MATHEMATICAL MODELING AND PARAMETER ESTIMATION FOR AN OPTIMAL SOLAR FOOD DRYER

By

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A THESIS SUBMITTED TO THE SCHOOL OF SCIENCE AND AEROSPACE STUDIES, DEPARTMENT OF MATHEMATICS, PHYSICS AND COMPUTING IN FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF DOCTOR OF PHILOSOPHY IN APPLIED MATHEMATICS

MOI UNIVERSITY

2025

DECLARATION

Declaration by the Student

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DEDICATION

To my beloved wife, Juliet Jerono Kipsang, whose unwavering love and support have been my anchor throughout this journey. To my cherished children, Adrian Kipngetich Cheruiyot, Malin Cherotich Korkoren, and Eliana Cherop Korkoren, your joyous spirits and endless encouragement inspire me every day. To my dear father, John Kimutai Torongei, and my beloved mother, Ruth Torongei, your guidance and sacrifices have shaped the person I am today. To my siblings, Lily Chepkirui, Beatrice Mutai, Aron Mutai, Willy Korkoren, and Joyce Cherono, your constant belief in me has been a source of strength. This thesis is dedicated to each of you, for your boundless love, understanding, and unwavering belief in my dreams.

ACKNOWLEDGMENT

I would like to extend my deepest gratitude to my supervisors, Dr. Rotich Titus and Prof. Rotich Samwel, whose guidance, expertise, and unwavering support have been invaluable throughout my thesis journey. I am also grateful to Dr. Ramkat Rose, Dean of the School of Science and Aerospace Studies and Prof. Mathew Kosgei, Associate Dean, for their encouragement and administrative support. Grateful acknowledgment to Prof. Nyamwala Fredrick, Chair of the Mathematics Department, for his guidance and leadership, Physics and Computing, Prof. Kiprop Ambrose, former Dean of the School and Amb. (Prof) Emmy Kipsoi for their mentorship and insights.

Heartfelt appreciation goes to my wife, whose love, patience, and understanding sustained me through this endeavor, and to my dear parents for their endless encouragement and prayers. I am indebted to my colleagues Nicholas Sang, Dr. Koech Wesley, Dr. Kweyu Cleophas, and Faith Kosgei for their camaraderie and intellectual exchanges. I fondly remember the late Dr. Mumo Nyamai for his impactful contributions.

I also extend my gratitude to my brothers, the late Edwin Mutai, Aron Mutai, and Willy Korgoren, and my sisters Lily Chepkirui, Beatrice Mutai, and Joyce Cherono, whose support and belief in me have been unwavering. To my friends and family, especially Japhet Mutai and Andrew Chepkwony, your encouragement kept me motivated. Lastly, I thank my church members at AGC Cheptenye for their prayers and spiritual support. This thesis would not have been possible without each of you, and I am truly grateful for your presence in my life.

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ABSTRACT

Food shortage in most countries is not only associated with unfavorable weather conditions, but also significantly blamed on ineffective post-harvest handling of food. This calls for an urgent need to address food insecurity in Kenya, in line with Vision 2030 and Government Big 4 Agenda. Eminent threat caused by post-harvest losses due to inadequate drying and poor storage is responsible for up to 40-60% loses of agricultural produce each season. In order to address this issue, this project seeks to model and simulate the characteristics of a solar dryer for the purpose of designing an effective and sustainable, low-cost thermal solar dryer suitable for dehydrating a variety of agricultural produce to ensure prolonged shelf life hence reduce losses. The proposed model is to be formulated using mathematical equations describing integration of four divisions, namely; solar heat collector, circulation of fluid in insulated closed loop pipe network, heat exchangers to generate heated air supplied to the drying chamber and dryer, equipped with humidity control systems, temperature, mass flow rate and energy balance. The mathematical model was formulated and simulation done in order to realize the objectives of delivering a solar drier suitable for drying a wide variety of food products. The simulation results showed that, a solar panel of it was found that a solar collector with aperture area of $A_c = 14.4m^2$ and volume of $V_c = 500l$, when exposed to solar irradiation of $I_c = 1.367KW/m^2$ at $\eta_c = 80\%$ efficiency is able to heat water from $T_{in} = 22^0C$ to $T_{co} = 70^0C$ in 12 hours at a flow rate of $\dot{v}_c = 1.128l/s$, and cumulatively to130^0C in 6 days. This energy if transmitted by insulated pipes to a set of 5 heat exchangers each of $A = 1m^2$, and radiative heat transfer coefficient $h_r = 100W/m^2K$ cumulatively dissipates hot air of 230^0C at $\dot{v} = 250cm^3/s$, 130^0C at $\dot{v} = 1000cm^3/s$ and 90^0C at $\dot{v} = 2000cm^3/s$ air mass flow rate. This output temperatures of dry air are regulated as desired according to the specifications of the food products to be dried. During the night or on cloudy day with minimum or no solar insolation, alternative supplementary source of heat is obtained from petroleum cooking gas, which is regulated automatically depending on the level of solar insolation. It is found that the optimal cost of the gas is $Ksh\ 180/day$ as opposed to $Ksh\ 560/day$ when used alone. This is over 67.86% reduction in cost, which makes the use of solar an ideal green energy.

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LIST OF SYMBOLS AND ACRONYMS

Symbol	Description
T_{c0}	Output temperature of the collector (^0C)
T_{ci}	Input temperature of the collector (^0C)
T_{ca}	Ambient temperature of the collector ($K\ or\ ^0C$)
T_{av}	Average temperature of the fluid ($K\ or^0C$)
c_p	Specific heat capacity of the product and $\overline{c_p}$ the average density
ρ	Density of the water (Kg/m^3), with $\bar{\rho}$ being the average density
$h_{air,roof}$	Convective Air - Roof heat transfer coefficient (W/m^2K)
$h_{air,wall}$	Convective Air - Wall heat transfer coefficient (W/m^2K)
$h_{air,wind}$	Convective Air - Window heat transfer coefficient(W/m^2K)
$A_{s,wind}$	Area of each window (m^2)
$A_{s,roof}$	Area of the roof (m^2)
$A_{s,wall}$	Area of the walls (m^2)
c_{fuel}	Cost of gas fuel per litre (Ksh)
ρ_{roof}	Density of the roof (kg/m^3)
ρ_{wall}	Density of the wall (Kg/m^3)
ρ_{wind}	Density of the window (Kg/m^3)
wid	Width of the dryer (m)
ht	Height of the dryer chamber (m)
ht	Height of the window (m)
le	Length of the dryer (m)
No	Number of windows in the dryer
ε_{roof}	Percentage of heat leakage through the roof

ε_{wall}	Percentage of heat leakage through the wall
ε_{wind}	Percentage of heat leakage through the window
θ	Pitch of the roof in radians ($\pi\ rads$)
h_r	Radiative (radiator) heat transfer coefficient (W/m^2K)
$h_{air,roof}$	Convective roof - Atmosphere heat transfer coefficient (W/m^2K)
L_{roof}	Roofing material thickness (m)
$c_{p,air}$	Specific heat capacity of air
$c_{p,wind}$	Specific heat capacity of the window material (J/kgK)
$c_{p,roof}$	Specific heat capacity of the roofing material (J/kgK)
$c_{p,wall}$	Specific heat capacity of the wall material (J/kgK)
$A_{s,radi}$	Surface area of the radiator (m^2)
k_{roof}	Thermal conductivity of the roof (W/mK)
k_{wall}	Thermal conductivity of the wall (W/mK)
k_{wind}	Thermal conductivity of the window
$h_{air,wall}$	Convective wall - Atmosphere heat transfer coefficient
L_{wall}	Wall thickness
L_{wind}	Window thickness
wid	Width of the window
$h_{air,wind}$	Convective window - Atmospheric heat transfer coefficient
Q_{cond}	Conductive heat transfer rate (heat loss) (W)
Q_{conv}	Convective heat transfer (heat loss) rate (W)
U	Overall (total) heat transfer coefficient (W)
h_{conv}	Convective heat transfer rate (W)
T_p	Temperature of the pipe (K)

T_∞	External environmental temperature (K)
Q_{loss}	Total heat loss due to radiation, convection and conduction (W)
R_{tot}	Total thermal resistance of a material (K/W)
R_{conv}	Convective thermal resistance (K/W)
R_{cond}	Conductive thermal resistance (K/W)
R_{rad}	Radiative thermal resistance of a material (K/W)
r_o, r_i	Outer and inner radius of a pipe (m)
ε	Radiative thermal emissivity coefficient
σ	Stefan – Boltzmann constant $5.6697 \times 10^{-8}\ W/m^2K^4$
$T_m(x)$	Temperature profile along the x-axis of the pipe/material (K)
l	Longitudinal length of the pipe (m)
q_{in}	Thermal flux per unit area, with $\dot{q}$ as the rate of heat generation per unit area
$\dot{m}$	Mass flow rate of material (air or water)
D	Diffusivity of material
n	Shape factor of food particle, with $n = 0$ rectangular or disc shaped, $n = 1$ cylindrical and $n = 2$ spherical shaped food particle.

CHAPTER ONE

INTRODUCTION

1.0 Background of the Study

The background of food and food conservation is rooted in the essential role that food plays in sustaining human life and the need to preserve and manage food resources effectively. Throughout history, human societies have developed various methods and practices to ensure to promote food system stability and reliability, alongside efforts to reduce waste and deterioration. The early agricultural practices of cultivating crops and domesticating animals marked a significant turning point in human history, allowing for a more reliable and consistent food source. Over time, advancements in farming techniques, irrigation systems, and the selective breeding of livestock further improved food production and availability. As human populations grew, so did the need to efficiently store and preserve food. Early civilizations developed strategies such as drying, salting, and fermenting to extend the shelf life of perishable foods. These preservation techniques not only helped prevent food waste but also allowed communities to sustain themselves through periods of scarcity or harsh environmental conditions.

Food conservation refers to the methods and techniques used to preserve food and prevent it from spoiling. There are several traditional and modern methods of food conservation, including refrigeration, freezing, canning, drying, pickling, and fermenting. Refrigeration and freezing are common methods used to slow down the growth of bacteria and spoilage organisms in perishable foods. Canning involves sealing food in airtight containers and heating it to destroy microorganisms, while drying removes moisture from food to inhibit the growth of bacteria and mold. Pickling and fermenting use acidic environments to preserve food, while also enhancing flavor.

Each method of food conservation has its own advantages and is suitable for different types of food. Effective food preservation methods minimize waste and keep food safe and enjoyable to eat for extended periods.

Today, food preservation has become a highly advanced discipline that blends principles from biology, chemistry, engineering, and environmental science. Cutting-edge methods like vacuum sealing, modified atmosphere packaging (MAP), and high-pressure processing (HPP) have transformed the way we store food. These innovations not only prolong shelf life but also help retain nutritional value and ensure safety. For instance, MAP modifies the surrounding gas environment to inhibit microbial activity, while HPP applies intense pressure to destroy harmful pathogens without using heat, thereby maintaining the food's taste and nutrients.

The significance of food conservation is heightened by pressing global issues like climate change, population growth, and dwindling resources. As the world's population expands, the demand for food intensifies, straining agricultural systems and supply chains. Climate change further complicates matters by disrupting traditional farming patterns, resulting in erratic harvests and a greater threat of food insecurity. In this scenario, robust food preservation strategies become vital—not only to curb waste but also to promote fair access to nourishment.

Moreover, food conservation is a cornerstone of economic progress. In many developing nations, a large share of food waste stems from post-harvest losses. Strategic investments in infrastructure—such as refrigerated storage, efficient transportation, and farmer education—can significantly enhance food preservation. These improvements boost food availability, help stabilize market prices, and strengthen livelihoods across communities.

Culturally, food conservation has deep roots in tradition and community practices. Indigenous methods such as sun-drying, smoking, and fermenting have been passed down through generations and remain relevant today. These practices reflect local knowledge and adaptation to environmental conditions, highlighting the importance of preserving cultural heritage alongside technological advancement.

Consumer behavior plays a crucial role in advancing food sustainability and encouraging eco-friendly practices and conservation efforts. Public awareness campaigns, education on effective storage practices, and programs aimed at minimizing household food waste are all essential components. Everyday habits—like meal planning, interpreting expiration labels correctly, and composting—can collectively drive meaningful change.

Ultimately, food and its preservation are fundamental to human health, survival, and well-being. The evolution of food conservation—from ancient techniques to modern technological breakthroughs—showcases humanity's creativity and adaptability. As we confront emerging global challenges, blending time-tested practices with innovative solutions were vital to building resilient and sustainable food systems to serve future generations.

Food conservation idea, rose to prominence during periods marked by war, economic instability, and food scarcity. In response, governments and organizations introduced rationing systems, advocated for home gardening and food preservation, and urged citizens to reduce waste. These initiatives advanced equitable food access while fostering a collective commitment to sustainable consumption. A notable example is the "Victory Gardens" movement during World War II, which inspired individuals to grow their own produce, easing the burden on public food supplies and encouraging self-sufficiency. Canning and storing excess harvests became widespread household practices, helping communities endure times of limited resources.

In the modern era, conserving food is recognized as a crucial component of both sustainable farming and environmental stewardship. The global food system grapples with issues like excessive production, losses during distribution, and the ecological toll of wasted food. The Food and Agriculture Organization (FAO) estimates that nearly one-third of all food produced—around 1.3 billion tons annually—is either lost or wasted. This alarming statistic highlights a major economic loss while intensifying environmental issues like greenhouse gas emissions, deforestation, and dwindling water resources.

Addressing these challenges demands a comprehensive strategy, including fostering conscious consumption habits, minimizing waste across consumer and retail sectors, and advancing farming techniques that prioritize efficient resource use and biodiversity preservation. Public campaigns like "Love Food, Hate Waste" and "Too Good to Go" have played a crucial role in raising awareness and inspiring more sustainable behaviors among individuals and businesses. Furthermore, both governments and NGOs are channeling resources into critical infrastructure—like enhanced storage facilities and transport systems—to reduce post-harvest losses, especially in developing areas.

In addition, modern technology and innovative strategies have significantly advanced food conservation practices. Enhanced packaging and storage systems, along with cutting-edge preservation methods, are increasingly focused on streamlining food supply chains and minimizing waste while retaining nutritional integrity. For example, smart packaging can track food freshness and notify consumers when items are approaching spoilage. Cold chain logistics maintain ideal temperatures for perishable goods throughout distribution, helping to prevent spoilage and extend shelf life.

Biotechnology also contributes to these efforts. Genetically modified organisms refer to organisms whose DNA has been engineered to express specific traits and engineered to withstand diseases and pests, and extreme nature related conditions, boosting crop productivity and reducing reliance on chemical treatments. Furthermore, breakthroughs in food advanced methods of food processing, including HPP and pulsed electric field technology (PEF) technology—enable effective preservation without sacrificing taste or nutritional value.

Food is the most essential component to sustain the lives of living things, as it is the source of different types of nutrients, which when metabolized, play several roles in the body, including growth and development, protection from infections, energy production, and thermoregulation. Without adequate food intake, the human body cannot perform its basic functions, leading to malnutrition, weakened immunity, and increased susceptibility to disease.

Other benefits are outlined below:

1. Food supplies the essential nutrients our bodies require to operate efficiently and maintain optimal health. Included among these nutrients are carbohydrates, proteins, fats, vitamins, and minerals—each essential to maintaining health, serving a distinct purpose. Carbohydrates and fats act as primary energy sources, proteins aid in tissue repair and muscle development, vitamins help regulate various metabolic functions, and minerals are vital for maintaining strong bones, proper nerve activity, and fluid balance within the body.

2. Energy: Food is the body's primary energy source. The calories it provides power physical activity, support metabolic functions, and sustain vital organ operations. Inadequate energy intake can result in fatigue, diminished productivity, and impaired mental performance.
3. Growth and Progress: Adequate nutrition plays a critical role in healthy growth and progress, particularly over the span of childhood as well as adolescence. Key nutrients contribute to bone formation, muscle growth, and overall physical maturation. A lack of adequate nutrition during these critical stages can lead to stunted growth, developmental delays, and lasting health issues.
4. Health and Well-being: The observation of a balanced diet is important in keeping the overall status of an individual in good health. Good nutrition contributes to the general resilience and therefore lowering the risks associated with health conditions. Dietary benefits abundant in fruits, vegetables, whole grains, and lean proteins reduce the incidences of obesity, diabetes, heart disease, and certain types of cancer.
5. Social and Cultural Importance: Food holds deep social and cultural value, serving as a focal point for gatherings, traditions, and celebrations. Shared meals nurture relationships, reinforce cultural identity, and offer opportunities for passing down knowledge and customs across generations.

In addition to its personal advantages, food security—guaranteeing reliable access to nourishment—is a fundamental human right and a cornerstone of societal resilience. Disruptions to food systems caused by conflict, climate events, or economic hardship can lead to widespread hunger, displacement, and social unrest. As such, food conservation is not merely a personal duty but a shared global responsibility that demands collaborative efforts across communities, governments, and international organizations.

Education and public awareness are fundamental to successful food conservation. Educational institutions, local organizations, and media campaigns are instrumental in raising awareness about minimizing food waste, proper food storage, and embracing sustainable consumption practices. Integrating food literacy into educational programs, for instance, equips young people with the knowledge to make healthier dietary choices and recognize the environmental consequences of their eating behaviors.

Policy measures are equally vital. Governments can promote food conservation through targeted regulations and incentives—such as offering tax benefits to businesses that donate excess food, imposing fines for excessive waste, and funding food recovery initiatives. Globally, collaboration is vital since food security is a universal issue that transcends borders. Initiatives such as the United Nations' Zero Hunger Challenge and the Sustainable Development Goals (SDGs) aim to eliminate hunger and build robust, sustainable food systems across the world.

The private sector holds significant influence in shaping outcomes. Food manufacturers, retailers, and restaurants can implement strategies to reduce waste, including better inventory control, donating unsold products, and designing packaging that extends shelf life. Additionally, advancements in e-commerce and digital platforms are creating new ways to redistribute surplus food to those in need—bridging the gap between waste reduction and food access.

Food conservation is a complex and multidimensional issue that spans historical traditions, cutting-edge technologies, and socio-economic dynamics. It is closely linked to public health, environmental stewardship, and social justice. As global populations rise and ecological pressures mount, the urgency for robust and effective food conservation strategies grows stronger. Adopting a comprehensive approach—one that blends ancestral wisdom, scientific advancements, and collaborative efforts—is essential to creating resilient food systems capable of sustaining both humanity and the environment.

Beyond its role in providing essential nourishment, food carries profound cultural, social, and emotional meaning. It is a cornerstone of human experience, serving as a powerful expression of identity, heritage, and community. Shared meals often mark important life events, religious observances, and family traditions, embodying values of unity, generosity, and belonging. The act of preparing and enjoying food together strengthens social ties and brings comfort, joy, and a deep sense of connection.

