drying process went on. This decline is attributed to the reduced moisture content available for evaporation toward the later stages of drying. The change in drying rates over time is seen in Figure 4.7. Coffee beans dried more quickly in the solar kiln than in the open air, and this difference decreased steadily as the number of drying days rose. Peak sunlight hours, which correlate to the highest levels of solar radiation intensity and drying air temperature, were when the maximum drying rate was observed. Interestingly, because of the beans' decreased residual moisture content, the drying rate decreased after the first seven hours of the drying time.

6 kg of wet washed beans had 3.024 kg of moisture evaporated from them, lowering the green bean's moisture content from 62% (w.b.) to 11.7% (w.b.). An estimated 658 Wh/m² of solar radiation intensity falls on the solar air heater's surface on average. The solar air heater's size was 1.125 square meters, and the fan used 10 W of power. Every day for seven hours, the kiln is in operation.

$$h_{fg} = 4.186 * (597 - 0.56T_p)$$

Where; T_p is maximum allowable temperature of the dried product in °C.

Thus, $h_{fg} = 4.186 * (597 - 0.56 * 50) = 2382$ kJ/kg and the amount of energy required to evaporate 3.024 kg of moisture is:

$$Q_r = 3.024 * 2382 = 7203 \text{ KJ} = 7.2 \text{ MJ}$$

The instantaneous drying efficiency of drying chamber was calculated by:

$$\eta_{dc} = \frac{m_w * h_{fg}}{m_a C_{p_a} (T_{c,out} - T_{dc,out})}$$

Where m_w is mass of moisture removed per hour, $T_{c,out}$ is collector outlet temperature and $T_{dc,out}$ is outlet temperature of drying chamber

solar time	$\eta\%$ DC 1st day	$\eta\%$ DC 2nd day	$\eta\%$ DC 3rd day	$\eta\%$ DC last day	batch
10:00	53.74637805	37.38878473	14.79972729	11.68399523	29.40472132
11:00	51.86823388	33.87313233	13.76096001	9.526818467	27.25728617
12:00	52.81704156	29.95593402	12.21886782	8.277297558	25.81728524
13:00	52.38901299	24.77432241	9.625692145	6.627525739	23.35413832
14:00	50.48084371	22.16232163	9.234300679	5.540580407	21.85451161
15:00	50.09175926	21.87915922	9.212277566	4.606138783	21.44733371
16:00	48.92840818	20.76612673	9.102959661	0	19.69937364
average	51.47452538	27.25711158	11.13639788	6.608908026	24.11923572

Table 4.2 drying efficiency of drying chamber for one hour interval

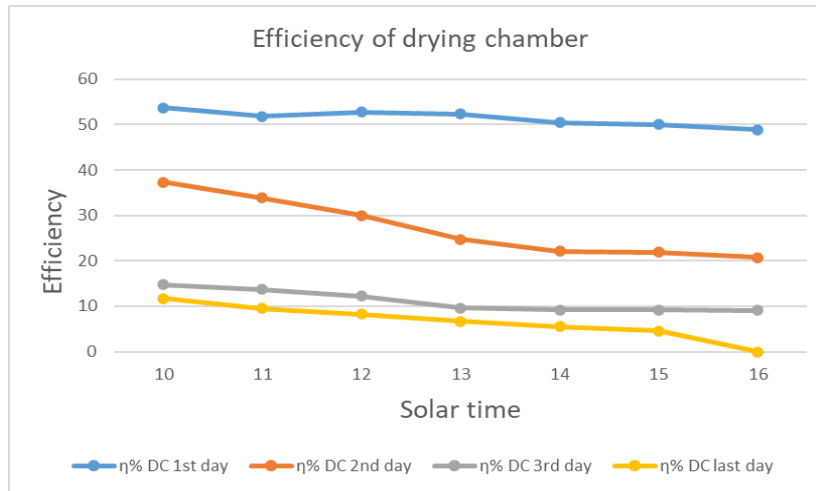


Figure 4.8 drying efficiency of drying chamber during experiment.