Sources of Food

The various sources of food include plants, animals, fungi, and microorganisms. These sources are foundational to human diets and have been utilized for millennia, evolving with cultural practices, technological advancements, and environmental conditions.

1. **Plants**: Fruits, vegetables, grains, legumes, nuts, and seeds are all derived from plants and form the foundation of many diets around the world. They are rich in essential nutrients such as fiber, vitamins, minerals, and antioxidants. Staples like rice, wheat, maize, and potatoes are primary sources of carbohydrates and energy. Leafy greens, berries, and legumes contribute to disease prevention and overall health. Plant-based diets are also increasingly recognized for their environmental sustainability, requiring fewer resources compared to animal-based diets.

2. **Animals**: Meat, poultry, fish, eggs, and dairy products are derived from animals and are important sources of protein, iron, vitamin B12, and essential fatty acids. Animal-based foods have been central to many traditional diets and are often associated with cultural practices and economic livelihoods, especially in pastoral and agricultural communities. Nonetheless, rising concerns over animal welfare, ecological consequences, and potential health issues have sparked increasing interest in plant-based and alternative protein options.

3. **Fungi**: Mushrooms and other fungi are also consumed as food and are a source of various nutrients, including B vitamins, selenium, and antioxidants. Certain edible fungi, such as shiitake and maitake, are valued not only for their culinary appeal but also for their medicinal properties. Fungi contribute significantly to various food processing applications, such as in the production of soy sauce and tempeh.
4. **Microorganisms**: Some microorganisms, such as certain types of yeast and bacteria, are used in food production, such as in the fermentation of bread, cheese, yogurt, kimchi, and kombucha. These microbes enhance flavor, texture, and shelf life while contributing to gut health through probiotics. Fermentation is one of the oldest food preservation techniques and remains vital in both traditional and industrial food systems.

These sources of food provide the nutrients necessary for human health and are used in a wide variety of culinary traditions and food preparation methods. The diversity of food sources ensures dietary variety, cultural richness, and resilience in the face of environmental and economic challenges.

Primary Determinants of Agricultural Output

The successful cultivation of food crops largely depends on soil fertility and optimal climatic conditions, alongside other essential factors. Agriculture operates within a complex framework shaped by environmental, technological, economic, and policy-driven factors. Gaining a comprehensive understanding of these influences is vital for achieving food security and promoting sustainable development.

- Climate: Climate is a fundamental determinant of which crops can thrive in a given region. Variables such as temperature, rainfall, and sunlight directly impact agricultural output. climate change poses significant challenges, such as increased frequency of extreme weather, shifting agricultural seasons, and the proliferation of pests and diseases. To address these risks, adaptive measures like cultivating climate-resilient crops, practicing agroforestry, and enhancing irrigation systems are essential.

- Soil Quality: Soil health and composition are fundamental to achieving optimal crop yields. Elements like pH balance, organic content, and nutrient levels directly affect the soil's capacity to support agriculture. However, degradation from erosion, salinization, and overuse of chemical fertilizers threatens productivity and jeopardizes long-term food security. To safeguard soil vitality, it is essential to adopt sustainable practices such as crop rotation, cover cropping, and the application of organic amendments.

- Water Availability: A reliable water supply is indispensable for both crop irrigation and livestock care. Whether sourced from rainfall or irrigation infrastructure, water availability is a cornerstone of agricultural success.

Increasing water scarcity—driven by climate change and overuse—poses a significant threat to food production and intensifies competition for resources. Solutions like efficient irrigation systems, rainwater harvesting, and integrated water resource management can greatly enhance water efficiency in farming.

Land Resources: The availability of arable land and its suitability for cultivation are fundamental to food production. Land use practices, land degradation, and land tenure systems also influence agricultural output. Urbanization, deforestation, and land grabbing reduce the amount of land available for farming. Ensuring secure land rights, promoting land restoration, and implementing land-use planning are key to preserving agricultural land.

- **Biodiversity**: Agricultural biodiversity, including the variety of crops, livestock, and microorganisms, contributes to ecosystem resilience, pest control, and food diversity. Monoculture farming, habitat destruction, and genetic erosion threaten biodiversity and increase vulnerability to shocks. Conservation of traditional crop varieties, agroecological practices, and seed banks are important for safeguarding biodiversity.

· Technology and Innovation:

The adoption of modern agricultural tools—such as advanced machinery, fertilizers, pesticides, and high-yield crop varieties—can greatly boost food production. Innovative tools such as precision agriculture, remote sensing, and data analytics enable farmers to optimize resource use and make informed decisions. Advances in biotechnology—including genetically modified organisms (GMOs) and gene-editing methods—offer significant potential to boost crop productivity, strengthen pest resistance, and enhance resilience to climate-related challenges. Nonetheless, these advancements must be implemented with careful attention to ethical, environmental, and socio-economic implications.

- **Labor and Human Capital**: The availability of skilled labor and agricultural knowledge influences productivity and innovation. Rural-urban migration, aging farming populations, and lack of education can constrain agricultural development. Investment in agricultural education, extension services, and youth engagement is crucial for building a resilient agricultural workforce.
- **Market Access and Infrastructure**: Efficient transportation, storage, and market infrastructure are essential for connecting producers with consumers and reducing post-harvest losses. Poor infrastructure leads to delays, spoilage, and reduced profitability. Investments in roads, cold chains, and digital platforms can enhance market access and value chain efficiency.

Economic and Policy Environment:

Food production and agricultural practices are significantly shaped by economic policies, subsidies, trade regulations, and investment in research and development. Well-crafted policies that promote sustainable farming, empower smallholder farmers, and uphold fair trade principles can strengthen food security and improve rural livelihoods. Conversely, inadequate or misaligned policies can destabilize markets, promote unsustainable farming methods, and exacerbate socio-economic inequalities.

Sociocultural Determinants

Agricultural practices and food preferences are deeply influenced by cultural traditions, dietary habits, and ancestral wisdom. Indigenous farming systems frequently embody sustainable techniques tailored to local ecosystems. By integrating cultural values into agricultural development, communities are more likely to engage actively, promoting the enduring sustainability of food systems.

International Trade and Global Integration

International trade significantly shapes food distribution, pricing structures, and production patterns. It can enhance food security by broadening access to diverse food sources across regions. However, it also brings challenges, including market volatility and the potential weakening of local food systems. Achieving an equilibrium between open trade policies and the protection of food sovereignty and community resilience remains a pressing concern for policymakers.

Food transcends its role as a basic biological need—it is a foundational element of human society, culture, and overall well-being. The wide array of food sources, including plants, animals, fungi, and microorganisms, showcases both the abundance of nature and the creativity of human innovation. Achieving a secure and sustainable food supply demands a comprehensive grasp of the many interconnected factors that shape food production. By tackling environmental, technological, economic, and social challenges, we can cultivate resilient food systems that sustain communities, safeguard the planet, and preserve the deep cultural and emotional value that food holds in our lives.

Land Resources and Agricultural Productivity

Land is one of the most critical resources in agriculture. The availability of arable land—land suitable for growing crops—is a foundational element of food production. However, not all land is created equal. The fertility, topography, and accessibility of land determine its agricultural potential. Fertile soils rich in organic matter and essential nutrients support higher yields and healthier crops. In contrast, degraded or marginal lands, often affected by erosion, salinization, or nutrient depletion, pose significant challenges to sustainable farming.

Land Use Practices

Land management plays a crucial role in agricultural productivity. Unsustainable methods—such as overgrazing, deforestation, and monoculture farming—can degrade soil quality and diminish yields. In contrast, sustainable practices like crop rotation, agroforestry, and conservation tillage help preserve soil fertility and promote biodiversity. Additionally, land tenure systems significantly influence how land is utilized. When farmers have secure land rights, they are more likely to invest in long-term improvements. Insecure tenure, however, often leads to short-term exploitation and underinvestment, undermining sustainability.

Technology and Agricultural Inputs

Technological advancements have transformed the agricultural landscape, dramatically improving food production. Mechanization—including the use of tractors, harvesters, and modern irrigation systems—has enhanced operational efficiency and reduced reliance on manual labor. By harnessing GPS technology, sensors, and data analytics, precision agriculture empowers farmers to closely track crop health, optimize resource use, and make informed decisions. These advancements boost productivity while minimizing harm to the environment.

Equally vital is access to high-quality agricultural inputs. Improved seed varieties, fertilizers, and pesticides contribute to higher productivity and resilience against pests, diseases, and climate stressors. Fertilizers restore essential nutrients to the soil, while pesticides safeguard crops from infestations. Nonetheless, overuse or misapplication of chemical inputs may lead to ecological damage, pollute water sources, and pose risks to human health. As a result, sustainable alternatives such as integrated pest management (IPM) and organic farming are gaining momentum, offering more eco-friendly approaches to crop protection and soil health.

Market Demand and Economic Forces

Market demand significantly influences what crops are grown, how they are produced, and where they are distributed. Consumer preferences, dietary trends, and purchasing power shape agricultural production patterns. For instance, the rising demand for plant-based foods has led to increased cultivation of legumes and alternative protein sources. Similarly, global demand for cash crops like coffee, cocoa, and palm oil drives monoculture farming in many tropical regions.

International trade also plays a role. Export-oriented agriculture can generate income and foreign exchange, but it may also divert resources away from local food needs. Price volatility in global markets can affect farmers' incomes and investment decisions. To navigate these dynamics, farmers and policymakers must balance domestic food security with economic opportunities from trade.

Government Policies and Institutional Support

Government policies are instrumental in shaping agricultural systems. Subsidies for inputs, price supports, and crop insurance programs can incentivize production and reduce risks for farmers. Investment in agricultural research and extension services promotes innovation and knowledge transfer. Trade regulations, tariffs, and export bans influence market access and competitiveness.

Land reform policies, infrastructure development, and rural credit schemes also impact food production. For example, building rural roads improves market access, while affordable credit enables farmers to invest in equipment and inputs. However, poorly designed policies can lead to inefficiencies, environmental harm, and social inequities. Therefore, evidence-based policymaking and stakeholder engagement are essential for effective governance

Seasonal Variability and Food Availability

Agricultural production is inherently seasonal, influenced by climatic conditions such as rainfall, temperature, and daylight hours. In many regions, especially those dependent on rain-fed agriculture, food production peaks during harvest seasons and declines during dry or lean periods. This seasonal variability affects food availability, prices, and nutrition.

During periods of abundance, markets may be flooded with produce, leading to lower prices and potential waste. Conversely, during lean seasons, food scarcity can drive up prices and increase the risk of hunger and malnutrition. Seasonal hunger is a persistent challenge in many developing countries, particularly among smallholder farmers who rely on their harvests for both income and sustenance.

Regional Disparities and Food Distribution

The productivity of land is not uniform across regions. Some areas benefit from fertile soils, favorable climates, and access to technology, resulting in surplus production. Others face constraints such as poor soils, water scarcity, and limited infrastructure, leading to food deficits. These disparities contribute to unequal food distribution and exacerbate regional food insecurity.

Addressing food distribution imbalances requires the creation of systems that facilitate the smooth and efficient movement of surplus food to regions facing scarcity. Achieving this requires reliable data on production and consumption trends, well-integrated markets, and robust transportation networks. Essential logistical components such as transportation networks, storage facilities, and cold chain systems play a vital role in reducing post-harvest losses and ensuring timely delivery of food to its intended destinations.

Food Conservation and Storage Infrastructure

Robust food preservation infrastructure is essential for maintaining the integrity and safety of food across the supply chain. Structures like silos, storage warehouses, and refrigeration systems help preserve freshness during transit and buffer against seasonal variability.

Without adequate storage, food is vulnerable to spoilage, contamination, and financial loss.

Traditional storage methods, such as granaries and root cellars, are still used in many rural areas. However, modern technologies offer improved efficiency and control. For example, hermetic storage bags prevent pest infestation and moisture ingress, while solar-powered cold rooms provide off-grid refrigeration for perishable goods. Investing in such infrastructure enhances food security and reduces reliance on emergency food aid.

Transportation and Market Access

Efficient transportation systems are critical for connecting producers with consumers. Poor road conditions, lack of vehicles, and high fuel costs can hinder the movement of food, especially in remote areas. This not only limits market access for farmers but also contributes to food spoilage and price volatility.

Developing rural transport infrastructure, such as feeder roads and bridges, improves mobility and reduces transaction costs. Additionally, digital platforms and mobile technologies can link farmers to buyers, provide market information, and facilitate e-commerce. These innovations empower smallholders, increase transparency, and promote inclusive growth.

Balancing Supply and Demand

To balance regions with surplus and deficit food production, coordinated efforts are needed across the supply chain. Food banks, cooperatives, and aggregation centers can collect surplus produce and redistribute it to areas in need. Public-private partnerships and community-based initiatives can enhance efficiency and accountability.

Regional Trade and Policy Support

Policies that encourage regional trade and eliminate barriers to food distribution are vital for enhancing food security across borders. Aligning regulatory standards, simplifying customs procedures, and investing in cross-border infrastructure can significantly improve the movement of food within regions. Entities like the East African Community (EAC) and the African Continental Free Trade Area (AfCFTA) are instrumental in promoting intra-regional trade and encouraging cooperative initiatives aimed at enhancing the resilience and efficiency of food systems.

Climate Resilience and Future Outlook

As climate change intensifies, the need to build resilient food systems becomes increasingly critical. Agricultural output faces mounting risks from droughts, floods, and extreme weather that destabilize supply chains. Climate-smart agriculture (CSA) offers a proactive strategy by integrating methods that bolster resilience, lower greenhouse gas emissions, and boost yields—charting a sustainable course amid growing environmental challenges.

Climate-smart agriculture (CSA) involves a range of practices including growing drought-tolerant crop varieties, utilizing efficient irrigation technologies, encouraging agroforestry, and embracing conservation-based farming methods. These methods contribute to improved ecosystem services, lower greenhouse gas emissions, and enhanced livelihoods. Expanding CSA on a larger scale requires strategic investments in research, capacity development, and supportive policy frameworks.

A complex interplay of environmental conditions, technological advancements, economic forces, and institutional frameworks shapes the processes of food production and distribution. Factors like land availability, access to technology, market dynamics, and regulatory policies collectively influence agricultural productivity and the accessibility of food. Seasonal fluctuations and geographic disparities add further complexity, underscoring the importance of resilient systems for food conservation, storage, and transportation.

Tackling these challenges demands a comprehensive strategy that integrates infrastructure development, policy innovation, technological advancement, and active community participation. Fostering collaboration across sectors and regions paves the way for a more inclusive, efficient, and environmentally sustainable food system—one that upholds food security for all communities.

Understanding Food Spoilage

Food spoilage is a natural and unavoidable process that leads to the decline in food quality, rendering it unfits for consumption. Gaining insight into the underlying causes of spoilage is crucial for crafting effective preservation methods, minimizing waste, and maintaining food safety. As previously noted, spoilage can result from a range of factors, including microbial and enzymatic activity, oxidation, moisture fluctuations, temperature extremes, and physical damage.

Microbial Activity

Microorganisms such as bacteria, yeast, and molds are among the most common culprits of food spoilage. These organisms thrive in environments where nutrients, moisture, and favorable temperatures are present. Once they colonize food, they begin to break down its organic matter, leading to undesirable changes in taste, texture, appearance, and odor. For example, *Pseudomonas* species are known to cause spoilage in meat and dairy products, while molds like *Aspergillus* and *Penicillium* can grow on bread and fruits, producing visible colonies and sometimes harmful mycotoxins (Tapia, Alzamora, & Chirife, 2020).

Enzyme Activity

Enzymes are biological catalysts naturally present in food. After harvest or slaughter, these enzymes can remain active and initiate biochemical reactions that alter the food’s properties. Enzymatic browning is a process in which polyphenol oxidase enzymes interact with oxygen, causing fruits such as apples and bananas to develop a brown coloration. Although this reaction is not necessarily harmful, it can diminish the visual attractiveness and perceived freshness of the food, potentially impacting consumer preferences (Rawat, 2015).

Oxidation

Oxidation is another significant factor in food spoilage, particularly in foods high in fats and oils. When exposed to oxygen, these fats undergo chemical changes that result in rancidity, off-flavors, and nutrient loss. Oxidation is accelerated by exposure to light, heat, and metal ions. For example, nuts and cooking oils are especially prone to oxidative spoilage if not stored in airtight, light-resistant containers (Tapia et al., 2020).

Moisture

Moisture content plays a dual role in food systems: it improves the flavor and mouthfeel of various food items, enhancing their sensory appeal. On the other hand, it provides favorable conditions for microbial growth, which can accelerate spoilage—particularly in moisture-rich items like fruits, vegetables, and meats. In dry goods such as cereals and powdered milk, excess moisture can lead to undesirable physical changes like clumping or sogginess. Therefore, managing moisture through methods such as drying, dehydration, or the application of desiccants is essential for effective food preservation (Rawat, 2015).

Temperature

It plays a key role in influencing how quickly food deteriorates.

Would you like to continue expanding this idea into a full paragraph on food preservation?

Most spoilage microorganisms grow rapidly at temperatures between 5°C and 60°C, commonly referred to as the "danger zone." Refrigeration slows down microbial activity, while freezing can halt it altogether. However, improper temperature control—such as frequent thawing and refreezing—can compromise food safety and quality. Conversely, some foods are sensitive to freezing and may suffer texture and flavor degradation if stored at too low temperatures (Veld, 1996).

Physical Damage and Its Impact on Food Spoilage

Physical harm to food items—such as bruising, cuts, or punctures—can weaken their natural protective layers, exposing inner tissues to microbial contamination. Fruits and vegetables are especially susceptible, as damaged skin provides an entry point for microorganisms, accelerating the spoilage process. To preserve freshness and extend shelf life, careful handling, appropriate packaging, and efficient transportation are essential.

Moisture's Role in Food Decay

As previously discussed, food spoilage is primarily the result of decay, a process largely driven by microbial and biochemical activity. Moisture is a key factor in this deterioration. All food items contain some degree of moisture, which is vital for maintaining their texture, flavor, and overall quality. For example, fresh produce like fruits and vegetables can consist of up to 90% water, contributing to their crispness and juiciness—but also making them more prone to spoilage if not properly managed. Yet, the presence of moisture also creates favorable conditions for spoilage organisms to flourish. A key factor in this process is water activity (aw), which measures the ratio of the vapor pressure of water in a food item to that of pure water. This metric indicates how prone a product is to microbial contamination. While most bacteria thrive at aw levels above 0.91, molds and yeasts can survive at lower thresholds. Lowering the moisture content effectively reduces water activity, thereby curbing microbial growth and prolonging shelf life (Veld, 1996).

Drying as a Preservation Technique

Drying is among the oldest and most reliable methods of preserving food. It works by reducing moisture content to levels that inhibit the growth of spoilage-causing organisms. Ancient societies relied on sun drying to preserve items like fruits, vegetables, fish, and meat. Today, advanced techniques such as air drying, freeze drying, spray drying, and vacuum drying are tailored to different food types and quality requirements.