Fan Power consumption was given by

$$P_{fan} = 10 * 3600 * 28 = 1,008MJ$$

Overall efficiency of the drying system

$$\eta_{sys} = \frac{7,200,000 - (10W * 3600 * 28)}{2255561.4 * 1.125 * 28} * 100 = 8.7\%$$

The rate at which the moisture content changes between time t and t+Δt is calculated to establish the drying rate (DR), as indicated by Equation. When employing direct and passive solar drying techniques instead of open sun drying, the percentage of drying time saved may be computed using the following equation.

$$Evaporation\ rate(DR) = \frac{h_{fg} * m_w}{\Delta t}$$

1 st day		2 nd day		3 rd day		Last day	
Mw(gm)	DR	Mw(gm)	DR	Mw(gm)	DR	Mw (gm)	DR
144	95.28	108	71.46	42	28	30	19.85
168	111.16	120	79.4	50	33	39	26
246	162.77	144	95.28	55	36.4	41	27.3
312	206.44	138	91.31	57	37.7	42	28
294	194.53	132	87.34	54	35.7	38	25
264	174.68	102	75.43	48	31.76	26	16.6
252	166.74	102	59.55	42	28	0	0
1680		846		348		216	

Table 4.3 Evaporation rate in 1 hour interval during experiments

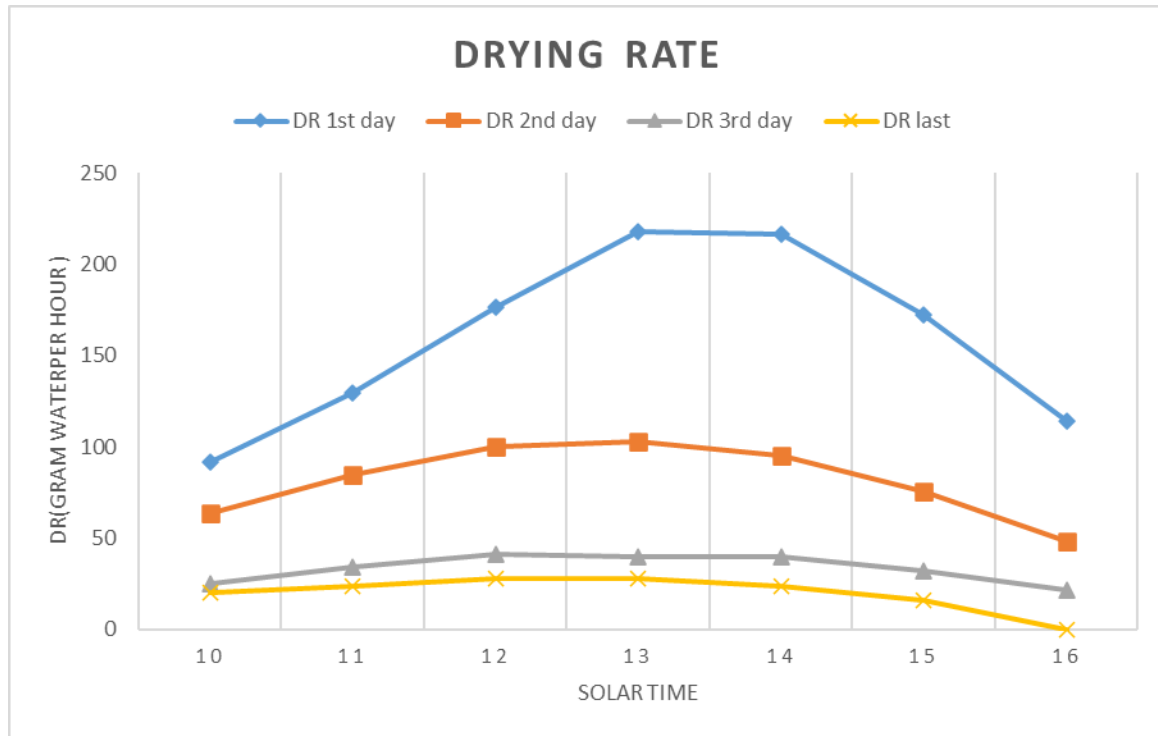


Figure 4.9 Evaporation rate throughout experiments

A Modified Page Model with Arrhenius temperature dependency provides the best possible compromise between accuracy and usefulness for modeling the drying behavior of green coffee beans under various temperature settings. This model describes moisture loss through the equation $MR = \exp(-k \cdot t)^n$, where the drying rate constant (k) follows an Arrhenius relationship ($k = k_0 \cdot \exp(-E_a/RT)$) to account for temperature effects, and the exponent (n) may also vary with temperature.

Thin-layer drying models are evaluated and can be compared using statistical measures. Statistical measures including the coefficient of determination (R^2), root mean square error (RMSE), and chi-square statistic (χ^2) are essential for assessing model performance when comparing various drying models for green coffee beans under various temperature settings. Goodness of fit is said to have occurred in a model if R^2 value is high and lower for remaining two. The moisture ratio (MR) variation explained by the model is measured by R^2 , which has a range of 0 to 1. A value nearer 1 indicates a better match and more accurate model is shown by a lower RMSE. By weighing errors according to their variance, the chi-square statistic (χ^2) provides further information. A better fit is indicated by a lower χ^2 value.

Model	RMSE	R ²	χ^2
Modified Page	0.08	0.992	0.014

Table 4.3 statistical measures experimental data to predicted model

4.2. Evaluation and Comparison of Biochemical Composition

Sensory tests were conducted to evaluate the quality of the green coffee bean samples. Biochemical compositions were quantified using FT-NIR spectrometer prediction model (IS50 ABX Thermoscientific, USA) at AASTU. FT-NIR operates by measuring the absorption of near-infrared light by chemical bonds (such as O-H, C-H, N-H), which correspond to specific molecular vibrations. The FT-NIR results display transmittance as a function of wavenumber. The percentages of bioactive compounds can be inferred from the FT-NIR spectrum by correlating the characteristic absorption peaks at specific wavenumbers with the functional groups associated with known bioactive constituents. This spectral interpretation enables qualitative and quantitative assessment of bioactive composition. The results from the analysis indicate that the drying methods significantly affected all biochemical compositions determined. The present study point out that the variations among the drying method evaluated for the caffeine content of green coffee beans. The caffeine content of the evaluated Arabica coffee shows that higher caffeine content in solar kiln drying compared to open sun drying. Also effect drying methods showed significant variations in the CGA content of green coffee beans. Solar drying method retains more trigonelline content compared to sun drying.

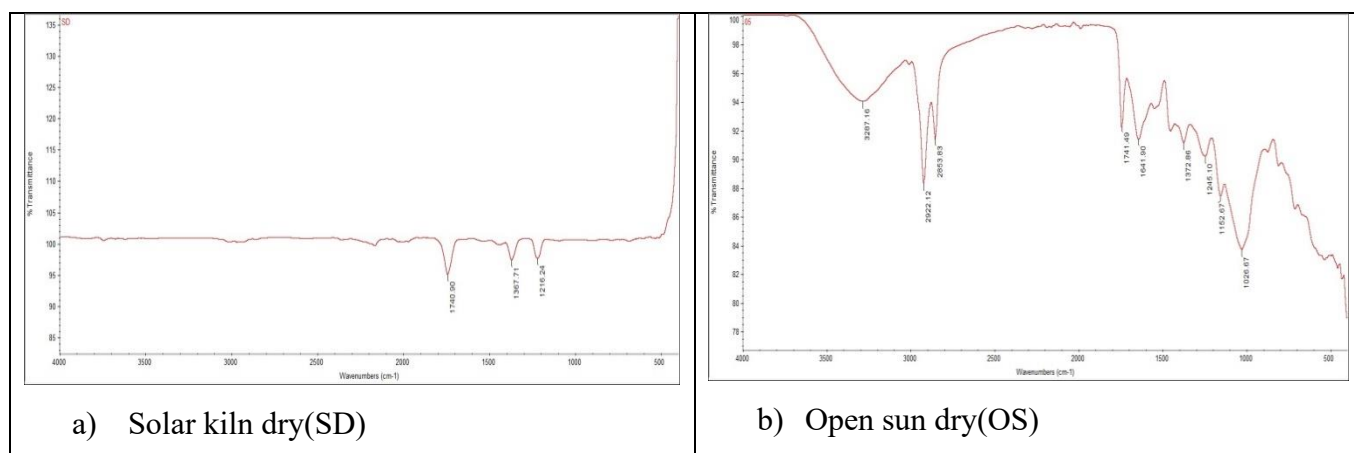


Figure 4.10 FT-NIR results display transmittance as a function of wavenumber

In general, greater mean values of caffeine, CGA, trigonelline and sucrose content of green coffee beans were predictable from solar kiln dryer. Therefore, from the current study, we can conclude that the effect of drying methods on the biochemical compositions of green coffee beans is highly influenced.