Beyond extending shelf life, drying also decreases the weight and volume of food, making it more convenient to store and transport. For instance, dried grains and legumes can be kept for extended periods without refrigeration. Dried fruits and vegetables retain much of their nutritional value and can be rehydrated for culinary use. In addition, drying is a fundamental step in food processing, facilitating the production of flours, powdered ingredients, and convenient ready-to-eat products.

Food Security and Spoilage Reduction

Addressing food spoilage is vital for strengthening food security. In many developing regions, particularly sub-Saharan Africa, post-harvest losses represent a substantial share of total food waste. According to the FAO, up to 40% of food produced in the region is lost before reaching consumers, largely due to insufficient storage, poor handling practices, and inadequate preservation infrastructure.

Improving preservation techniques can yield significant benefits. It enhances food availability, helps stabilize market prices, and improves nutritional outcomes by maintaining food quality and safety. Furthermore, minimizing food spoilage lessens the environmental footprint of agriculture by reducing the demand for additional inputs needed to replace wasted produce. Innovations in Food Preservation

Modern science and technology have introduced a range of innovative preservation techniques that go beyond traditional methods. These include:

- **Modified Atmosphere Packaging (MAP)**: This technique alters the composition of gases within food packaging to slow down microbial growth and oxidation.
- **High-Pressure Processing (HPP):** is a non-thermal technique that employs intense pressure to eliminate pathogens and spoilage microbes, all while preserving the food's original flavor and nutritional value.
- **Edible Coatings:** Delicate layers of consumable substances applied to fruits and vegetables to minimize moisture evaporation and inhibit microbial growth.
- **Smart Packaging**: Packaging materials embedded with sensors that monitor temperature, humidity, and freshness indicators.

These technologies are particularly valuable in global supply chains, where food must travel long distances and remain fresh for extended periods.

Consumer Responsibility in Reducing Food Spoilage

Consumers play a crucial role in minimizing food spoilage and waste. By practicing proper food handling and storage techniques, and understanding expiration labels, households can significantly cut down on discarded food. For example, understanding the difference between "best before" and "use by" dates can prevent unnecessary food waste by identifying items that remain safe for consumption beyond their peak quality. Simple practices such as storing perishables at appropriate temperatures, using airtight containers, and following the first-in-first-out (FIFO) method for rotating food items are highly effective.

Promoting Awareness and Sustainable Habits

Educational initiatives and community outreach programs are instrumental in promoting food preservation and waste reduction. Teaching individuals how to store food correctly, repurpose leftovers creatively, and compost organic waste encourages more responsible and sustainable consumption patterns.

Sustainability and the Future of Food Preservation

From ancient preservation methods to contemporary sustainability initiatives, the quest to ensure a reliable, equitable, and sustainable food supply remains an integral part of human development and progress. As the global population approaches 10 billion by 2050, the pressure on food systems were intensify. Climate change, resource scarcity, and urbanization further complicate food production and distribution.

In this context, food preservation is not just a technical challenge but a moral and environmental imperative. Reducing spoilage helps conserve water, energy, and land, while lowering greenhouse gas emissions associated with food waste. It also supports resilience by ensuring that food remains available during emergencies, supply chain disruptions, and seasonal shortages.

Investing in research, infrastructure, and education is essential for advancing food preservation. Collaboration among governments, industry, academia, and civil society can drive innovation and scale up successful practices. Policies that support cold chain development, subsidize preservation technologies, and incentivize waste reduction can create enabling environments for change.

Food spoilage is a complex phenomenon driven by biological, chemical, and physical interactions. Although moisture is vital for maintaining food quality, it also accelerates the process of decay. By gaining insight into spoilage mechanisms and applying effective preservation techniques—particularly drying—communities can substantially reduce food waste, strengthen food security, and support sustainable practices. The progression from ancient sun drying methods to advanced smart packaging technologies illustrates humanity's ongoing dedication to sustaining nourishment while protecting the Earth's resources.

1.1 Evolution of Food Drying Technologies

Food drying and dehydration are age-old methods of food preservation that have been practiced for centuries to extend the shelf life of perishable foods. These techniques involve removing the moisture content from food items, thereby inhibiting the growth of microorganisms and preventing spoilage. The development of food drying technologies has evolved over centuries, with early techniques involving sun drying, air drying, and smoking to preserve food. These traditional methods were simple, cost-effective, and relied heavily on natural environmental conditions.

However, as societies advanced and the demand for safe, long-lasting, and high-quality food increased, modern food drying technologies emerged. These innovations incorporate scientific principles, automation, and precision engineering to enhance drying efficiency, reduce energy consumption, and maintain the nutritional and sensory qualities of food.

Traditional Drying Methods

1. Sun Drying:

Sun drying, one of the most ancient food preservation methods, entails placing food under direct sunlight for prolonged durations to remove moisture. While it works well in dry, sunny climates, the process is slow, reliant on weather conditions, and vulnerable to contamination from dust, insects, and animals.

2. Air Drying:

Building on the principles of sun drying, air drying uses either natural airflow or mechanical ventilation to extract moisture from food. Commonly applied to herbs, fruits, and vegetables, this method offers more control but still depends on environmental conditions and may lead to inconsistent drying results.

3. Smoking: Smoking combines drying with the antimicrobial effects of smoke. It is traditionally used for meats and fish, imparting a distinctive flavor while preserving the product.

Modern Drying Technologies

1. Solar Drying:

An advancement of traditional sun drying, solar drying utilizes solar dryers to remove moisture from food in a more controlled and hygienic setting. These dryers shield food from dust, insects, and animals while enabling quicker and more consistent dehydration. Available in various forms—from basic cabinet models to more complex tunnel and greenhouse designs—solar dryers are especially beneficial in rural or off-grid communities, offering an eco-friendly and affordable preservation method for smallholder farmers.

2. Hot Air Drying:

Also referred to as convective drying, this technique employs heated air to draw moisture out of food products. Contemporary hot air dryers feature precise controls for temperature and humidity, ensuring uniform drying and reducing nutrient degradation. This method is commonly used in the commercial processing of dried fruits, vegetables, and herbs.

3. Freeze Drying (Lyophilization):

Freeze drying is an advanced preservation method that involves freezing food and then lowering the surrounding pressure to allow ice to transition directly into vapor through sublimation. This process maintains the food's original texture, taste, and nutritional value to a remarkable degree. The resulting products are lightweight, have an extended shelf life, and can be easily rehydrated, making them ideal for applications such as space travel, military provisions, and emergency food storage.

4. Microwave Drying: Microwave drying uses electromagnetic waves to heat and evaporate moisture from food. It offers rapid drying times and energy efficiency, making it suitable for heat-sensitive products. This method is often combined with vacuum technology to further enhance drying performance and product quality.

5. Vacuum Drying: Vacuum drying involves removing moisture from food under reduced atmospheric pressure, which lowers the boiling point of water and enables drying at gentler temperatures. This is beneficial for preserving heat-sensitive nutrients and flavors. Vacuum drying is commonly used for pharmaceuticals, fruit powders, and specialty food products.

6. Infrared Drying: This technique utilizes infrared radiation to heat the surface of food, prompting the evaporation of moisture. It is known for its rapid drying speed and energy efficiency, especially when applied to thin-layered items. Infrared drying is frequently integrated with other drying methods to enhance overall effectiveness.

7. Osmotic Dehydration: This technique involves immersing food in a hypertonic solution (usually sugar or salt) to draw out moisture through osmosis. It is a gentle method that helps retain color, flavor, and nutrients. Osmotic dehydration is commonly employed as a preliminary step to enhance the efficiency of subsequent drying techniques.

Benefits of Modern Drying Technologies

The advancements in food drying technologies have brought numerous benefits to both producers and consumers:

- Extended Shelf Life: Lowering the moisture content in foods inhibits microbial growth, making dried products more resistant to spoilage and suitable for extended storage without the need for refrigeration.
- Nutrient Retention: Modern drying methods, especially freeze drying and vacuum drying, preserve vitamins, minerals, and bioactive compounds better than traditional methods.
- Convenience and Portability: Because dried foods are light and space-efficient, they are particularly well-suited for transport, storage, and deployment in remote areas or emergency scenarios.
- Reduced Food Waste: Drying surplus produce during harvest seasons helps prevent post-harvest losses and ensures food availability during off-seasons.
- Economic Opportunities: Small-scale drying enterprises can add value to agricultural products, create jobs, and enhance rural livelihoods.

Applications of Dried Foods

Dried foods are used in a wide range of applications across the food industry:

- Snack Foods: Dried fruits, vegetable chips, and jerky are popular healthy snacks.
- Ingredients: Dried herbs, spices, and powders are essential in culinary preparations.
- Convenience Foods: Instant soups, noodles, and ready-to-eat meals often contain dehydrated components.

- Emergency and Military Rations: Lightweight and long-lasting dried foods are crucial for disaster relief and military operations.
- Space Missions: NASA and other space agencies rely on freeze-dried foods for astronauts due to their low weight and high nutritional value.

Challenges and Considerations

Despite their advantages, food drying technologies face several challenges:

- Energy Consumption: Some drying methods, such as freeze drying and hot air drying, require significant energy inputs. Developing energy-efficient systems is essential for sustainability.

- Initial Investment: Advanced drying equipment can be costly, limiting access for small-scale producers.

- Quality Control: Over-drying or uneven drying can lead to texture degradation, nutrient loss, and reduced consumer acceptance.

- Food Safety: Inadequate drying or poor hygiene during processing can result in microbial contamination and spoilage.

To address these challenges, researchers and engineers are exploring hybrid drying systems that combine multiple techniques to optimize efficiency and product quality. For example, combining microwave and vacuum drying can reduce drying time while preserving sensitive nutrients.

Sustainability and the Future of Food Drying

With a rising global population and the escalating impacts of climate change on food security, the need for sustainable preservation techniques has never been more critical. Food drying technologies significantly contribute to sustainability in multiple ways:

- Reducing Food Waste: By preserving surplus produce, drying helps reduce the amount of food lost post-harvest.
- Lowering Carbon Footprint: Dried foods require less energy for storage and transportation compared to refrigerated or frozen products.
- Empowering Communities: Solar dryers and low-cost drying technologies can empower rural communities to preserve food, improve nutrition, and generate income.

Future developments in food drying are likely to focus on:

- Smart Drying Systems: The integration of sensors, automation, and artificial intelligence enables real-time monitoring and precise control of drying parameters, enhancing efficiency and product quality.
- Renewable Energy Integration: Expanding the use of solar, wind, and biomass energy in drying systems to reduce reliance on fossil fuels.
- Nutrient Optimization: Developing methods that maximize the retention of vitamins, antioxidants, and other bioactive compounds.
- Customized Drying Solutions: Tailoring drying technologies to specific crops, climates, and cultural practices to enhance adoption and effectiveness.

The development of food drying technologies represents a remarkable journey from ancient practices to cutting-edge innovations. From sun-dried tomatoes in Mediterranean villages to freeze-dried strawberries in space missions, drying has proven to be a versatile and indispensable method of food preservation. As global challenges like food insecurity, climate change, and limited resources intensify, prioritizing the development of efficient, inclusive, and sustainable drying technologies becomes essential for strengthening food system resilience.

By integrating time-honored practices with cutting-edge scientific advancements, we can safeguard the availability, safety, and nutritional quality of food—no matter the season, geography, or situation. Whether through a solar dryer in a rural Kenyan village or a high-tech freeze dryer in a global food processing plant, the future of food drying is bright, and its role in feeding the world is more vital than ever.

Heat-Based Dehydration: Versatility and Precision

Heat-Based Dehydration:

Applying controlled heat to food is one of the most prevalent methods of preservation worldwide. This process removes moisture through evaporation, effectively curbing microbial growth and enzymatic reactions that cause spoilage. Its adaptability makes it suitable for a wide range of foods, accommodating different textures and desired outcomes.

Oven Drying:

A popular technique in home kitchens, oven drying utilizes standard ovens to dehydrate items like fruits, vegetables, herbs, and meats. Although it may not match the energy efficiency of dedicated dehydrators, it remains a convenient and user-friendly option.

By maintaining low temperatures (typically between 50°C and 70°C) over extended periods, individuals can achieve reliable results for small-scale drying needs.

Electric Food Dehydrators are purpose-built appliances designed to dry food efficiently. They feature multiple trays, adjustable temperature settings, and built-in fans to ensure uniform airflow. These devices are ideal for home use and small-scale commercial operations, offering consistent results and preserving the nutritional integrity of food.

Solar Drying with Solar Dehydrators modernizes traditional sun drying by enclosing food in a controlled environment that harnesses solar energy. Solar dehydrators protect food from contaminants, regulate airflow, and accelerate drying times. They are especially valuable in rural and off-grid communities, providing a sustainable and low-cost solution for preserving seasonal harvests.

Heat-based dehydration is suitable for a wide range of foods, including:

- Fruits: Apples, bananas, mangoes, and berries retain their sweetness and become chewy or crisp depending on the drying method.

- Vegetables: Tomatoes, carrots, and bell peppers can be dried for soups, stews, and snacks.

- Meats: Beef jerky and dried fish are popular protein-rich snacks with long shelf lives.

- Herbs: Basil, mint, oregano, and thyme maintain their flavor and aroma when dried properly.

Freeze-Drying: Advanced Preservation for Maximum Quality

Freeze-Drying (Lyophilization): This sophisticated drying technique begins by freezing the food, then reduces the surrounding pressure to allow the frozen water content to sublimate—transforming directly from ice to vapor without passing through a liquid phase. By bypassing the liquid phase, freeze-drying helps maintain the food's structural integrity and nutritional value.

The process unfolds in three primary stages:

1. Freezing: The food is quickly brought to low temperatures to maintain its cellular integrity and prevent structural damage.

2. Primary Drying (Sublimation): In a vacuum environment, the frozen water content in the food undergoes sublimation—shifting directly from solid ice to vapor—effectively eliminating the majority of moisture.

3. Secondary Drying (Desorption): Remaining bound moisture is extracted by gradually increasing the temperature, ensuring the final product reaches optimal dryness and stability.

Freeze-dried foods excel at preserving their original shape, texture, taste, and nutritional value. Their lightweight nature, extended shelf life, and rapid rehydration make them especially suitable for:

- Emergency Supplies: With their long-lasting stability and minimal preparation needs, freeze-dried foods are a vital component of survival kits and disaster response provisions.

- Backpacking and Camping: Lightweight and compact, these foods are perfect for outdoor adventures.

- Space Travel: NASA and other space agencies rely on freeze-dried meals for astronauts due to their efficiency and quality.

- Medical and Specialty Diets: Freeze-dried foods are used in hospitals and for individuals with dietary restrictions due to their purity and ease of digestion.

Structural Changes in Food During Drying

Food particles are composed of a porous skeletal matrix filled with moisture. During drying, this moisture is removed, leaving behind a dry matter with a reduced water activity level. The structural integrity of the food is influenced by the drying method, temperature, and duration.

- Porosity: As moisture evaporates, voids form within the food matrix, increasing porosity. This affects texture and rehydration capacity.

- Shrinkage: Some foods shrink during drying due to the collapse of cellular structures, which can alter appearance and mouthfeel.

- Color Changes: Heat can cause browning or fading, depending on the food type and drying conditions.

- Flavor Concentration: Removing water intensifies the natural flavors, making dried foods more robust and aromatic.

Grasping these transformations is essential for fine-tuning drying conditions and maintaining high product standards. Modern drying technologies are designed to reduce unwanted outcomes while amplifying beneficial qualities.

Advantages of Food Drying and Dehydration

Food drying offers a wide array of benefits that go far beyond simple preservation:

1. Prolonged Shelf Life: By significantly lowering moisture levels, dried foods become less susceptible to microbial contamination and can be safely stored for extended periods without the need for refrigeration.

2. Flavor Enhancement: Concentrated flavors make dried foods ideal for culinary applications, from baking to seasoning.

3. Nutritional Retention: Modern drying methods preserve vitamins, minerals, and antioxidants, maintaining the health benefits of fresh produce.

4. Space Efficiency: Dried foods occupy less space, making them convenient for storage and transport.

5. Weight Reduction: Lightweight products reduce shipping costs and are easier to handle.

6. Waste Reduction: Drying surplus produce prevents spoilage and contributes to food waste mitigation.

7. Economic Value Addition: Farmers and producers can increase income by processing and selling dried products.

8. Convenience: Ready-to-use dried ingredients simplify meal preparation and reduce cooking time.

Contribution to Food Security and Environmental Sustainability

Drying and dehydration techniques are essential contributors to global food security and environmental sustainability. By preserving food during peak harvest seasons, these techniques ensure year-round availability and reduce dependence on imports.

They also support climate resilience by mitigating the impact of crop failures and supply chain disruptions.

In developing countries, drying technologies empower smallholder farmers to preserve their harvests, reduce losses, and access new markets. Solar dryers, in particular, offer an affordable and eco-friendly solution for communities with limited infrastructure.

From an environmental perspective, drying reduces the need for refrigeration and freezing, lowering energy consumption and greenhouse gas emissions. It also minimizes packaging waste, as dried foods often require less protective material.

Challenges and Innovations

Despite their advantages, food drying and dehydration face several challenges:

- Energy Consumption: Some methods, like freeze-drying, are energy-intensive and costly.
- Initial Investment: Advanced equipment may be inaccessible to small-scale producers.
- Quality Control: Over-drying or uneven drying can compromise texture and taste.
- Food Safety: Inadequate drying or poor hygiene can lead to contamination.

To address these issues, researchers and engineers are developing innovative solutions:

- Hybrid Drying Systems: Combining methods (e.g., microwave and vacuum drying) to optimize efficiency and quality.

- Intelligent Drying Systems:

Modern drying systems incorporate smart sensors and automated control mechanisms, allowing continuous monitoring and fine-tuned adjustments during the entire drying cycle.

- Sustainable Energy Use: An increasing number of drying technologies harness renewable energy sources like solar, wind, and biomass, fostering greater energy efficiency and supporting environmentally responsible practices.

- Community-Based Models: Shared drying facilities and cooperatives to support small producers.

Food drying and dehydration are time-tested preservation methods that have evolved into sophisticated technologies capable of meeting modern demands. From heat-based dehydration using ovens and electric dehydrators to advanced freeze-drying systems, these techniques offer unparalleled benefits in terms of shelf life, flavor, nutrition, and sustainability. As the pressures of climate change, rising populations, and dwindling resources grow more severe, the need for effective and widely accessible food preservation methods becomes ever more urgent. Food drying plays a pivotal role—not just in supporting households and enterprises, but in advancing global objectives like food security, sustainable development, and environmental care.

By fostering innovation in drying technologies and valuing time-tested traditions, we can create robust food systems that sustain communities, minimize waste, and safeguard the planet for future generations.

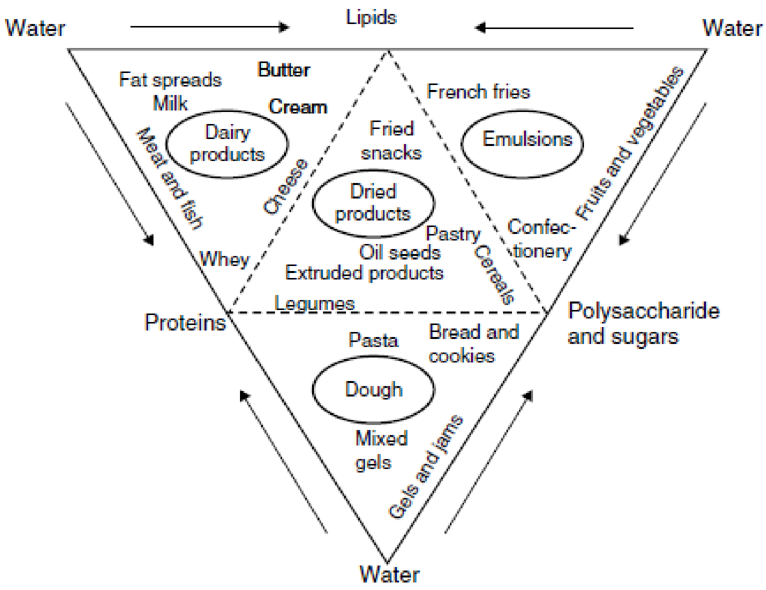

Figure 1-1 Typical food products and their Water content. Source: (Ramadan & Al-Ameri, 2022).

1.2 Moisture and Microbes: A Critical Relationship in Food Safety

The moisture content of food plays a pivotal role in determining its shelf life, safety, and quality. Microorganisms—including bacteria, yeast, and mold—require water to carry out essential metabolic processes such as nutrient transport, enzymatic activity, and reproduction. High moisture content in food creates favorable conditions for microbial growth, potentially resulting in spoilage, undesirable flavors, compromised texture, and the formation of harmful toxins. Therefore, gaining insight into and managing moisture levels is fundamental to ensuring food safety and effective preservation.

1.2.1 Water Activity vs. Moisture Content

Moisture content indicates the overall quantity of water within a food item, but it is the water activity (aw) that more precisely determines the potential for microbial growth. Water activity is defined as the ratio of the vapor pressure of water in a food to the vapor pressure of pure water at the same temperature. It ranges from 0 (completely dry) to 1.0 (pure water). Bacterial growth generally occurs when water activity exceeds 0.91, whereas molds and yeasts can thrive at lower thresholds—typically above 0.80 and 0.60, respectively.

For example:

- Fresh meat and dairy products have a water activity close to 0.99, making them highly perishable.

- Dried fruits and cereals typically exhibit water activity levels ranging from 0.60 to 0.80. This range effectively suppresses bacterial growth, though certain molds and yeasts may still thrive.

- Powdered milk and dried pasta possess water activity below 0.60, rendering them highly shelf-stable and suitable for long-term storage.

Microbial Growth and Food Spoilage

Understanding water activity is essential for predicting and controlling microbial activity, which directly impacts food safety and longevity.

Microbial spoilage manifests in various ways depending on the type of microorganism and the food matrix:

- Bacteria such as Salmonella, Listeria monocytogenes, and Escherichia coli can cause foodborne illnesses and thrive in moist, protein-rich environments like meat, poultry, and dairy.

- Yeasts are responsible for fermentation and spoilage in sugary and acidic foods like fruit juices and jams.

- Molds can grow on bread, cheese, and fruits, producing visible colonies and, in some cases, mycotoxins that pose serious health risks.

The presence of moisture accelerates these processes, making moisture control essential for both food safety and quality.

1.2.2 Preservation Techniques to Control Moisture

To mitigate the risks associated with high moisture content, various preservation methods are employed to reduce or control water activity:

1.2.2.1 Drying and Dehydration:

These preservation techniques work by physically extracting moisture from food, thereby reducing water activity to levels that suppress microbial development. Common approaches include sun drying, hot air drying, freeze-drying, and vacuum drying. Although these processes may affect the food’s texture and visual appeal, they greatly enhance shelf life and minimize spoilage risks.

1.2.2.2 Canning:

Involves sealing food in airtight containers and heating them to destroy microorganisms. The sealed environment prevents recontamination, and the heat treatment ensures microbial inactivation.

1.2.2.3 Freezing:

Although freezing does not reduce moisture content, it immobilizes water in the form of ice, making it unavailable for microbial metabolism. Freezing also slows down enzymatic reactions and microbial growth, preserving food for months.

1.2.2.4 Osmotic Dehydration:

This technique uses high concentrations of sugar or salt to draw water out of food through osmosis. It is commonly used for fruits, vegetables, and meats and can be combined with other drying methods for enhanced preservation.

1.2.2.5 Modified Atmosphere Packaging (MAP):

By altering the composition of gases within a food package—typically reducing oxygen and increasing carbon dioxide—MAP slows microbial growth and oxidation, especially in high-moisture foods.

1.2.2.6 Vacuum Packaging:

By extracting air from the packaging, this method limits the presence of oxygen—an essential element for the survival of aerobic microorganisms. It is commonly employed to preserve meats, cheeses, and various dried food.

1.2.3 Monitoring and Measuring Moisture

Accurate measurement of moisture content and water activity is essential for quality control in food processing. Common techniques include:

- Gravimetric Methods: Involve drying a food sample and measuring the weight loss to determine moisture content.
- Karl Fischer Titration: A chemical method used for precise moisture analysis, especially in low-moisture foods.
- Water Activity Meters: Instruments that measure the equilibrium relative humidity of a food sample to determine its water activity.

These measurements help food manufacturers ensure that products meet safety standards, maintain quality, and comply with regulatory requirements.

1.2.4 Regulatory Standards and Guidelines

Food safety authorities around the world recognize the importance of moisture control in preventing microbial contamination. Regulatory bodies such as the U.S. Food and Drug Administration (FDA), the European Food Safety Authority (EFSA), and the Codex Alimentarius Commission provide guidelines on acceptable water activity levels for various food products.

For example:

- Dried foods should have a water activity below 0.60 to prevent microbial growth.
- Intermediate-moisture foods (e.g., dried fruits) should be monitored for mold and yeast activity.
- Ready-to-eat products must be stored under conditions that prevent the growth of Listeria monocytogenes, which can thrive at refrigeration temperatures if moisture is not adequately controlled.

1.2.5 Moisture and Food Packaging

Packaging plays a crucial role in maintaining the desired moisture content of food. Moisture-barrier materials such as polyethylene, polypropylene, and aluminum foil are used to prevent moisture ingress or loss. In addition, desiccants (e.g., silica gel) may be included in packaging to absorb excess moisture and maintain product stability.

Innovations in smart packaging now allow for real-time monitoring of moisture levels within packages. These systems use sensors and indicators that change color or send alerts when moisture exceeds safe thresholds, enabling timely intervention and reducing waste.

1.2.6 Moisture Control in Supply Chains

Effective moisture control is essential not only within food processing facilities but throughout the entire supply chain—from initial production to final consumption. During transport and storage, shifts in temperature and humidity can cause condensation, foster mold development and increasing the risk of spoilage.

1.2.7 Cold Chain and Packaging Innovations

Modern food distribution relies heavily on cold chain logistics, temperature-controlled storage, and moisture-resistant packaging to maintain product quality and safety. Improving these systems by training personnel in correct handling practices and implementing advanced monitoring technologies can greatly minimize spoilage and reduce food waste.

1.2.8 Role of Research and Innovation

Continued advancements in food science are uncovering novel strategies to manage moisture and suppress microbial activity. One such innovation is:

- Edible Coatings: These are thin films made from natural polymers that are applied to fruits and vegetables to minimize moisture loss and protect against microbial contamination.

- Nanotechnology: Development of nano-encapsulated antimicrobials and moisture sensors for enhanced preservation.

- Bio preservation: Use of beneficial microorganisms and natural antimicrobials (e.g., bacteriocins, essential oils) to inhibit spoilage organisms without altering moisture content.

These advancements aim to improve the safety and shelf life of food items, reduce dependence on synthetic preservatives, and minimize their ecological footprint.

Moisture and microbial activity are closely intertwined when it comes to food safety and preservation. Elevated moisture levels create favorable conditions for microbial growth, which can result in spoilage, shortened shelf life, and health concerns. By mastering the principles of water activity and applying robust moisture management techniques, both producers and consumers can effectively mitigate contamination risks and minimize food waste.

Preservation methods such as drying, dehydration, canning, and freezing are essential tools in managing moisture levels and ensuring food safety. Moreover, innovations in packaging, monitoring, and bio preservation offer promising solutions for the future.

Ultimately, managing moisture transcends mere technical accuracy—it underpins the integrity and sustainability of the entire food ecosystem. By placing emphasis on effective moisture management, we can safeguard public health, minimize food loss, and uphold the availability of safe, nourishing food for everyone.

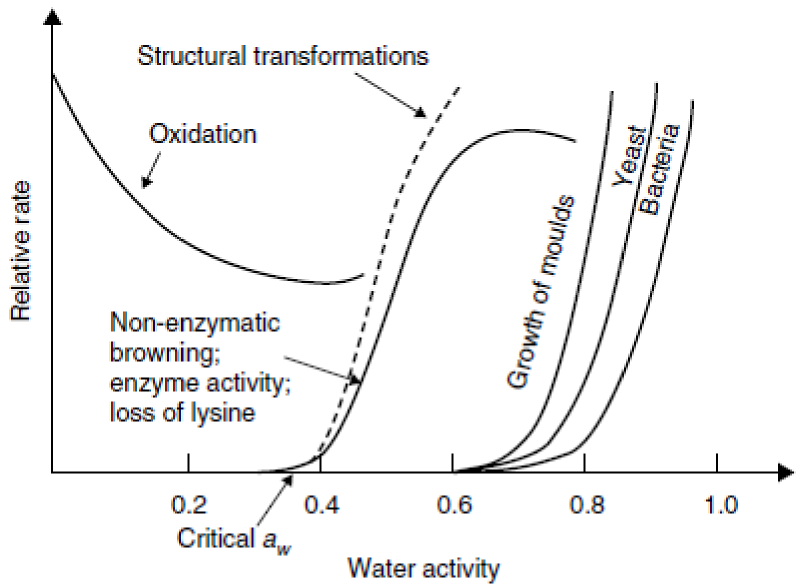

Figure 1-2 Water Activity in relation to enzymatic reactions and microbial growth. Source: (Li, 1998)

Here, water activity refers to the quantification of water available for interaction for microbial growth, chemical and enzymatic reactions. It is usually expressed as a percentage, between 0 and 1, so that a value of unity indicates that 100% of water is available for microbial growth, and a value of zero indicates that none of the water is available for such interactions. This means that the measure of water activity is an important parameter in determining the shelf life of food.

1.3 Microbes and Healthy Food: Balancing Risks and Benefits

Microorganisms, commonly known as microbes, are found everywhere in our surroundings and play a complex role in food systems. While certain microbes are beneficial—contributing to food production and supporting human health—others can compromise food safety and pose public health risks. A thorough understanding of how microbes interact with food, especially in relation to water activity and environmental factors, is essential for preserving food quality, safety, and nutritional integrity.

1.3.1 Water Activity: A Key Driver of Microbial Growth

Water activity (aw) measures the level of free, unbound water in a food product that microorganisms can utilize for growth and reproduction. It plays a pivotal role in determining the shelf life, safety, and stability of food items.

Unlike total moisture content, which accounts for both bound and unbound water, water activity specifically measures the fraction that microbes can exploit for their metabolic functions. It is quantified on a scale from 0 (completely dry) to 1.0 (pure water).

Microorganisms have specific water activity thresholds for growth:

- Most bacteria require aw > 0.91
- Most yeasts grow at aw > 0.88
- Molds can grow at aw > 0.80
- Xerophilic molds and osmophilic yeasts can grow at aw as low as 0.60

By reducing water activity through drying, salting, or adding sugar, food manufacturers can inhibit microbial growth and extend shelf life. For example, dried fruits, salted meats, and jams have low water activity levels that prevent spoilage despite their high nutrient content.

1.3.2 Microbial Hazards in Food

While many microbes are harmless or even beneficial, certain species can cause foodborne illnesses or produce harmful toxins. Among the most concerning are:

- Pathogenic Bacteria: Certain species—including Salmonella, Listeria monocytogenes, Escherichia coli O157:H7, and Clostridium botulinum—are capable of causing serious illness and even fatal outcomes. These bacteria thrive in moist, nutrient-rich environments and are often found in undercooked meats, unpasteurized dairy, and contaminated produce.

- Fungi and Mycotoxins: Certain fungal species, notably *Aspergillus flavus* and *Aspergillus parasiticus*, produce aflatoxins—potent carcinogenic toxins that frequently contaminate agricultural commodities like maize, peanuts, and various tree nuts.

Because aflatoxins are resistant to heat and can survive food processing, rigorous prevention and monitoring measures are essential (Ramadan & Al-Ameri, 2022).

- Viruses: Norovirus and Hepatitis A: Viral Threats in Food Safety. Norovirus and Hepatitis A are prevalent foodborne viruses typically spread via contaminated water or food that has been handled by infected individuals. Unlike bacteria, these viruses do not multiply in food; however, they can persist on surfaces and remain infectious, posing a significant health risk when ingested.

- Parasites: Organisms such as Giardia, Cryptosporidium, and Toxoplasma gondii can contaminate water and food, leading to gastrointestinal and systemic infections.

1.3.3 Factors Influencing Microbial Growth

To effectively control microbial contamination, it is essential to understand the environmental factors that influence microbial proliferation:

1. Temperature: Microbes have optimal temperature ranges for growth. Mesophilic bacteria, which include many pathogens, thrive between 20°C and 45°C. Refrigeration (below 5°C) slows microbial growth, while freezing halts it. Conversely, cooking at temperatures above 70°C can destroy most pathogens.

2. Moisture: As discussed, water is essential for microbial metabolism. Foods with high moisture content, such as fresh produce, meats, and dairy, are more prone to spoilage. Moisture control through drying, packaging, and storage is vital for food safety.

3. pH Level: The acidity or basicity of a food product plays a significant role in determining microbial viability. Most bacteria thrive in environments with a near-neutral to mildly acidic pH (typically between 6.5 and 7.5), whereas molds and yeasts are more adaptable to acidic conditions. Techniques like acidification—such as pickling—are widely used to preserve food by creating an environment that suppresses microbial growth.

4. Nutrient Availability: Microbes require nutrients to grow. Foods rich in proteins, carbohydrates, and fats provide an ideal medium for microbial proliferation. Limiting nutrient availability through processing or formulation can reduce microbial risks.

5. Oxygen Availability: Microbes vary in their oxygen requirements. Aerobic microbes need oxygen, while anaerobic microbes, such as Clostridium botulinum, thrive in oxygen-free environments. Packaging methods like vacuum sealing and modified atmosphere packaging (MAP) can manipulate oxygen levels to control microbial growth.

6. Time: Under ideal conditions, microbial populations can multiply every 20 minutes, rapidly increasing the risk of contamination. To curb this growth, it's vital to minimize the duration food remains within the "danger zone"—temperatures between 5°C and 60°C. Timely refrigeration, swift cooling of cooked items, and strict observance of expiration dates are key practices for preventing microbial spread.

1.3.4 Beneficial Microbes and Healthy Food

Not all microbes are harmful. In fact, many plays essential roles in food production and human health:

- Probiotics: Helpful bacteria like Lactobacillus and Bifidobacterium are commonly found in fermented foods such as yogurt, kefir, kimchi, and sauerkraut. These microorganisms promote digestive health, support gut microbiota balance, and may strengthen the immune system.

- Fermentation: Microbial fermentation is a key process in the production of numerous foods and drinks, including cheese, bread, beer, wine, soy sauce, and vinegar. Beyond preservation, fermentation enriches the sensory qualities of food—enhancing its taste, texture, and nutritional profile.

- Bio preservation: Certain microbes produce antimicrobial compounds (e.g., bacteriocins) that inhibit spoilage organisms and pathogens. These natural preservatives are increasingly used in clean-label food products.

- Soil Microbiota: In farming ecosystems, soil microbes are essential for recycling nutrients, enhancing plant growth, and naturally defending against plant pathogens. A thriving soil microbiome is crucial for achieving sustainable crop production and maintaining resilient ecosystems.

1.3.5 Food Safety Management and Water Activity Regulation

Within the food industry, effective oversight of water activity is a cornerstone of food safety protocols. Systems like Hazard Analysis and Critical Control Points (HACCP) frequently designate water activity as a key control parameter, particularly for products susceptible to microbial contamination.

Key practices include:

- Moisture Testing: Regular testing of water activity using specialized meters ensures that products remain within safe thresholds.

- Packaging Design: Moisture-barrier packaging materials prevent water ingress and maintain product stability.

- Environmental Controls: Humidity and temperature control in storage and processing areas reduce the risk of microbial growth.

- Ingredient Selection: Using low-moisture ingredients or incorporating humectants (e.g., glycerol, sorbitol) can help manage water activity.

1.3.6 Aflatoxins and Public Health

Aflatoxins are among the most dangerous microbial toxins in the food supply. Produced by Aspergillus species under warm and humid conditions, aflatoxins contaminate crops during growth, harvest, and storage. Prolonged exposure to aflatoxins has been associated with serious health consequences, including liver cancer, weakened immune function, and impaired growth in children (Adebo et al., 2017).To mitigate aflatoxin risks, several strategies are employed:

- Pre-Harvest Management: Crop rotation, resistant varieties, and proper irrigation reduce fungal infection.

- Post-Harvest Handling: Rapid drying, proper storage, and sorting of damaged grains minimize contamination.

- Regulatory Standards: Numerous nations have set legal thresholds for the permissible concentration of aflatoxins in both food and animal feed to safeguard public health.

- Detection Methods: Advanced analytical techniques such as ELISA, HPLC, and biosensors are used to detect aflatoxins in food products.

Microbial Risk Assessment and Consumer Awareness

Educating consumers about microbial risks and safe food handling practices is essential for public health. Key messages include:

- Wash hands, utensils, and surfaces regularly.
- Cook foods to safe internal temperatures.
- Refrigerate perishable items promptly.
- Avoid cross-contamination between raw and cooked foods.
- Check expiration dates and storage instructions.

Public health campaigns, food labeling, and school-based education programs can raise awareness and promote safe food practices.

Microbes and moisture are central to the science of food safety and preservation. While some microbes are beneficial and essential for producing healthy, flavorful foods, others pose serious risks to human health. Water activity plays a pivotal role in controlling microbial growth and stands as a foundational element of contemporary food safety practices.