4.3. Assessment and Comparison of Physical Property of Green Coffee Bean

Determining the physical properties of green coffee beans is a crucial aspect of evaluating their quality, processing potential, and market value. Properties such as moisture content, size, density, color, weight, and hardness are measured using specific tools and techniques to ensure consistency and optimal performance during roasting and brewing.

Green coffee beans reached a stable, constant weight after 28 hours of drying in a solar kiln, whereas the open sun drying method required 48 hours to achieve the same result. Moisture content was determined using the oven drying method by drying the sample at 105°C for 16 hours, followed by measuring the initial and final mass to calculate moisture loss.

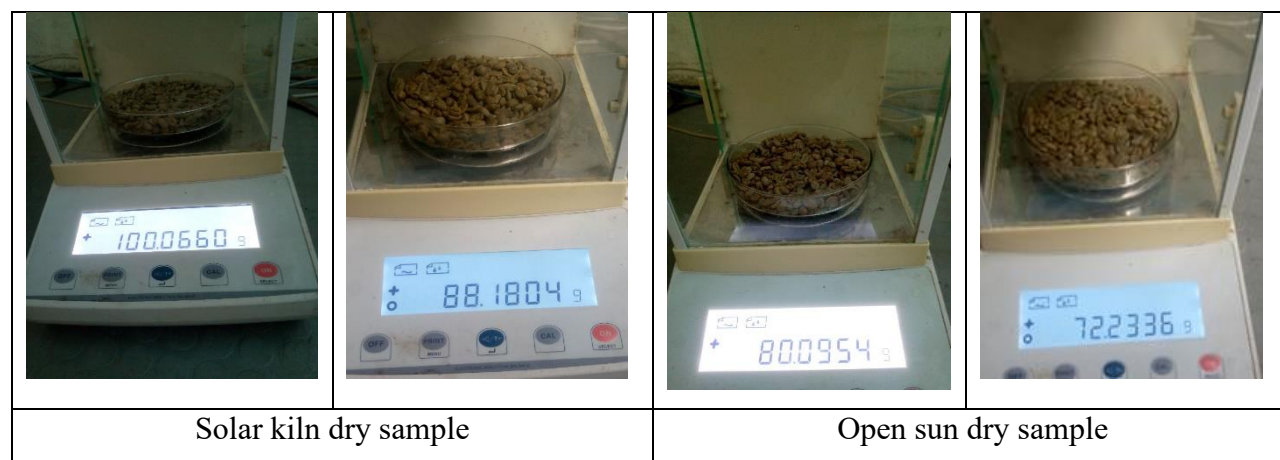


Figure 4.11 mass of sample before and after oven dried

The percent moisture content of the coffee bean sample was calculated using Equation(3.10).

No	Sample	Initial mass(g)	Final mass(g)	Moisture content(%)
1	SD1	120.06	106.05	11.668
2	SD2	100.06	88.18	11.873
3	SD3	80.00	70.56	11.8

4	OS1	120.06	108.3	9.795
5	OS2	100.04	90.2	9.81
6	OS3	80.08	72.23	9.8

Table 4.4 moisture content percentage of sample

The moisture content of green coffee beans was reduced from an initial value of 62% (wet basis) to 11.7% using a solar kiln dryer, and to 9.8 % through open sun drying, indicating effective moisture reduction by both methods with varying final levels. Compared to traditional open sun drying, solar kiln drying is more effective at maintaining ideal moisture content in coffee beans. Open sun drying often leads to over-drying, which can degrade bean quality.

Bean density

Bean density is a critical physical property used to assess the quality of green coffee beans, as it reflects growing conditions, drying method, bean structure, and potential flavor development.

The density of green coffee beans is evaluated using a combination of methods that assess both bulk density (mass including air gaps) and true density (mass of the solid bean material). Bulk density was determined using the volume displacement method, where a fixed-volume cylinder was filled with green coffee beans, and the mass per unit volume was calculated (Eq...3.11).

$$\text{Bulk density(solar kiln)} = \frac{100g}{130cm^3} = \frac{0.769g}{cm^3}$$

$$\text{Bulk density(open sun)} = \frac{100g}{138cm^3} = 0.72464g/cm^3$$

A comparison of bulk density reveals that open sun drying requires 5.8 quantals more per 100 quantals of product than solar kiln drying for the same weight. This indicates a significant difference in volume efficiency between the two methods, with solar drying demonstrating superior space utilization during transporting and storage.

The true density of green coffee beans was determined using the liquid displacement method, in which the beans were placed in a graduated cylinder and the volume of liquid displaced was measured and calculated using (Eq..3.12).

$$\text{True density(solar kiln)} = \frac{100g}{85cm^3} = 1.176g/cm^3$$

$$\text{True density(open sun)} = \frac{100g}{87cm^3} = 1.15g/cm^3$$

This indicates significant variation of internal structure relevant for roasting. Solar kiln dry sample were compacted internal structure suitable for better roasting and grinding.

Porosity measures the proportion of void (empty) spaces within a bulk material. For green coffee beans, it indicates how much of the total volume is made up of air spaces between and within the beans. This affects drying, roasting, and packaging behavior.

Porosity was calculated using Eq.....3.13

$$\text{porosity(open sun)} = \frac{1.15 - 0.72464}{1.15} * 100 = 36.98\% \sim 37\%$$

$$\text{porosity(solar kiln)} = \frac{1.176 - 0.769}{1.176} * 100 = 34\%$$

The presence of microscopic air pockets(porosity) within the bean's cellular structure plays a crucial role in determining coffee quality, shelf life, and behavior during storage and transportation. Green bean dried by solar kiln attain desired lesser percentage value of porosity.

Color comparison

The color of green coffee beans provides valuable insights into their freshness, processing method, storage conditions, and potential cup quality. High-quality green beans are typically a consistent green color, maybe with some bluish or greyish tones. Color measurement of green coffee beans was performed using a colorimeter, which objectively quantifies color attributes based on reflectance values, typically following standardized color scales. The bean color is an essential visual determinant of both freshness and quality of processing, and correct drying practices are a significant element in this case. It was demonstrated through comparative research that solar kiln drying has improved color retention when compared to traditional drying techniques. The improved color retention is due to the controlled drying conditions of the system, which ensures that the optimum temperature and airflow are sustained throughout the drying process. The uniform thermal control obtained in solar kiln drying prevents discoloration and uneven drying that is often linked with open sun drying. As a result, the

method better preserves natural pigments of the beans and yields a final product that is not just aesthetically appealing but also meets quality standards set for specialty coffee markets.



Figure 4.12 color comparison dried sample solar kiln dry(left) and open sun dry(right)

The drying process had a major impact on the toughness of green coffee beans. Significant variations in textural qualities between open-sun-dried and solar-dried beans are found when comparing their hardness characteristics; these variations are directly related to the drying processes used. Dried beans showed a greater average breaking force than beans that were sun-dried, indicating improved mechanical stress resistance and structural integrity. This may result in a more consistent roast profile and better handling throughout processing.

The fracture patterns of solar-dried and open sun-dried coffee bean exhibit extensive differences in structural strength and maintenance of quality. Solar dried samples will typically possess more uniform and regular fractures, attributed to the temperature and airflow conditions moderated in solar drying system that allows the progressive movement of moisture. The structural defects result from uncontrolled environmental conditions like daytime temperature fluctuations, direct UV exposure, and unsteady air flow that creates uneven moisture gradients and leads to differential, quick Shrinkage. Better fracture characteristics of solar-dried products result in improved quality. parameters: enhanced

visual appeal for sale ability, enhanced rehydration ability through preservation porosity, and mechanical strength at the time of handling and storage.

The physical surface outlook of open sun-dried and solar-dried bean is quite different that greatly affect their quality and marketability. Solar-dried foods generally have a more a uniform and aesthetically pleasing surface quality, characterized by even color retention, low browning, and reduced surface defects. This enhanced visual quality is due to controlled drying environment, which maintains the optimum temperature (45-60°C) and ventilation, thereby preventing unwanted excessive thermal conditions and oxidative degradation. Controlled parameters also restrict case hardening to generate smoother skin with fewer wrinkles and cracks. Direct sun exposure and changing environmental factors causes photo-oxidation, leading to faded or darkened patches, especially in products with high pigment concentrations. Also, the absence of protection from and control of airflow dust and insects cause surface contamination and physical deterioration, further smudging the products aesthetic value.

These facts warrant the technical advantages of solar drying systems over traditional open-air methods, specifically value-added green coffee beans, where structural integrity is directly related in terms of commercial feasibility and consumer acceptance. The results indicate that controlled solar drying not only optimizes drying efficiency but also considerably improves the end-product's physical attributes due to better microstructural preservation. As opposed to conventional open sun drying, solar kiln drying has significant advantages in maintaining the visual and physical quality of the product retains more of the bean's natural color and yields a smoother, more even texture. Controlled drying through the process minimizes exposure to environmental impurities and uneven drying procedures, resulting in improved overall product quality.