By understanding the environmental factors that influence microbial behavior—like temperature, pH, moisture content, nutrient levels, oxygen availability, and duration—food producers and consumers alike can adopt well-informed practices to maintain food safety, preserve quality, and protect nutritional integrity. Tackling microbial threats like aflatoxins demands a holistic approach that encompasses every stage of the food supply chain, from cultivation to consumption.

Ultimately, the aim in promoting healthy food is not to eradicate all microbes, but to manage them effectively—leveraging their beneficial properties while mitigating potential risks. Through science, innovation, and education, we can build a safer, more resilient food system that supports public health and sustainable development.

1.4 Effects of Unhealthy Food and Prevention

Unhealthy food can be defined as food that contains high levels of substances that are detrimental to human health when consumed regularly or in large quantities. This can include food that is high in added sugars, saturated fats, trans fats, sodium, and low in essential nutrients such as vitamins, minerals, and fiber. Unhealthy food choices can contribute to various health issues, including obesity, heart disease, type-2 diabetes, and other chronic conditions. Furthermore, the term "unhealthy food" can also apply to items tainted by dangerous bacteria, parasites, toxins, or other pathogens capable of triggering foodborne illnesses and endangering human health. Such foods are classified as contaminated and may contain a range of hazardous substances, including both chemical and biological contaminants.

Health Effects of Unhealthy Food

The consumption of unhealthy food has far-reaching consequences on both individual and public health. Some of the most significant effects include:

1.4.1 Obesity and Weight Gain

Unhealthy foods tend to be high in calories but low in essential nutrients. Frequent intake of fast food, sugary drinks, and heavily processed snacks can contribute to excessive calorie consumption, ultimately leading to weight gain and obesity. In turn, obesity significantly increases the risk of various chronic health issues, such as heart disease, type 2 diabetes, osteoarthritis, and several forms of cancer.

1.4.2 cardiovascular diseases

Diets high in saturated fats, trans fats, and sodium contribute to elevated cholesterol levels and high blood pressure. These are key risk factors for heart disease and stroke. Over time, the buildup of plaque in the arteries can lead to atherosclerosis, increasing the likelihood of heart attacks and other cardiovascular complications.

1.4.3 Type-2 Diabetes

Consistently consuming foods and beverages high in sugar can promote insulin resistance—a condition where the body's cells become less responsive to insulin's effects. Over time, this dysfunction can progress to type 2 diabetes, a long-term metabolic disorder that impairs blood sugar regulation and may lead to severe complications, including kidney damage, nerve impairment, and loss of vision.

1.4.4 Digestive Disorders

Unhealthy foods often lack dietary fiber, which is essential for healthy digestion. A diet low in fiber can lead to constipation, bloating, and other gastrointestinal issues. Additionally, processed foods may contain additives and preservatives that can irritate the digestive tract.

1.4.5 Mental Health Impacts

Emerging research suggests a strong link between diet and mental health. Diets high in processed foods and sugars have been associated with an increased risk of depression, anxiety, and cognitive decline. Nutrient deficiencies, particularly in omega-3 fatty acids, B vitamins, and antioxidants, can negatively affect brain function and mood regulation.

1.4.6 Weakened Immune System

An inadequate diet can weaken the immune system, increasing vulnerability to infections and diseases. Essential nutrients like vitamin C, zinc, and selenium are vital for proper immune function, and lacking them can hinder the body's capacity to defend against harmful pathogens.

1.4.7 Hormonal Imbalances

Certain additives and chemicals found in processed foods, such as bisphenol A (BPA) and phthalates, can disrupt endocrine function. These substances may interfere with hormone production and regulation, potentially leading to reproductive issues, thyroid dysfunction, and developmental problems in children.

1.4.8 Effects of Contaminated Food

Contaminated food can have severe effects on human health, ranging from mild gastrointestinal discomfort to serious illness and even death. Consumption of food contaminated with bacteria, viruses, parasites, or toxins can lead to foodborne illnesses, also known as food poisoning. Common symptoms of foodborne illnesses include nausea, vomiting, diarrhea, abdominal pain, fever, and in severe cases, organ damage. Some of the specific effects of consuming contaminated food include:

1. Gastrointestinal Infections: Pathogenic bacteria such as Salmonella, Escherichia coli (E. coli), Campylobacter, and Listeria can cause gastrointestinal infections, leading to symptoms such as diarrhea, vomiting, and abdominal cramps (Sell & Dolan, 2018).

2. Foodborne Toxins: Toxins produced by certain bacteria and molds, such as Staphylococcus aureus and Clostridium botulinum, can contaminate food and cause symptoms ranging from mild food poisoning to severe neurological effects and paralysis (Sell & Dolan, 2018).

3. Parasitic Infections: Parasites such as Giardia, Cryptosporidium, and Toxoplasma gondii can contaminate food and water, leading to parasitic infections that affect the digestive and immune systems (Packi et al., 2023).

4. Allergic Reactions: Food allergens—including peanuts, tree nuts, shellfish, and dairy—can provoke allergic responses in sensitive individuals, with symptoms ranging from mild skin irritation and hives to life-threatening anaphylaxis. These potential health hazards underscore the urgent importance of implementing rigorous food safety measures throughout all stages of production, handling, and preparation. Such practices are essential to minimizing cross-contamination and protecting public health (Packi et al., 2023).

Prevention of Unhealthy and Contaminated Food

Safeguarding against the intake of unhealthy and contaminated food demands a comprehensive strategy that engages individuals, communities, the food industry, and governmental bodies. Below are several key approaches:

1. Nutrition Education and Awareness

Educating the public about the dangers of unhealthy food and the benefits of a balanced diet is crucial. Educational institutions, professional environments, and local community hubs hold significant potential to foster healthier eating behaviors. By offering nutritious food options, organizing wellness programs, and providing nutrition education, these settings can empower individuals to make informed dietary choices and support long-term public health. Nutrition labels should be clear and informative, helping consumers make better food choices.

2. Promoting Whole Foods

Promoting the intake of whole, minimally processed foods—like fruits, vegetables, whole grains, lean proteins, and healthy fats—can greatly decrease exposure to harmful additives and preservatives. These nutrient-dense options provide vital vitamins, minerals, and antioxidants that contribute to overall well-being and disease prevention.

3. Regulation and Policy

Governments have the ability to shape healthier food environments by enacting policies that restrict the availability and promotion of unhealthy foods, particularly to children. Measures may include imposing taxes on sugary beverages, prohibiting the use of trans fats, and establishing maximum limits for sodium and sugar in processed products. Additionally, offering subsidies for nutritious food choices can help make them more affordable and widely accessible to the public.

4. Food Safety Practices

To prevent contamination, food producers and handlers must adhere to strict hygiene and safety standards. This includes:

- Proper Hygiene: Practicing good personal hygiene and maintaining clean food preparation environments.

- Food Safety Training: Educating food handlers on sanitation and safe food handling.

- Temperature Control: Ensuring proper storage and cooking temperatures.

- Washing and Sanitizing: Cleaning food, utensils, and surfaces thoroughly.
- HACCP Implementation: Identifying and controlling hazards in the food production process.
- Source Control: Vetting suppliers and ensuring ingredient quality.
- Pest Control: Preventing pest infestations in food storage and preparation areas.
- Proper Storage: Using appropriate containers and storage conditions to prevent spoilage.

5. Encouraging Home Cooking

Cooking meals at home empowers individuals to choose their ingredients and preparation techniques, helping to limit dependence on processed and fast foods. This not only supports healthier eating habits but also enhances food safety and nutritional quality. Home cooking also fosters healthier eating habits and family bonding.

6. Promoting Physical Activity

While not directly related to food, regular physical activity complements healthy eating by helping maintain a healthy weight, improving metabolic health, and reducing the risk of chronic diseases.

7. Supporting Local and Organic Food

Locally sourced and organic foods are often fresher and less likely to contain harmful additives or contaminants. Supporting local farmers also strengthens community food systems and promotes sustainability.

The Role of Food Preservation: Drying

Drying food serves several significant purposes, including:

- Preservation:

Drying eliminates moisture from food, creating conditions that hinder microbial growth and spoilage. By lowering the water content, it significantly prolongs shelf life, enabling storage without the need for refrigeration.

- Flavor Enhancement:

The drying process can amplify the taste of foods like fruits and vegetables by removing water and concentrating their natural sugars and flavor compounds.

- Space and Weight Reduction: Removing moisture through drying reduces the weight and volume of the food, making it easier to transport and store, especially in situations where space and weight are limited, such as during camping or hiking trips.

- Preserving Nutrients:

When executed with care, drying methods can effectively retain vital vitamins and minerals, helping to preserve the nutritional quality of food over time.

- Practicality:

Dried foods offer great convenience for snacking, cooking, and meal prep. They can be easily rehydrated and incorporated into diverse recipes, making them a versatile option in the kitchen.

Drying represents just one approach to food preservation that enhances safety and accessibility. Other techniques—such as freezing, canning, fermentation, and vacuum sealing—also contribute to minimizing food waste and maintaining a reliable food supply.

1.5 Drying and Physical Properties of Food: An In-Depth Analysis

Drying is a core method of food preservation that works by eliminating moisture, thereby suppressing microbial activity and enzymatic reactions. Although it effectively prolongs shelf life and helps reduce food waste, the process also brings about notable alterations in the food's physical structure, chemical composition, and sensory characteristics. Understanding these changes is essential for food scientists, producers, and consumers alike.

1.5.1 Moisture Removal and Its Consequences

Moisture content is one of the most influential factors in food stability. During drying, water is removed from the food matrix, leading to a cascade of physical changes:

- Shrinkage: As moisture is removed during drying, the internal pressure within food cells drops, leading to cell collapse. This causes a visible decrease in volume, particularly in foods with high water content such as fruits and vegetables.
- Porosity: The drying technique used can influence the development of a porous structure in the food. For instance, freeze-drying maintains the integrity of cellular structures, producing a lightweight, airy texture that rehydrates efficiently.
- Glass Transition: As moisture content drops, food components such as sugars and proteins may transition from a rubbery to a glassy state, affecting texture and stability.

1.5.2 Texture and Mechanical Properties

Texture is a key quality attribute that influences consumer perception and product functionality. Drying alters texture in several ways:

- Firmness and Crispness: Dehydrated foods often become harder or crispier. For instance, dried apples become chewy, while dried kale turns brittle.
- Brittleness and Fragility: Excessive drying can make foods prone to breakage. This is a concern in packaging and transport, especially for snack foods.
- Elasticity Loss: The removal of water reduces the flexibility of food matrices, making them less resilient to mechanical stress.

These transformations are shaped by key drying factors, including temperature, humidity, and airflow speed. While elevated temperatures can speed up the drying process, they may also lead to case hardening—a phenomenon where the surface dries too rapidly, sealing in moisture and resulting in an inconsistent texture.

1.5.3 Color and Visual Appeal

Color is a primary indicator of food quality and freshness. Drying can significantly impact color through:

- Enzymatic Browning: In fruits like bananas and apples, polyphenol oxidase catalyzes the oxidation of phenolic compounds, resulting in brown pigments.
- Non-Enzymatic Browning: The Maillard reaction, a chemical interaction between amino acids and reducing sugars, leads to browning and flavor changes in food—particularly in protein-rich products. This process enhances taste and aroma but can also affect nutritional quality and appearance.

- Pigment Degradation: Natural pigments such as chlorophyll (green), carotenoids (orange/yellow), and anthocyanins (red/blue) are sensitive to heat and light. Their degradation can lead to faded or off-colors.

To mitigate color loss, pre-treatments like blanching, sulfiting, or using antioxidants (e.g., ascorbic acid) are commonly employed. Additionally, drying under controlled atmospheres (e.g., nitrogen) can reduce oxidative discoloration.

1.5.4 Size, Shape, and Density

The physical dimensions of food change markedly during drying:

- **Size Reduction**: As moisture is lost, the food contracts. This is particularly evident in fruits like grapes (raisins) or tomatoes.
- **Shape Distortion**: Uneven drying can cause warping or curling, which may affect consumer appeal and packaging efficiency.
- **Increased Density**: With water removed, the mass decreases while the solid content remains, leading to a denser product. This is advantageous for storage and transport but may affect rehydration.

1.5.5 Rehydration Characteristics

Rehydration is a critical quality parameter for dried foods, especially those intended for soups, ready meals, or reconstituted products. Ideal dried foods should:

- **Absorb Water Rapidly**: Porous structures facilitate faster water uptake.
- **Regain Original Texture**: Proper drying preserves the cellular matrix, allowing the food to return to its pre-dried state.

- **Maintain Nutrient and Flavor Integrity**: Excessive drying or high temperatures can impair rehydration and reduce palatability.

Rehydration ratio (weight of rehydrated food to dry weight) and rehydration capacity (amount of water absorbed) are commonly used metrics to assess this property.

1.5.6 Nutritional Implications

Drying can affect the nutritional profile of food, particularly heat-sensitive nutrients:

- **Vitamin Loss**: Vitamins C, B1 (thiamine), and B6 are highly susceptible to heat and oxidation. For example, sun-dried tomatoes may lose up to 50% of their vitamin C content.

- **Mineral Stability**: Minerals like calcium, iron, and magnesium are generally stable during drying, though leaching can occur if blanching is used.

- **Protein and Fat Stability**: Proteins may denature, and unsaturated fats can oxidize, leading to off-flavors and reduced nutritional value.

To preserve nutrients effectively, drying techniques that operate at low temperatures—such as freeze-drying or vacuum drying—are generally favored. Thermal Properties and Heat Transfer

Understanding the thermal behavior of food is essential for optimizing drying processes:

- **Thermal Conductivity**: This determines how efficiently heat moves through the food. Moist foods have higher thermal conductivity, which decreases as drying progresses.

- **Specific Heat Capacity:** When moisture levels decline in food, its specific heat capacity is reduced, influencing the rate at which it absorbs and responds to heat.

- **Convective Heat Transfer**: Airflow over the food surface removes moisture. Forced convection (e.g., in tray or tunnel dryers) enhances drying efficiency compared to natural convection.

The drying rate is influenced by both internal (moisture diffusion) and external (air velocity, temperature) factors. Mathematical models such as Fick's law of diffusion and Newton's law of cooling are often used to predict drying kinetics.

1.5.7 Consumer Preferences and Color Psychology

According to Li (1998), color is a dominant factor in consumer food choices. Birren's color preference graph illustrates how certain hues evoke emotional responses:

- **Red and Yellow**: Associated with warmth and appetite stimulation—common in dried fruits and snacks.

- **Green**: Signals freshness and health, important for dried vegetables.

- **Brown or Dull Colors**: May be perceived as stale or over-processed, even if the product is safe and nutritious.

Maintaining appealing color through careful control of drying parameters is essential for marketability.

1.5.8 Industrial Applications and Quality Control

In commercial food processing, drying must balance efficiency with quality:

- **Process Optimization**: Parameters like drying temperature, humidity, and time must be tailored to each food type.
- **Quality Assurance**: Physical attributes—including moisture content, color, texture, and rehydration capacity—are regularly evaluated to ensure product quality and consistency.
- **Packaging Considerations**: Dried foods are hygroscopic and must be stored in moisture-proof packaging to prevent spoilage and texture degradation.
- Innovative drying techniques—such as infrared drying, microwave-assisted processes, and combined hybrid systems—are currently being explored to improve energy efficiency and elevate the quality of dried food products.
- Innovations and Future Directions: Current advancements in food drying emphasize sustainability, accuracy, and the retention of nutrients:
- Intelligent Drying Systems: These systems utilize sensors and artificial intelligence to continuously monitor and fine-tune drying parameters in real time, optimizing performance and product outcomes. Energy Recovery: Heat exchangers and solar-assisted dryers reduce energy consumption.
- Encapsulation: Protects sensitive nutrients and flavors during drying, especially in powdered products like milk or coffee.

Drying is more than just a preservation method—it is a transformative process that reshapes the physical, chemical, and sensory attributes of food. From texture and color to nutritional value and mechanical strength, the effects of drying are profound and multifaceted. By diligently observing and regulating these transformations, food producers can ensure the development of shelf-stable, premium-quality products that satisfy consumer expectations for taste, appearance, and nutritional integrity.

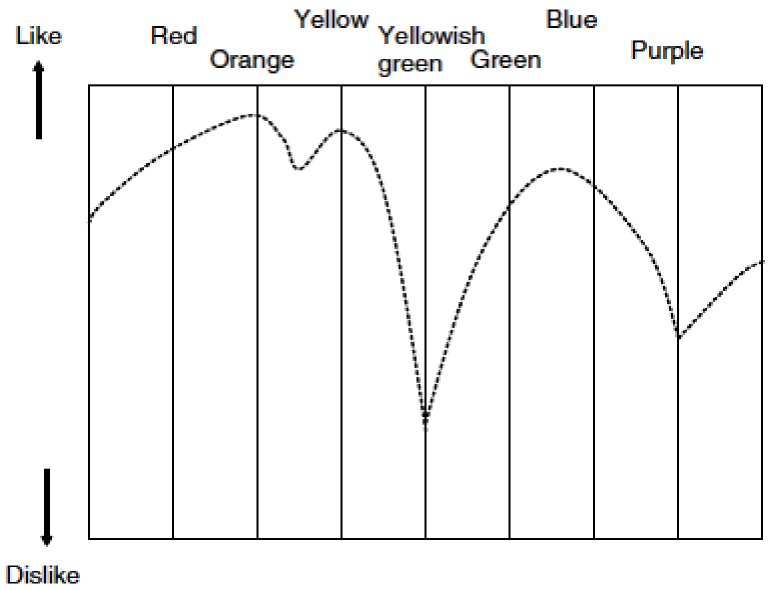

Figure 1-3 Quantitative impact of food colour on consumer preference. Source: (Li, 1998)

For the purpose of food preservation, the moisture isotherm is an extremely valuable for the food scientists because of its usefulness in predicting the food stability (Rahman, 2007). Properties of food quality such as growth and production of toxins by microorganisms as well as deterioration of chemical and physical characteristics like crispness, hardness, color, caking, texture, flavor and aroma, are important characteristics which needs to be optimized.

The rate of food quality loss begins to increase with increase of water activity beyond 0.2 – 0.3. Here, the amount of water absorbed become sufficient to affect the overall dielectric properties, thus chemical species can dissolve, become mobile and reactive. Generally, the higher the water activity, the higher the rate of reaction because of greater solubility and mobility of reactants (Rahman, 2007).