4.4. Economic Analysis

Economic analysis often takes payback duration, drying cost, and fixed cost into account. Fixed costs are expenses in economics that are independent of the quantity of goods produced. The cost of all parts, such as the fan, insulation, drying chamber with trays, solar air heater, and manufacturing cost, is known as the fixed cost (FC). Construction costs and component prices for the solar kiln dryer are shown in Table 4.3.

S.No	Materials	Specification	cost
------	-----------	---------------	------

1.	Glass cover	0.75m*1.5m	1600
2.	Galvanized iron sheet	1m*2m	1800
3.	Fan(round base)	10W	1000
4.	Square steel and angle iron	8m, 2m	2200
5.	Paint (black)	1 unit	400
6.	Thermocouple wire	2.5m	750
7.	Black polyethylene sheet	1m*3m	1200
8.	Wire mesh	4(0.6m*1m)	500
9.	Wood (plywood)	-	560
10	Manufacturing cost	-	3500
	Sub total		13,510 ETB

Table 4.5 Capital cost of the solar kiln dryer

The annual cost of the dryer ($C_{a,d}$) can be calculated as (Tadele, 2020):

$$C_{a,d} = C_{ac} + C_m - SV_a + C_{ec} \quad 4.1$$

Where, C_{ac} is annual capital cost

C_m is maintenance cost

SV_a is annual salvage value

C_{ec} is annual electricity cost for running the fan.

Let the maximum working month per year is equal to 4 and the maximum service life of the dryer is eight (8) years, working hour per day equals to seven hours and interest rate per year is 10%. Cost and benefit per year must be calculated in order to perform cost analysis of the dryer (Arvind & Shyam, n.d.).

1) Annual capital cost and salvage value

The annual capital cost and salvage value are calculated using;

$$C_{ac} = C_{ccd} * CRF \quad 4.2...$$

And,

$$SV_a = SV * SFF \text{_____} 4.3...$$

Where C_{ccd} – capital cost system and CRF – capital recovery factor

Sv is salvage value and SFF is sinking fund factor

The capital recovery factor and the sinking fund factor are given by equation below;

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \text{_____} 4.4..$$

And,

$$SFF = \frac{i}{(1+i)^n - 1} \text{_____} 4.5...$$

Where, i is the interest rate assumed to be 10 % and n is the life period assumed to be 8 years.

2) Annual cost of electricity consumed by fan

$$C_{ec} = P_{fan} * t_T * C_{uec} \text{_____} 4.6.$$

Where, P_{fan} is the power consumed by the fan, t_T is the number of hours the fan run each year and C_{uec} the unit charge for electricity.

The cost of drying per kilogram of dried product (C_d) is then calculated by equation

$$C_d = \frac{C_{ad}}{m_y} \text{_____} 4.7.$$

The mass of the annually dried product in the solar dryer was calculated by;

$$m_y = \frac{m_{p,b} * n_{d,y}}{n_{d,b}} \text{_____} 4.8...$$

Where, $m_{p,b}$ - mass of the product dried per batch.

$n_{d,y}$ - number of days of operation of the dryer per year and

$n_{d,b}$ - number of days of operation of the dryer per batch.

The payback period (PP) is the time required for retrieving the money invested in the solar dryer considering the time value of money. The Payback time for the solar kiln dryer is evaluated by using the Equation (Mani, 2021).

$$pp = \frac{\ln \left[1 - \left(\frac{C_{c,d}}{S_j} (i-d) \right) \right]}{\ln \left(\frac{1+d}{1+i} \right)} \quad 4.9$$

Equations (4.1) through (4.9) are used to do the economic analysis, which is then displayed in Tables 4.5 and 4.6. Ethiopian electricity costs 5.2 ETB/kWh, while the dryer's capital cost is 13,510 ETB. The dryer's use results in an annual savings of 8481 ETB, with a 1.76-year payback period.