1.6 Statement of the Problem

The rapidly expanding global population has led to a surge in food demand, making efforts to meet this need an increasingly pressing global challenge. In Sub-Saharan Africa, food shortage is experienced by many people to the tune of 70% of the total population. This has led to food shortages and fluctuation of prices due to seasonal production. According to (Zhongming, Linong, Xiaona, Wangqiang, & Wei, 2020), over 10 million of Kenyan population is facing acute food shortage due to food loss and waste. Over the years the Kenyan government is trying to provide 51% of Kenyans who lack access to food due to poverty index at 46% (Kiome, 2009). Kenya is an agricultural country with 70% of the people depending on Agriculture as an economic activity. With a land mass of approximately 592,000Km^2, only 20% is arable. In line with the Kenyan government vision 2030, food security is one of the priority areas outlined in the "Big four Agenda" and the country has put in place necessary policies to enhance production of food sufficient to feed over 45million of her inhabitants (Njura, Kaberia, & Taaliu, 2020). The food loss is associated with insect and pest infestation (80 – 90%), humidity and growth of microorganism (70%) and mycotoxins (25 – 40%) (D. Kumar & Kalita, 2017). Food wastage and loss is over 1.3 billion tons globally per annum. Among the numerous causes of food waste, the major one is poor post-harvest management, which include; poor handling, moisture control, poor storage, transportation among others. Post-harvest loss is known to cause between 15 - 25% of the total food losses. Cereal grains alone, account for the maximum post-harvest calorific basis losses up to 50 – 60%. The major cause of this loss is associated with water activity and growth of microbes, and development of aflatoxins (P. Kumar, Mahato, Kamle, Mohanta, & Kang, 2017). Water activity is the major contributor of microbial growth and development of mycotoxins. Aflatoxin is known to be group one carcinogenic and the leading cause of liver diseases, anemia, poor appetite and growth in humans and livestock. Optimal drying of cereals to achieve the threshold of less than 40% moisture content eliminates humid conditions favourable for the growth of secondary metabolites and therefore reducing damage of cereals and associated losses to less than 1% (D. Kumar & Kalita, 2017). The cost of drying food stuff is enormous. The use of fuels has negative environmental impact, while use of electricity attracts high cost not affordable by majority of farmers. Most farmers dry their cereals in an open air, using canvas sheets. This would expose the food to unhygienic conditions, dust, grass, leaves and wood particles which makes the food unclean. Through these indigenous methods, food is also exposed and eaten by birds and other animals, leading to losses. It is for this reason that in this research study, we propose to harness solar energy, convert to heat energy and then channeled into an enclosed, clean and controlled environment, where food products are dried. A mathematical model representing the proposed solar food drier was formulated and analyzed for estimation of threshold values of parameters, to guarantee optimality and efficiency of the solar food dryer prototype. This research forms part of the efforts to mitigate food loss and therefore a contribution to the achievement of Kenya Vision 2030 agenda of food security.

1.7 Research Objectives

1.7.1 General Objective of the Study

The general objective of this research was to formulate a mathematical model of a solar food drier, using differential equations, and through simulation estimate parameter threshold values of the dryer, to achieve optimal performance.

1.7.2 Specific Objectives of the Study

The specific objectives of this study were;

i. To formulate a mathematical model of solar food dryer using differential equations coupled with food dehydration model equations.

ii. To perform sensitivity analysis to identify significant parameters that affects optimal operation of the solar dryer.

iii. To carry out simulation and determine parameter threshold values for optimal operation of the solar dryer using SIMULINK.

iv. To perform optimization analysis in relation to solar irradiation and LPG as an alternative source of heat energy.

1.8 Justification of the Study

The findings of this research study, is helpful not only to other researchers as the starting point for further research, but also provides the common man with alternative optimal dryer technology, which can be used both at domestic and commercial level in drying food. The research study produced valuable information to the agricultural sector in the government, which are used to enhance the struggle to minimize food loss due to post-harvest challenges, and thus reduce hunger and access to food.

The research provided valuable information for technology transfer. The information is specifically on the threshold values of control parameters which contribute to the construction of a prototype optimally performing dryer. The design of the solar food dryer is environmentally friendly and in line with the global efforts to explore green energy and protect the environment.

Solar drying offers several benefits for food conservation, including:

Cost-Effectiveness: Solar drying provides a low-cost method for preserving food, especially in regions where access to electricity or other energy sources may be limited. It reduces the reliance on expensive energy sources for food preservation.

Maintaining Nutritional Value: Solar drying helps safeguard the nutritional integrity of food by gradually removing moisture without exposing it to high temperatures. This gentle process preserves key vitamins, minerals, and nutrients, supporting both food security and dietary health.

Extending Shelf Life: Effectively dried foods can be preserved for long durations without the need for refrigeration. This not only helps minimize food waste but also supports a reliable food supply—particularly in regions with limited cold storage infrastructure or during emergencies where access to fresh food is restricted.

- Economic Opportunity: Solar drying empowers farmers and food processors to extend the shelf life of excess harvests, enabling them to market dried products during off-peak seasons or in regions with greater demand. This not only boosts income but also strengthens financial stability.

- Eco-Friendly Preservation: As an environmentally conscious technique, solar drying minimizes dependence on fossil fuels and significantly reduces greenhouse gas emissions compared to conventional drying methods, promoting sustainable food processing practices.

Food Security:

Solar drying supports communities and regions in maintaining a steady food supply by extending the shelf life of seasonal crops and decreasing reliance on imported or heavily processed foods.

Food Safety:

Effectively dried food minimizes the likelihood of microbial growth and foodborne diseases, enhancing overall food safety and promoting better public health outcomes.

Overall, solar drying offers a clean, sustainable, cost-effective, and nutritionally beneficial method for food conservation, making it a valuable approach for communities and regions seeking to preserve food resources. This is in tandem to the contemporary inclination to the use of green energy and environmental conservation.

CHAPTER TWO

LITERATURE REVIEW

2.0 Overview of this Chapter

This chapter covers a summarized work done by researchers in the field of renewable energy. This includes use of solar energy in form of electricity and as a source of heat in various applications. This chapter also covers methods used by researchers in the analysis and optimization of solar models. The chapter is divided into various sections which include; literature related to solar power, literature on the application of solar power, methods used to analyze solar models and the last section shows the gap of our study.

2.1 Food Drying

Drying is a time-honored method of food preservation that works by extracting moisture from food to inhibit microbial growth and prevent spoilage. Practiced for centuries, this technique effectively extends the shelf life of a wide range of foods—including fruits, vegetables, meats, herbs, and seafood—by creating conditions unfavorable to bacteria and mold.

Various drying methods exist; each tailored to specific food types and offering distinct advantages. For instance, air drying relies on natural airflow to gradually remove moisture. Extensive research, particularly on fruits and vegetables, has focused on identifying optimal drying conditions to maximize efficiency and product quality (Mercer, 2012). The motivation behind such studies lies in the benefits of extended shelf life, which not only reduces food waste but also opens up broader market opportunities. Longer preservation enables the transportation of dried goods over great distances and ensures year-round availability. To illustrate, fruits typically contain between 60% and 95% moisture, yet can be dried down to as little as 10%.

Beyond preservation, drying is a transformative process that significantly alters the food's physical, chemical, and nutritional characteristics. The removal of water impacts texture, color, flavor, and structural integrity—factors that must be carefully controlled to maintain consumer appeal and product quality. Key variables influencing the drying process include the type of food, its original moisture level, the chosen drying technique, and the surrounding environmental conditions.

One of the most critical aspects of food drying is the control of temperature and humidity. Elevated temperatures can speed up the drying process, but they may also cause unwanted effects like nutrient loss, discoloration, and increased hardness in texture. On the other hand, low temperatures may preserve quality but result in longer drying times and increased energy consumption. Therefore, finding the right balance is essential for efficient and effective drying.

There are various methods of drying, each with its own set of advantages and limitations. Sun drying is one of the oldest and simplest methods, relying on natural sunlight and ambient air to remove moisture. It is cost-effective and environmentally friendly but is highly dependent on weather conditions and poses risks of contamination from dust, insects, and animals. Air drying, which involves the use of controlled airflow and temperature, offers more consistency and safety. It is suitable for a wide range of foods and can be scaled for industrial use.

Lyophilization, commonly referred to as freeze drying, is a sophisticated technique that preserves food by first freezing it and then extracting moisture through sublimation under vacuum conditions. This technique preserves the structure, flavor, and nutritional content of food exceptionally well, making it ideal for high-value products such as pharmaceuticals, specialty fruits, and instant meals. However, freeze drying is expensive and energy-intensive, limiting its use to specific applications.

Vacuum drying is a technique that functions under low-pressure conditions, enabling moisture to evaporate at reduced temperatures. This gentle process helps retain heat-sensitive nutrients and flavors, making it ideal for preserving delicate items such as juices and soft foods. Spray drying, on the other hand, is primarily used for liquid products. It works by dispersing the liquid into a stream of hot air, quickly transforming it into a fine powder. This method is commonly applied to items like milk, coffee, and various flavoring agents.

Microwave and infrared drying are modern techniques that use electromagnetic radiation to heat and evaporate moisture. These methods offer rapid drying and energy efficiency but require careful control to avoid uneven heating or scorching. Hybrid drying systems that combine multiple methods are also being developed to optimize drying performance and product quality.

The drying process affects the physical properties of food in several ways. Texture is one of the most noticeable changes, as the removal of moisture leads to increased firmness, crispness, or brittleness. Fruits like apples and bananas become chewy, while vegetables like carrots and kale may turn crisp. The structural integrity of food is also altered, with cell walls collapsing and volume decreasing. This shrinkage can affect the visual appeal and mouthfeel of the product.

Color changes are another significant effect of drying. Enzymatic browning, caused by the oxidation of phenolic compounds, can lead to darkening in fruits such as apples and bananas. Non-enzymatic browning processes, such as the Maillard reaction involving amino acids and sugars, can significantly impact the color and taste of foods high in protein. Pigment degradation due to heat and light exposure can result in faded or off-colors, affecting consumer perception and acceptance.

Flavor is influenced by the concentration of natural sugars and the loss of volatile compounds. In fruits, drying often intensifies sweetness, while in herbs and spices, it can enhance aroma. However, some delicate flavors may be lost during drying, especially if high temperatures are used. Nutritional content is also affected, with heat-sensitive vitamins such as vitamin C and certain B vitamins being susceptible to degradation. Minerals are generally stable, but protein denaturation and fat oxidation can impact nutritional value and taste.

Rehydration capacity is an important quality parameter for dried foods, especially those intended for cooking or reconstitution. Foods that rehydrate well should absorb water quickly and return to their original texture and appearance. This depends on the drying method and the extent of structural damage during drying. Freeze-dried foods typically have excellent rehydration properties due to their porous structure, while air-dried foods may be less efficient.

Pre-treatment Methods:

To enhance drying efficiency and ensure high product quality, various pre-treatment techniques are commonly applied. Blanching—briefly immersing food in hot water or steam—deactivates enzymes and softens tissues, which shortens drying time and helps prevent discoloration. Sulfiting, which involves treating food with sulfur dioxide, maintains color and inhibits microbial growth. Osmotic dehydration is a process where food is soaked in a sugar or salt solution prior to drying, effectively removing moisture while also boosting its flavor. Additionally, cutting food into uniform pieces promotes consistent drying and reduces overall processing time.

Packaging and Storage:

Maintaining the quality of dried foods depends heavily on proper packaging and storage. Since dried foods are hygroscopic and easily absorb moisture from the surrounding air, they should be stored in airtight, moisture-resistant packaging like vacuum-sealed bags, foil-lined pouches, or glass jars with desiccants. Effective packaging also shields the food from light, oxygen, and physical damage. For optimal shelf life and to preserve taste, texture, and appearance, dried foods should be stored in cool, dry, and dark environments.

Food drying offers notable economic and environmental advantages. By preserving excess harvests that might otherwise go to waste, it helps minimize food loss. It also promotes rural development by empowering small-scale producers to process and market dried goods. On a global scale, drying simplifies trade by enabling long-distance transport and storage without the need for refrigeration. Environmentally, it is a more energy-efficient alternative to methods like freezing or canning, contributing to more sustainable food preservation practices.

Innovations in food drying continue to emerge, driven by the need for efficiency, quality, and sustainability. Smart drying systems equipped with sensors and artificial intelligence can monitor moisture content and adjust drying conditions in real-time. Hybrid drying techniques that combine microwave, vacuum, and infrared methods offer improved performance and energy savings. Encapsulation technologies protect sensitive nutrients and flavors during drying, enhancing the quality of powdered products. Solar-assisted dryers integrate traditional sun drying with modern technology, providing a cost-effective and hygienic solution for small-scale operations.

Food drying is a multifaceted preservation method that plays a vital role in the global food system. Drying techniques offer numerous benefits: they prolong shelf life, minimize food waste, stimulate economic growth, and strengthen food security. When producers grasp the underlying science and methods of drying, they can refine product quality, align with consumer demands, and foster a more sustainable and robust food supply system. Whether through traditional methods or cutting-edge technologies, food drying remains an indispensable tool in the preservation and distribution of nutritious, safe, and accessible food.

Table 2.1 below shows the moisture content of various fruits during harvest.

Table 2-1 Moisture content of various food products

Food Product	**Moisture Content (Wet basis %)**
Celery	95.4%
Tomatoes	94%
Strawberries	90%
Peaches	89%
Carrots	89%
Papaya	87%
Mangoes	85%
Apples	84%
Pineapples	84%
Potatoes	78%
Green peas	74%
Yams	69%
Cassava	65%
Plantain	60%

From the table above, the interpretation is that, a 10kg of strawberries will contain 9 liters of water and 1kg of 'solid', and drying to 10% moisture content implies that 8.1 liters is removed from a 10kg of strawberries, leaving a balance of 1.9kg, of which it comprises of 1kg solid and 0.9kg water.

During the drying process, food undergoes several physical changes, even though much of its nutritional value is generally preserved. These changes stem from the loss of moisture, which is essential for maintaining the food's structure and sensory qualities. As a result, noticeable shifts occur in aspects such as color, size, shape, crispness, texture, appearance, flavor, and aroma.

These changes can affect consumer perception and acceptance, making it essential for food processors to employ drying techniques that preserve as much of the original food quality as possible. As noted by Lozano, Rotstein, and Urbicain (1983), the goal of quality drying is not merely to remove water but to do so in a way that retains the food's desirable physical and sensory properties.

Color change is one of the most immediate and visible effects of drying. It can result from enzymatic browning, non-enzymatic reactions such as the Maillard reaction, and pigment degradation due to heat and light exposure. For example, fruits like apples and bananas tend to darken during drying, which may be perceived as a loss of freshness or quality. To mitigate this, pre-treatment methods such as blanching or sulfiting are often used to preserve color and inhibit enzymatic activity. However, even with these interventions, some degree of color change is inevitable, especially when high temperatures are involved.

Drying causes notable changes in the size and shape of food. As moisture is extracted, the internal pressure within the cells drops, resulting in shrinkage and structural distortion. These effects are especially pronounced in foods with high water content, like tomatoes, mangoes, and berries. The degree of shrinkage is influenced by factors such as the drying technique, the speed of moisture removal, and the food's cellular strength. If drying occurs too rapidly, it can lead to case hardening—where the surface dries prematurely, sealing in moisture and causing uneven shrinkage and possible spoilage.

Crispness and texture are closely linked to the moisture content and the drying kinetics. Foods that are dried slowly and evenly tend to retain a more desirable texture, while those subjected to rapid or high-temperature drying may become excessively brittle or tough. For instance, dried apples can be chewy and pleasant if dried properly, but may turn leathery or hard if over-dried. Texture also influences mouthfeel and rehydration capacity, which are important for consumer satisfaction, especially in products intended for reconstitution.

The feel and look of dried food are also affected by drying. The surface may become rough, wrinkled, or glossy depending on the drying conditions and the food's composition. These changes can influence packaging decisions and marketing strategies, as consumers often associate appearance with quality. Taste and aroma, although less visible, are equally important. Volatile compounds responsible for flavor and smell may be lost during drying, particularly at high temperatures. This can result in bland or off-flavored products, which are less appealing to consumers. Techniques such as vacuum drying or freeze drying are preferred for preserving these delicate compounds.

Dryer design plays a pivotal role in determining the final quality of dried food. The configuration of the dryer, the materials used for trays, and the control systems for temperature and airflow all influence the drying process. For example, tray dryers allow for batch processing and are suitable for small-scale operations, while tunnel dryers and fluidized bed dryers are more efficient for continuous, large-scale drying. Selecting the appropriate drying equipment requires careful consideration of the specific food being processed, the intended qualities of the final product, and the financial limitations of the production setup.

Several intrinsic characteristics of food affect drying time and efficiency. Initial moisture content is a primary factor; foods with higher water content require longer drying times and more energy. Surface characteristics, such as roughness and permeability, influence how easily moisture can escape. The shape and thickness of food items influence their surface area-to-volume ratio, which in turn impacts the efficiency of heat and moisture transfer during drying.

Porosity and internal structure influence how moisture migrates from the interior to the surface. Composition, including the presence of sugars, fats, and proteins, can alter drying behavior due to their thermal properties and interactions with water. Even the variety of the food item—such as different cultivars of apples or tomatoes—can result in varying drying responses.

Environmental and operational conditions play a crucial role in influencing the effectiveness of the drying process. The temperature of the drying air influences both the speed of moisture removal and the potential for nutrient loss. While elevated temperatures can hasten drying, they may also negatively impact the overall quality of the food. Air velocity plays a vital role in drying by helping to sweep away moisture-saturated air from the surface of the food, thereby improving the overall efficiency of the drying process. Dryer humidity must be controlled to maintain a gradient that favors moisture loss. Duration of drying must be optimized to balance energy use and product quality. Air flow rate and patterns determine how uniformly heat is distributed across the food surface. The material of dryer trays can affect heat conduction and product contamination risks; stainless steel is commonly used for its durability and inertness.

As water is removed from food particles, several physical properties change. Color alteration, as discussed earlier, is both a sensory and chemical transformation. Shrinkage results from the collapse of cellular structures, leading to reduced volume and altered shape. Porosity may increase or decrease depending on the drying method; freeze drying tends to preserve porosity, while hot air drying may reduce it. Bulk density, which is the mass per unit volume of the dried product, typically increases due to the loss of water and the compaction of solids. These properties can be measured and estimated using mathematical models and empirical data, as outlined by Lozano et al. (1983). Understanding these changes is essential for designing drying processes that meet quality standards and consumer expectations.

The process of food drying is primarily driven by two key mechanisms: heat transfer and mass transfer. Heat transfer refers to the movement of thermal energy—typically from heated air—to the surface of the food via convection. Once the surface is warmed, conduction carries this heat deeper into the food, enabling internal moisture to migrate outward. Heat transfer efficiency during drying is shaped by several key factors: the thermal conductivity of the food, the temperature gradient between the drying medium and the food, and how well the two surfaces interact or make contact. Mass transport, on the other hand, refers to the movement of moisture from the interior of the food to the surface and then into the surrounding air. This occurs through diffusional transport, where water molecules migrate through the food matrix, and through evaporation, where surface moisture transitions into vapor and is carried away by the airflow. Mass transport during drying is governed by factors such as the moisture gradient within the food, its porosity, and the vapor pressure of water at the surface. These elements, in conjunction with heat transfer, shape the drying kinetics and significantly impact the overall efficiency of the drying process.