No.	Specifics	Symbol	Cost (ETB)
1	Capital cost	$C_{C,d}$	13,4510
2	Annual capital cost	C_{ac}	2,532
3	Salvage value	SV	1,351
4	Annual salvage value	SV_a	118
5	Maintenance cost	C_m	253
6	Annual electric cost	C_{ec}	98
7	Annual cost of the system	$C_{fp,d}$	2765
8	Saving per Kg	S_{ky}	95
9	Saving per batch	S_b	283
10	Annual Saving	S_j	8481
11	Payback period(years)	pp	1.76 years

Table 4.6 annualized cost solar kiln dryer

A solar kiln drying for wet washed coffee bean is an effective and sustainable way to reduce post-harvest losses and improve product quality, according to the feasibility study. From a technical perspective, the system works effectively by using solar energy to dry green bean instead of electricity or fossil fuels, making it suitable for off-grid and rural areas. Economically, even though it is rather pricey initially, the long-term advantages such as less spoilage, increased dried product market value, and possible government subsidies make the investment worthwhile with a two-year payback period. The solar kiln reduces carbon emissions and encourages environmentally responsible crop preservation.

Conclusion and Recommendation

2.7. Conclusion

A careful comparative analysis of solar kiln drying and conventional open sun drying shows significant differences between them in their impact on quality of green coffee beans, biochemical composition, and efficiency of processing. Solar kiln technique offers precisely controlled drying conditions that ensure optimal temperature and airflow, thereby allowing for better retention of critical physical characteristics such as bean texture, color uniformity, and structural cohesion. The controlled environment greatly minimizes physical defects like shrinkage, cracking, and case hardening. Conversely, sun drying of beans subjects the beans to ambient environmental conditions, which cause non-uniform drying rates, potential contamination by dust and insects, and high over-drying rates from extended exposure to solar radiation.

Biochemically, solar kiln drying depicts superior preservation of thermolabile nutrients and bioactive compounds through regulated thermal conditions that minimize oxidative stress. The enclosed system protects against UV degradation and microbial growth. On the contrary open sun drying, however, subjects' beans to extended ultraviolet light and uncontrolled microbial activity, leading to quicker nutrient loss, degradation of flavor compounds, and potential production of mycotoxins. The inherent differences indicate the benefits of solar kiln drying in yielding more stable and better-quality coffee beans with improved shelf stability and market value over traditional sun drying.

Comparative performance analysis demonstrates that solar kiln drying systems provide a substantial enhancement of processing efficiency, allowing for a 42% time saving compared to traditional open sun drying techniques. This technological benefit provides a more homogeneous removal of moisture from the product mass, while lowering the incidence of spoilage by a considerable amount. The closed system design sustains ideal drying conditions, improving temporal efficiency along with product preservation quality results. Although solar kilns require an initial investment in construction and maintenance, their long-term benefits such as improved product quality, reduced waste, and energy sustainability justify the cost. Open sun drying, while cost-effective and simple, remains a less reliable method, particularly for high-value or perishable goods.

2.8. Recommendations

To maximize drying efficiency and coffee bean quality, solar kilns should be prioritized where nutrient retention and appearance are crucial. Governments and agricultural organizations can promote adoption through subsidies, training programs, and low-cost kiln designs tailored to local conditions. For regions where open sun drying is still prevalent, simple improvements such as using raised drying racks, protective covers, and better airflow management can help reduce contamination and improve outcomes.

Further research should focus on optimizing solar kiln designs for different climates, integrating hybrid energy systems for continuous operation, and developing smart monitoring technologies to enhance performance. Additionally, representatives should establish quality standards for dried green bean to encourage the shift toward more efficient drying methods. While solar kilns represent the more advanced and reliable solution, a gradual transition combined with improved open sun drying techniques can help farmers balance economic constraints with the demand for higher-quality dried green coffee bean. Ultimately, investing in solar kiln technology can significantly reduce post-harvest losses, enhance marketability, and support sustainable agricultural practices.

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APPENDIXES

1.8. Appendix A: Calibration of the Thermocouple Thermometer

A thermocouple operates based on the thermoelectric principle known as the Seebeck effect, which forms the foundation of its temperature measurement capability. This device consists of two dissimilar metal wires joined together at both ends to create a complete electrical circuit. When one junction (the measuring junction) is exposed to heat while the other (the reference junction) remains at a known temperature, the temperature difference between these two points generates a small voltage. This millivolt-level electrical signal is directly proportional to the temperature differential and can be precisely measured to determine the temperature at the hot junction. Thermocouples essential to be calibrated to ensure the correct temperature and can be calibrated with a reference thermometer, where a temperature calibration test is performed by comparing the readings of the reference thermometer and the other thermometer. In this study, two single channel thermocouple was used due to absence of multi-channel thermocouple K-type, and waver thermometer was used for calibration. Calibration of thermometers can be carried out using a reference thermometer in a temperature calibration test by comparing both measurement values of a reference thermometer and other thermometers. Calibration test was conducted with standard laboratory thermocouples (WL362 model) by using 0.25L water boiling test for 20 minutes in 2-minute gap.