The interplay between these two processes is complex and requires careful control to achieve optimal drying. If heat is supplied too rapidly, it can cause surface hardening and inhibit moisture migration, leading to uneven drying and potential spoilage. If mass transport is too slow, drying times increase, raising energy costs and reducing throughput. Advanced drying systems use sensors and control algorithms to monitor temperature, humidity, and airflow, adjusting parameters in real-time to maintain ideal conditions.

In recent years, computational modeling and simulation have become valuable tools in understanding and optimizing drying processes. These models incorporate physical, chemical, and thermodynamic principles to predict drying behavior under various conditions. They help in designing dryers, selecting process parameters, and evaluating the impact of changes on product quality. Experimental validation of these models ensures their accuracy and applicability in real-world scenarios.

While food drying is an effective preservation method, it involves a delicate balance between removing moisture and retaining quality. The physical characteristics of food—color, texture, shape, flavor, and aroma—are all susceptible to change during drying. Dryer design, food properties, and environmental conditions must be carefully managed to minimize these changes. The scientific principles of heat and mass transport underpin the drying process, guiding the development of efficient and high-quality drying systems. By understanding and controlling these factors, food processors can produce dried products that are safe, nutritious, and appealing to consumers.

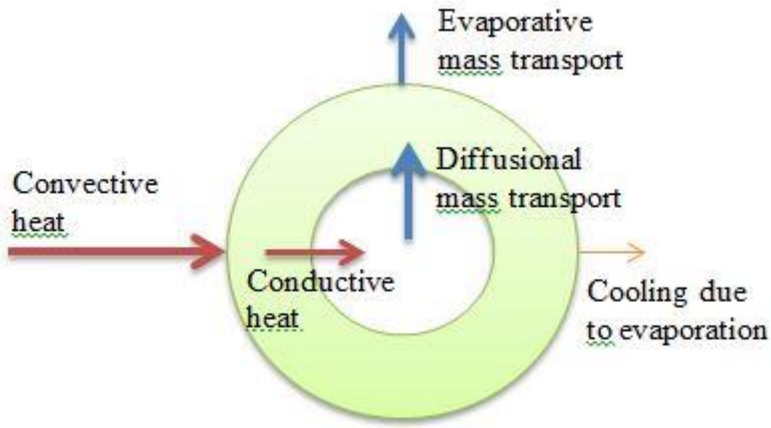

Figure 2-1 Drying Phenomenon in Spherical food particle. Source: Author

The drying rate of a food particle is influenced by several internal characteristics, including its physical properties, structural composition, size, shape, temperature, and initial moisture content. External influences also critically affect the efficiency of the drying process. Key factors include drying air velocity, molecular diffusion, capillary action, Kludsten flow, hydrodynamic movement, and surface diffusion, all of which contribute to the dynamics of moisture removal (Neto, 1997).

2.2 Food Drying Methodologies

Food drying stands as a foundational method of food preservation, originating from ancient traditions and continuously enhanced by modern innovations. Its primary purpose remains consistent: to eliminate moisture from food, thereby preventing microbial growth and enzymatic reactions that lead to spoilage. This process extends shelf life and ensures food safety. The selected drying method significantly influences the final product's texture, flavor, visual appeal, and nutritional value. A thorough understanding of these methods enables both producers and consumers to make informed choices suited to their specific needs.

Sun Drying: A Traditional Approach

Sun drying is the oldest and most widely practiced method, utilizing natural solar energy to remove moisture. It is especially common in areas with hot, arid climates and low rainfall. The technique involves laying out food—such as fruits, vegetables, or herbs—in thin layers on surfaces like mats, trays, or rooftops. Though sun drying is economical and eco-friendly, it is heavily reliant on weather conditions and susceptible to contamination from dust, insects, and animals. To address these challenges, solar dryers equipped with transparent covers and ventilation systems have been introduced. These improved designs help shield food from external pollutants while enhancing heat retention and airflow. Despite its limitations, sun drying continues to be a practical and accessible solution for small-scale farmers and rural communities.

Air drying, also known as ambient or natural drying, uses circulating air to remove moisture. This method can be passive, relying on natural airflow, or active, using fans and controlled environments. Air drying is suitable for low-moisture foods like herbs, spices, and certain fruits. It is relatively simple and energy-efficient but slower than other methods. The drying rate depends on air temperature, humidity, and velocity. In industrial settings, air drying is often enhanced with heated air and humidity control to accelerate the process and improve consistency. The use of racks and trays allows for uniform exposure and minimizes spoilage. Air drying is particularly valued for preserving aroma and flavor in delicate items like mint, basil, and oregano.

Freeze drying, or lyophilization, is a sophisticated method of food preservation that entails freezing the product and then extracting moisture through sublimation in a vacuum. By bypassing the liquid phase, this process enables ice to convert directly into vapor, preserving the food's structure, flavor, and nutritional integrity.

As a result, the food's cellular structure remains largely intact, leading to minimal shrinkage and excellent rehydration capabilities. Additionally, freeze drying excels at preserving flavor, color, and nutritional value more effectively than most other drying methods.

However, this process is both costly and energy-demanding, making it most practical for high-value items such as strawberries, mushrooms, instant coffee, and pharmaceutical products. The specialized equipment—comprising freeze chambers, vacuum systems, and condensers—adds to the overall expense. Despite these challenges, the exceptional quality of freeze-dried goods makes them highly desirable for use in space exploration, emergency food supplies, and premium culinary markets.

Dehydrator Drying: A Controlled Approach

Dehydrator drying utilizes purpose-built appliances that remove moisture from food through regulated heat and airflow. These machines are especially favored for household use and small-scale food processing. Standard dehydrators feature multiple stacked trays, a heating unit, and a fan to distribute warm air evenly. Users can customize temperature and drying duration depending on the type of food and desired results.

Highly adaptable, dehydrators can process a variety of items such as fruits, vegetables, meats, and herbs. They deliver consistent outcomes and offer improved hygiene compared to traditional sun or air-drying methods. However, their reliance on electricity and limited capacity make them less ideal for large-scale production. Modern advancements in dehydrator technology include programmable controls, energy-saving designs, and built-in humidity sensors to enhance drying efficiency and precision.

Oven drying utilizes conventional kitchen ovens to dehydrate food. This method is accessible and convenient, especially for small batches. By setting the oven to a low temperature—usually between 50°C and 70°C—and leaving the door slightly ajar for ventilation, moisture can be gradually removed. Oven drying is effective for fruits like apples, bananas, and tomatoes, as well as vegetables such as peppers and zucchini. However, it is less energy-efficient and may result in uneven drying due to limited airflow. Foods must be monitored closely to prevent scorching or over-drying. Additionally, ovens are not designed for prolonged low-temperature operation, which can affect their performance and lifespan. Despite these drawbacks, oven drying remains a practical option for occasional use.

Microwave drying is a rapid method that uses microwave radiation to heat water molecules within food, causing them to evaporate. This technique is suitable for small quantities and thin slices, such as herbs, spices, and fruit chips. Microwave drying offers speed and convenience but requires precise control to avoid overheating and nutrient loss. Uneven heating can lead to hot spots, burning, or incomplete drying. Advanced microwave dryers incorporate rotating trays, moisture sensors, and power modulation to improve uniformity and safety. While not ideal for bulk processing, microwave drying is valuable for quick preservation and experimentation.

Beyond these primary methods, several emerging technologies are reshaping food drying. Vacuum drying functions by lowering the ambient pressure, which enables moisture to evaporate at reduced temperatures. This gentle drying environment helps retain delicate nutrients and flavors, making the technique ideal for processing items like fruit juices, dairy-based goods, and pharmaceutical products. Spray drying is a technique commonly applied to liquid foods, where the liquid is transformed into fine droplets and exposed to a stream of hot air. This rapid drying process converts the droplets into powder form, making it ideal for producing items such as powdered milk, instant coffee, and dried egg products.

Infrared drying uses radiant energy to penetrate food surfaces, accelerating drying and reducing microbial load. Hybrid drying systems integrate methods like microwave-vacuum or infrared-hot air drying to strike an optimal balance between processing speed, product quality, and energy consumption. By leveraging the strengths of multiple technologies, these systems enhance drying performance while preserving the integrity of heat-sensitive foods. The choice of drying method depends on several factors. Food type is paramount—high-moisture items like tomatoes require different handling than low-moisture herbs. Desired product quality, including texture, flavor, and appearance, influences the method selected. Scale of operation—home, artisanal, or industrial—determines the feasibility of certain technologies. Resource availability, such as energy, equipment, and climate, also plays a role. For example, sun drying may be ideal in arid regions, while freeze drying suits high-tech facilities.

Each method carries trade-offs. Sun drying is sustainable but slow and risky. Freeze drying offers premium quality but at high cost. Dehydrators provide control and consistency but are limited in capacity. Oven and microwave drying are accessible but require vigilance. Understanding these nuances enables informed decisions that align with goals, budgets, and consumer expectations.

Food drying methodologies span a spectrum from ancient practices to cutting-edge innovations. They serve a vital role in food preservation, waste reduction, and global food security. By mastering the principles and applications of each method, producers can enhance product quality, optimize efficiency, and meet diverse market demands. As technology advances and sustainability becomes a priority, the future of food drying promises even greater precision, affordability, and environmental stewardship.

2.3 Sources of Food drying Energy

The ultimate source of heat energy for Earth is the sun. This vast, natural powerhouse provides the energy that drives weather systems, supports photosynthesis, and enables life itself. In the context of food drying, the sun's energy plays a foundational role, either directly through solar drying or indirectly through its transformation into other usable forms such as electricity or thermal energy. What makes solar energy particularly compelling is its abundance, renewability, and cost-free nature at the point of origin. The only costs associated with solar energy arise from the infrastructure required to capture, convert, and distribute it—such as solar panels, collectors, and storage systems.

The sun is a massive sphere of hot gases, primarily hydrogen and helium, held together by gravitational forces. It consists of roughly 70% hydrogen and 28% helium, with minor traces of elements like carbon, oxygen, neon, iron, silicon, magnesium, and sulfur (Asplund, Grevesse, Sauval, & Scott, 2009). These elements exist under extreme pressure and temperature, facilitating nuclear fusion reactions that convert hydrogen into helium. This process releases enormous amounts of energy in the form of heat and light, which radiates outward into space and reaches Earth as solar radiation.

The sun's surface temperature is around 5,700°C, and it radiates energy across the entire electromagnetic spectrum. When this energy reaches Earth, it warms the planet's surface through a process called insolation. Heating intensity varies depending on several environmental and physical factors, including geographic location, elevation above sea level, and the characteristics of the surface being heated. These elements influence how much solar radiation is absorbed, reflected, or retained, thereby affecting the overall thermal dynamics of a given area.

For instance, African deserts have recorded surface temperatures up to 58°C, while regions in Asia and Europe have seen highs of 54°C and 50°C, respectively. In stark contrast, Antarctica—due to its polar position and highly reflective ice cover—can experience surface temperatures as low as -15°C.

Harnessing solar energy for practical applications involves converting it into usable forms. Solar panels, for instance, convert sunlight into electricity using photovoltaic cells. This electricity can then be used to power appliances, heat water, or operate drying chambers. Solar thermal collectors, on the other hand, absorb sunlight and convert it into heat, which can be used directly for drying food, heating rooms, or boiling water. These technologies make it possible to utilize solar energy in diverse settings, from rural farms to urban food processing facilities.

When it comes to food drying, the choice of heat energy source is critical to the efficiency, cost-effectiveness, and environmental impact of the process. Several sources of heat energy are commonly used, each with distinct characteristics and suitability for specific applications.

Solar Drying: A Sustainable Solution

Solar energy stands out as one of the most sustainable and eco-friendly methods for food preservation. Solar dryers harness either direct sunlight or solar collectors to generate the heat needed for dehydration. In direct solar drying, food is exposed to sunlight within enclosed structures that shield it from pests and contaminants. Indirect solar dryers, on the other hand, use solar collectors to heat air, which is then channeled through drying chambers to remove moisture.

This technique is especially effective in areas with plentiful sunshine and low humidity. It is commonly used to dry fruits, vegetables, herbs, and fish, particularly in rural and agricultural settings. Key benefits of solar drying include low operational costs, reduced environmental impact, and independence from conventional energy sources. However, its reliance on weather conditions can be a limitation, often necessitating the use of backup systems or hybrid models to maintain consistent drying performance.

Electricity: A Flexible Heat Source for Drying

Electricity is a widely adopted and adaptable energy source for food drying, commonly used in both household and commercial environments. Electric dryers and dehydrators provide accurate temperature regulation, steady airflow, and programmable features, making them ideal for a broad spectrum of food items. This method is especially beneficial for small-scale operations and delicate products that require precise handling. However, high electricity costs can pose a challenge, particularly in regions with expensive energy rates. The environmental footprint of electric drying also varies depending on the energy source—renewables like solar, wind, or hydro are more sustainable than fossil-fuel-based electricity. To enhance eco-friendliness, recent innovations have focused on integrating solar panels with electric dryers, reducing dependence on grid power and boosting sustainability.

Fossil Fuels: High-Output but Environmentally Challenging

Natural gas, propane, and diesel have traditionally served as primary heat sources for large-scale industrial food drying. These fossil fuels deliver substantial thermal energy and are widely accessible, making them suitable for processing large quantities of food in commercial facilities. However, their use raises serious environmental concerns. The combustion of fossil fuels emits carbon dioxide and other pollutants, contributing to climate change, air quality issues, and the depletion of non-renewable resources. Despite these drawbacks, fossil fuels remain in widespread use due to their reliability, established infrastructure, and high energy density. Shifting away from fossil fuel dependency required significant investment in cleaner technologies and supportive policy frameworks.

Biomass: A Renewable and Localized Energy Option

Biomass offers a sustainable, carbon-neutral alternative to fossil fuels. It is derived from organic materials such as wood, agricultural residues, and animal waste. Biomass-powered dryers generate heat through combustion, which is then used to dehydrate food. This approach is particularly well-suited to rural and farming communities where biomass is readily available and cost-effective. Utilizing local biomass resources can lower transportation expenses and enhance local energy security. With proper design, biomass systems can be optimized for efficiency and reduced emissions. However, challenges such as maintaining consistent fuel quality, managing ash byproducts, and ensuring reliable operation must be addressed. When paired with modern control technologies and emission mitigation strategies, biomass presents a viable and environmentally responsible solution for food drying.

Choosing an appropriate heat energy source for food drying hinges on multiple factors, with the scale of the operation being a key determinant. Small-scale producers often favor electric or solar dryers due to their lower initial costs and ease of use. In contrast, large-scale industrial processors typically lean toward options like fossil fuels or biomass, which offer greater energy output and cost-efficiency for high-volume production.

The **availability of energy resources** also influences the choice; regions with abundant sunlight or biomass may favor those sources. **Environmental impact** is increasingly important, as consumers and regulators demand sustainable practices. Solar and biomass energy are preferred for their low carbon footprints, while fossil fuels are scrutinized for their emissions. **Economic considerations**, including capital investment, operating costs, and maintenance, play a crucial role in decision-making. Solar dryers have low operating costs but may require higher initial investment, while fossil fuel systems offer lower upfront costs but higher long-term expenses.

In addition to these core sources**,** hybrid systems are gaining popularity. These systems combine multiple energy sources to enhance reliability and performance. For example, a solar-electric hybrid dryer may use solar energy during the day and switch to electricity at night or during cloudy weather. Similarly, biomass-solar systems can use solar collectors for daytime drying and biomass combustion for backup heat. Hybrid designs offer flexibility, energy savings, and improved drying consistency, making them suitable for diverse environments and production scales.

Technological advancements are also shaping the future of energy use in food drying. Innovations in solar collector design**,** thermal storage**, and** smart control systems are improving the efficiency and reliability of solar drying. Energy-efficient electric dryers with moisture sensors and programmable logic controllers (PLCs) are enhancing precision and reducing waste. Biomass gasification and pyrolysis technologies are enabling cleaner combustion and energy recovery. These developments are helping to align food drying practices with global sustainability goals and climate action initiatives.

The sun remains the ultimate source of heat energy, offering a clean, abundant, and renewable foundation for food drying and other applications. Its energy can be harnessed directly or transformed into electricity and thermal energy to meet diverse needs. In addition to solar energy, electricity, fossil fuels, and biomass serve as viable heat sources for food drying, each offering distinct benefits and limitations. Selecting the most appropriate energy source requires a careful evaluation of technical feasibility, environmental impact, and economic viability to achieve efficient and sustainable drying operations. As technology evolves and climate concerns intensify, the shift toward renewable and hybrid energy systems is poised to revolutionize food drying methods, enhancing sustainability and reinforcing global food security.

2.4 Solar Energy and Food Drying

Solar heating and food drying are two practical and impactful applications of solar energy that have been utilized for centuries by various cultures around the world. These methods harness the abundant and renewable energy of the sun to achieve essential goals: solar heating provides warmth for living and working spaces, while solar food drying preserves food for long-term storage and consumption. Both applications exemplify how solar energy can be used sustainably to meet human needs while reducing dependence on fossil fuels and minimizing environmental impact.

Solar heating systems utilize the sun’s energy to generate thermal heat, which can be used to warm indoor spaces and supply hot water. These systems typically involve solar collectors that absorb sunlight and convert it into usable heat, offering an efficient and eco-friendly alternative to conventional heating methods. They are especially beneficial in homes, businesses, and industrial facilities with substantial heating needs. At the heart of these systems are solar collectors, which capture sunlight and transform it into thermal energy, and storage units—like tanks or thermal masses—that store this heat for future use. The efficiency of a solar heating system depends on several key elements, such as the type of solar collector used, the orientation and tilt angle of the panels, regional climate conditions, and the architectural layout of the building.

Types and Benefits of Solar Heating Systems

Solar heating systems generally fall into two main categories: active and passive. Active solar heating systems utilize mechanical components—such as pumps, fans, and control units—to transfer heat from solar collectors to designated areas within a building. These systems offer precise temperature regulation and can be seamlessly integrated with conventional heating setups to provide additional warmth when needed.

In contrast, passive solar heating systems depend on thoughtful architectural design and natural heat movement. These systems utilize materials with high thermal mass—such as stone, brick, or concrete—that capture solar energy during the day and slowly emit it as ambient temperatures decline, helping to maintain a stable indoor climate. Due to their simplicity and low maintenance requirements, passive systems are particularly well-suited for residential and small-scale buildings in regions with abundant sunlight.