Figure A.1 Calibration of single thermocouple with laboratory standard thermopile

Time	T ₁ (standard)(°C)	T ₂ (1-channel)(°C)	Uncertainty
	26.6	27	-0.01504
1	30.4	30	0.013158
3	37.2	37	0.005376
5	41.7	42	-0.00719
7	50.9	51	-0.00196
9	59.8	60	-0.00334
11	67.3	67	0.004458
13	73.4	73	0.00545
15	76.5	77	-0.00654
17	80.9	81	-0.00124
19	86.6	87	-0.00462
Average uncertainty			-0.001044

Table A- 1: Water temperature measuring test.

1.9. Appendix-B: properties of air at atmospheric pressure

T (K)	P (kg/m ³)	C_p (kJ/kg K)	μ (kg/m-s) $\times 10^{-5}$	ν (m ² /s) $\times 10^{-6}$	K (W/m ² K) $\times 10^{-3}$	α (m ² /s) $\times 10^{-5}$	Pr
100	3.6010	1.0259	0.6924	1.923	9.239	0.2501	0.770
150	2.3675	1.0092	1.0283	4.343	13.726	0.5745	0.753
200	1.7684	1.0054	1.3289	7.490	18.074	1.017	0.739
250	1.4128	1.0046	1.488	9.49	22.26	1.3161	0.722
300	1.1774	1.0050	1.983	15.68	26.22	2.216	0.708
350	0.9980	1.0083	2.075	20.76	30.00	2.983	0.697
400	0.8826	1.0134	2.286	25.90	33.62	3.760	0.689

Table A2 properties of air at atmospheric pressure

1.10. Appendix-C: Experimental results of temperature during experiments

Time, hour	T _{ambient} (°C)	T _p (°C)	T _{C,out} (°C)	T _{DC,out} (°C)
9:30	26	46	36	28.5
10:30	28	58	45	32.25
11:30	29	64	53	35
12:30	30	69	61	37.75
13:30	31	74	64	39.25
14:30	30	79	68	39.5
15:30	29	78	67	38.5
16:30	28	69	58	35.5
2 nd date				
9:30	26	48	39	29.25
10:30	28	60	48	33
11:30	30	67	56	36.5
12:30	31	73	62	38.75
13:30	31	78	67	40
14:30	31	79	68	40.25
15:30	30	78	66	39
16:30	29	72	59	36.5
3 rd date				
9:30	26	44	37	28.75
10:30	28	57	49	33.25
11:30	30	66	57	36.75
12:30	30	75	64	38.5
13:30	31	78	68	40.25
14:30	31	76	68	40.25
15:30	30	74	65	38.75
16:30	29	71	56	35.75
Last date				

9:30	26	45	38	29
10:30	28	59	51	33.75
11:30	29	67	58	36.25
12:30	30	75	65	38.75
13:30	31	78	70	40.75
14:30	31	76	68	40.25
15:30	30	75	64	38.5
16:30	29	72	55	35.5

Table A.2 Average experimental result of temperature

1.11. Appendix D: moisture removed throughout experiments

Solar time	Day 1		Day 2		Day 3		Day 4	
	MC	Mw(gm)	MC	Mw(gm)	MC	Mw(gm)	MC	Mw(gm)
9	62	3720	30.4	1824	18.9	1134	14.7	882
10	59.4	3564	29.1	1746	18.4	1104	14.2	852
11	55.8	3348	27.4	1644	17.7	1062	13.6	816
12	51	3060	25.2	1512	16.8	1008	12.9	774
13	45.2	2712	22.8	1368	15.8	948	12.3	738
14	39.4	2364	20.7	1242	15.1	906	11.8	708
15	34.3	2058	19.2	1152	14.5	870	11.6	696
16	29.6	1776	18	1080	14	840	11.6	696
Mw removed(gm)		1680		846		348		216

Table A.3 mass moisture removed from sample