One of the most significant advantages of solar heating lies in its ability to reduce dependence on conventional energy sources such as electricity, oil, and natural gas. Utilizing solar energy enables users to significantly reduce their energy expenses while also lowering their carbon footprint. This sustainable approach not only promotes cost savings but also supports environmental conservation by decreasing reliance on fossil fuels. This is especially critical in the fight against climate change, where lowering greenhouse gas emissions is a global imperative. Solar heating also fosters energy independence by enabling communities to produce their own thermal energy. This reduces reliance on centralized power grids or imported fuels, enhancing local resilience and supporting sustainable development. In regions with abundant sunlight, solar heating can be a highly cost-effective solution. Countries near the equator, such as Kenya, benefit from consistent solar radiation throughout the year, making solar heating a viable option for both urban and rural areas. In colder climates, solar heating can still play a role by preheating water or supplementing conventional heating systems during sunny periods. Advances in technology, such as improved insulation, smart thermostats, and hybrid systems, have further enhanced the performance and accessibility of solar heating.

Food drying, another ancient application of solar energy, serves a critical role in food preservation and security. By removing moisture from food, drying inhibits the growth of bacteria, molds, and yeasts that cause spoilage. This method enables long-term food storage without the need for refrigeration, making it particularly beneficial in areas with limited access to electricity or cold storage facilities. Solar food drying harnesses the sun's heat and natural airflow to remove moisture from foods like fruits, vegetables, herbs, and meats.

Traditional solar food drying involves placing food in direct sunlight on trays or mats. Although effective, this method leaves food vulnerable to contamination from external sources like dust, insects, and animals. Such exposure can compromise hygiene and safety, making it less suitable for applications requiring strict sanitary standards. To address these issues, modern solar dryers have been developed. These devices enclose the food in a protected chamber and use transparent covers to allow sunlight in while preventing contamination. Some solar dryers incorporate reflectors to concentrate sunlight and increase drying efficiency. Others use solar collectors to heat air, which is then circulated through the drying chamber using natural convection or small fans.

Solar food drying offers numerous advantages over conventional preservation methods like canning, freezing, or chemical treatments. It requires minimal energy input, relying solely on the sun's natural heat. This approach offers a sustainable and cost-effective solution, especially in remote and off-grid regions. Solar-dried foods maintain a high level of nutritional value—including essential vitamins, minerals, and antioxidants—that are often diminished by high-temperature drying methods. Additionally, the natural flavor and aroma are well preserved, enhancing their appeal for cooking and food preparation.

In addition to nutritional benefits, solar-dried foods are lightweight and compact, making them easy to transport and store. This is especially useful for outdoor activities such as camping and hiking, as well as for emergency preparedness and humanitarian aid. Dried foods offer extended shelf life and can be easily rehydrated when required, making them both practical and versatile. For farmers and food processors, solar drying presents a valuable opportunity to minimize post-harvest waste, enhance the value of their produce, and tap into broader market opportunities.

Despite its advantages, solar food drying faces several challenges. The drying process is weather-dependent and may be interrupted by rain, clouds, or high humidity. Inconsistent drying can lead to uneven moisture content, which affects quality and safety. To overcome these issues, hybrid systems that combine solar energy with backup heat sources such as biomass or electricity have been developed. These systems ensure continuous drying and improve reliability.

Another challenge is the initial cost of solar dryers, which may be prohibitive for small-scale producers. However, community-based drying facilities, cooperative models, and government subsidies can help make the technology more accessible. Training and education are also essential to ensure proper use and maintenance of solar dryers. By building local capacity and raising awareness, solar food drying can be scaled up to benefit entire communities.

The renewed interest in solar heating and food drying reflects a broader shift toward sustainable and resilient energy and food systems. As the world grapples with climate change, resource scarcity, and population growth, solar energy offers a clean, abundant, and versatile solution. Governments, NGOs, and private sector actors are increasingly investing in solar technologies to promote energy access, reduce emissions, and support rural development.

Innovations in solar technology are expanding the possibilities for heating and drying. Innovative materials like selective coatings, phase-change substances, and nanotechnology are enhancing the performance and efficiency of solar collectors.

Smart sensors and automation are enabling precise control of temperature and airflow in solar dryers. Integration with renewable energy systems, such as solar photovoltaic panels and battery storage, is enhancing performance and reliability.

Research and development are also exploring new applications of solar energy in agriculture and food processing. Solar-powered cold storage, pasteurization, and cooking are emerging as complementary technologies that can transform food systems. By combining solar heating and drying with other renewable energy solutions, communities can build integrated systems that support health, nutrition, and economic growth.

Solar heating and food drying are time-tested and forward-looking applications of solar energy. These technologies exemplify how solar energy can be effectively utilized to fulfill essential human needs in an environmentally responsible and economical way. Solar heating helps cut reliance on fossil fuels and reduces energy expenses, while solar food drying extends shelf life, minimizes food waste, and strengthens food security. With ongoing technological progress and growing environmental awareness, these approaches are poised to remain key contributors to a more sustainable, healthier, and equitable future. Embracing solar energy is not just a return to ancient wisdom—it is a leap toward a more sustainable future. Recent developments in solar technology have significantly improved the efficiency and affordability of solar heating systems. These advancements make solar heating an increasingly appealing choice for both homeowners and businesses aiming to lower energy expenses and shrink their environmental footprint. Similarly, solar food drying has gained popularity among small-scale farmers, homesteaders, and food enthusiasts who seek to preserve seasonal produce and minimize food waste (Chen & Mujumdar, 2009).

As of 2021, the global energy mix comprises a diverse array of energy sources, each contributing varying proportions to the overall energy supply. The primary energy sources include fossil fuels (such as coal, oil, and natural gas), nuclear energy, and renewable energy sources (including hydroelectric, solar, wind, geothermal, and biomass energy). The proportions of these energy sources in the global energy mix reflect regional variations, technological advancements, energy policies, and the evolving dynamics of energy demand and consumption. Fossil fuels, long a cornerstone of the global energy supply, still play a major role in fulfilling current energy needs.

As of 2021, coal, oil, and natural gas collectively account for a substantial share of the global energy supply. Coal has traditionally been a leading energy source for electricity generation, especially in emerging economies, while oil is a primary fuel for transportation and industrial applications. Natural gas, prized for its versatility and lower emissions compared to coal and oil, has become increasingly prominent in power generation and various industrial processes. Nuclear energy, though representing a smaller proportion of the global energy mix, is a notable source of low-carbon electricity production in many countries. Nuclear power plants produce electricity by harnessing heat generated from controlled nuclear reactions. This thermal energy is used to create steam, which drives turbines connected to electrical generators. While nuclear energy has the advantage of minimal greenhouse gas emissions, safety concerns and waste management issues have shaped its role and expansion in the energy mix. Renewable energy sources, including hydroelectric, solar, wind, geothermal, and biomass energy, have garnered increasing attention and investment due to their sustainability, environmental benefits, and declining costs. Hydroelectric power, derived from the energy of flowing water, has historically been a major contributor to global electricity generation. Solar energy—captured through photovoltaic panels and concentrated solar power systems—has grown swiftly, fueled by technological innovation and policy support. Wind energy, generated by turbines, has likewise expanded, especially in areas with strong and consistent wind patterns. Geothermal energy, derived from the Earth's internal heat, and biomass energy, created from organic materials, are important contributors to the renewable energy mix, providing solutions for both electricity generation and thermal applications. The regional distribution of energy sources differs significantly, shaped by factors like the availability of natural resources, the level of economic development, governmental policy frameworks, and environmental goals. These variables determine which energy technologies are prioritized and how they are integrated into local and national energy strategies. As the global energy landscape evolves, there is a growing emphasis on enhancing the share of renewable energy sources and reducing the reliance on fossil fuels to address climate change, improve energy security, and promote sustainable development. While fossil fuels continue to constitute a significant portion of the global energy mix, the increasing adoption and competitiveness of renewable energy technologies are anticipated to lead to a gradual shift in the proportions of energy sources, with renewable energy playing a larger role in meeting global energy demands in the coming years.

Solar energy refers to the power derived from the sun’s radiation. It is harnessed using photovoltaic devices, commonly known as solar panels, which can be designed to generate either electricity or thermal energy. Despite its vast potential, the combined global energy contribution from renewable sources such as wind, solar, geothermal, and biofuels remains below 2% of total consumption (De Castro, Mediavilla, Miguel, & Frechoso, 2013). The sun delivers an average of 174,000 terawatts (TW) of energy to the Earth's surface, with approximately 86,000 TW reaching land and 21,840 TW falling on non-ice-covered land. However, less than 10% of this immense energy is currently captured and converted into electricity (De Castro et al., 2013).

Solar irradiation is suns radiant energy incident on surface of unit area. Solar irradiation (energy) is equal to average irradiance (power) multiplied by time Peak sun hours (PSH) is average daily amount of solar energy received on surface. Solar irradiance is the power per unit area, received from the Sun in the form of electromagnetic radiation as reported in the wavelength range of the measuring instrument. Solar irradiance is often integrated over a given time period in order to report the radiant energy emitted into the surrounding environment, during that time period. This integrated solar irradiance is called solar irradiation, solar exposure, solar insolation, or insolation. Irradiance on the Earth's surface additionally depends on the tilt of the measuring surface, the height of the sun above the horizon, and atmospheric conditions (Lee & Levermore, 2020; MUTIE, 2020).

Electrical signals produced by a solar panel per square meter is measured in watts with units of kWh. Measurement of solar energy are used when sizing a Photovoltaic systems and heaters. There two methods which symbolize solar radiation of a given place; namely, solar radiance and Insolation. Solar radiance consists of global or direct radiation measurements, while solar insolation is the total amount of solar energy received at a particular location during a specified time period. These two measurements are affected by the environmental factors like clouds, smoke, obstacles like buildings, trees and other factors, (Schafer, Holben, Eck, Yamasoe, & Artaxo, 2002; Yeom, Han, & Kim, 2012).

Apart from photovoltaic extraction of solar energy in form of electrical energy, solar panels can also be used to extract thermal energy for the purpose of heating and cooking. Solar thermal collectors are currently on a high demand as a way of supplementing electric heating systems (Xiaowu & Ben, 2005).

Mathematical modeling is a representation of a real situation, using mathematical equations. These are either algebraic, differential or trigonometric equations or a combination of all. A physical phenomenon is transformed with stated assumptions and conditions to a mathematical system of equations, then solved and the results interpreted back to the physical situations.

Various mathematical models have been used to find a balance of energy mix, so as to minimize costs and improve customer satisfaction. Among them is the use of multi-objective optimization algorithms to simulate energy supply and demand (Best, Flager, & Lepech, 2015). Other methods of optimization were used to analyze consumption of energy and production of carbon (Best et al., 2015).

The work done by (Wahid & Hermawan, 2020), aimed at determining electricity demand projections and fulfilment of the obtained needs using renewable energy. It was found that the optimum energy mix had the proportion of renewable energy at 52%. The mathematical model used was of the type of a regression model, with data obtained from the government. In an attempt to find an optimal solution to energy mix, it is always faced with multiple options, constraints and objectives, which leads to a multi-objective problem. The most common and latest technology form of analyzing such complex systems is by use of a smart grid, and neural networks. Here, smart grid is not viewed as a global device for controlling and balancing optimal energy mix, but seen as a mathematical technique used to simulate and determine the optimal energy mix (Wahid & Hermawan, 2020).

2.5 Mathematical Modelling of Solar Collector

Mathematical Modeling in Solar Energy Systems

Mathematical modeling is vital for designing, assessing, and optimizing solar energy systems, allowing for the effective use of solar power in a wide range of applications.

This interdisciplinary domain integrates mathematical and computational methods to simulate and assess the performance of solar technologies, factoring in solar radiation, system components, energy conversion mechanisms, and environmental influences.

By leveraging these models, engineers and researchers gain deeper understanding of how solar systems operate, which informs the creation of more effective and dependable energy solutions. A key element of solar energy modeling is the accurate representation of solar radiation and its fluctuations. Essential data—such as direct normal irradiance, diffuse horizontal irradiance, and global horizontal irradiance—serve as foundational inputs. Models analyze and forecast radiation patterns based on variables like geographic location, time of day and year, atmospheric conditions, and shading effects. This allows for precise estimation of solar resource availability and optimal positioning of solar systems to enhance energy capture.

Moreover, mathematical modeling is vital for simulating solar photovoltaic (PV) systems, which convert sunlight into electricity. PV models address module performance, interactions between arrays, inverters, and the electrical grid, as well as external factors like temperature, dust accumulation, and long-term degradation. These simulations help predict system output under varying conditions, guiding design decisions, sizing, and performance evaluations. Additionally, they support the creation of advanced control strategies aimed at maximizing energy production and improving system reliability. Another area of focus within mathematical modeling of solar energy lies in solar thermal systems, which utilize the sun's heat to generate electricity or provide thermal energy for heating and cooling applications. Mathematical models are used to replicate and analyze the thermal dynamics of solar collectors, the flow and performance of heat transfer fluids, the efficiency of energy storage systems, and the mechanisms of power conversion. These simulations help optimize system design, predict performance under varying conditions, and improve overall energy efficiency.

These models enable engineers to analyze system performance, evaluate the impact of design parameters, and optimize the operation of solar thermal installations for enhanced efficiency and cost-effectiveness. Additionally, mathematical modeling is essential for integrating solar energy systems with energy storage solutions. It facilitates accurate forecasting of storage needs, fine-tuning of charging and discharging processes, and comprehensive evaluation of system efficiency and reliability.

This is particularly pertinent in addressing the intermittent nature of solar energy and enhancing the reliability and dispatchability of solar power. In addition, mathematical modeling plays a key role in the techno-economic evaluation of solar energy projects. It facilitates the analysis of investment returns, the calculation of the levelized cost of electricity (LCOE), and the determination of overall project viability, helping stakeholders make informed financial and strategic decisions.

By incorporating parameters such as capital costs, operational and maintenance expenses, energy yield projections, and financial incentives, these models provide valuable decision-support tools for project developers, investors, and policymakers. Notably, advancements in computational techniques, data analytics, and machine learning have expanded the capabilities of mathematical modeling in the realm of solar energy. The incorporation of big data, real-time monitoring, and predictive analytics enhances the precision and adaptability of solar energy models. This integration supports dynamic performance optimization, early fault identification, and proactive maintenance of solar energy systems. The mathematical modeling of solar energy represents a dynamic and evolving field that underpins the advancement of solar energy technologies and applications. Through the use of mathematical models, researchers, engineers, and stakeholders can gain a deeper understanding of solar energy dynamics, optimize system performance, and drive innovation in the pursuit of a more sustainable and renewable energy future. As the demand for clean energy solutions continues to grow, mathematical modeling will continue to play a vital role in shaping the development and deployment of solar energy systems across diverse sectors and applications.

A mathematical model is a representation of a real situation, using mathematical equations. These are either algebraic, differential or trigonometric equations or a combination of all. A physical phenomenon is transformed with stated assumptions and conditions to a mathematical system of equations, then solved and the results interpreted back to the physical situations.

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2.6 Improving the Effectiveness of Food Drying Techniques

Enhancing the food drying process is vital for boosting operational efficiency, preserving the quality of dried products, and minimizing energy consumption. To achieve consistent and high-quality outcomes, various factors must be optimized, including drying methods, equipment design, environmental conditions, and process control strategies. First, controlling the drying temperature and airflow is essential. The temperature should be carefully regulated to ensure efficient moisture removal without causing thermal degradation or loss of nutritional value in the food product. Additionally, optimizing the airflow within the drying chamber is critical to facilitate moisture evaporation and maintain uniform drying throughout the product. The proper selection of the drying method and equipment is also important for optimization. Various types of food often benefit from distinct drying methods, including air drying, oven drying, freeze-drying, or utilizing commercially available food dehydrators, depending on their unique characteristics and preservation needs. Every drying technique offers unique benefits and drawbacks, making it crucial to select the most appropriate method based on the characteristics of the specific food product. This tailored approach ensures optimal drying performance, preserves quality, and enhances overall efficiency. Furthermore, the thickness and size of the food pieces being dried should be carefully considered. Uniformly sizing the food items and maintaining a consistent thickness can help facilitate uniform drying and reduce the overall drying time, leading to increased efficiency and consistent product quality. Monitoring and controlling the relative humidity in the drying environment are critical for optimizing the process. Maintaining proper humidity levels helps prevent case hardening, where the surface of the food dries too quickly, forming a barrier that impedes moisture evaporation from the interior of the product. This can be achieved through the use of appropriate ventilation, air circulation systems, and humidity control measures. In addition, the prevention of microbial contamination and spoilage during the drying process is essential. Maintaining strict hygiene, sanitation, and preventive protocols during both the pre-drying and post-drying phases is essential to safeguard the safety and quality of dried food products. Additionally, enhancing the energy efficiency of the drying process is vital for promoting sustainability and reducing operational costs. This can include adopting energy-efficient drying technologies, incorporate renewable energy sources, and utilize heat recovery systems to reduce both energy usage and operational expenses. Careful attention to factors such as temperature control, airflow, equipment selection, food piece size, humidity management, hygiene practices, and energy efficiency is therefore necessary in the optimization process. By considering these factors and implementing best practices, it is possible to achieve optimal drying results, maintain product quality, and ensure the safety and efficiency of the drying operations.

While the primary goal of the food drying process is to reach a moisture content level that prevents spoilage, it's equally important to ensure the process is optimized for time efficiency, cost-effectiveness, and quality preservation. Achieving this balance requires adjusting and analyzing various operational parameters—such as temperature, airflow, and drying duration—through simulation techniques to identify the most effective combination for optimal performance. One of the major concerns is environmental conservation and use of green energy. The most common sources of heat in food dryers include electricity, fuel and thermal energy commonly referred to as solar energy.

Thermal energy from the sun can be trapped and utilized locally in various areas of applications. The most common application is solar heating and solar electric power. These two applications both use a special solar panel which can transform the energy from the sun to other forms. Several studies have been done on the improvement of efficiency, and application of thermal energy in various fields. Most of the studies use mathematical equations to model thermal heat dynamics.

The solar domestic hot water model studied composed of the solar collector, storage tank and the greenhouse, all interconnected with a series of insulated pipes ferrying hot and cold water. Heat and mass transfer equations were used in modeling the heat dynamics in a greenhouse. Block oriented approach was used in modeling domestic solar heating. Simulation were run for a period of 24-hours using MATLAB-SIMULINK, and the model results showed significant equivalence with the measured data. (Buzás & Farkas, 2000). In this study however, no heat exchangers were used.

As an intervention strategy to food security, studies on solar food drying technology was done by (Neto, 1997). The study focused on a fully packed continuous conveyor direct fired dryer. Food and drying air mass and energy balance equations were used to model the dryer. Simulation results were run to optimize the drying air velocity and temperature parameters. In this study, methane fuel was used as a source of energy, which hated hot air circulation in the dryer. It was found that mass and energy transfer equations were able to model the drying process of the food particle. Model optimal operation was found to closely equivalent to the experimentally measured data. In this model, the dryer is a directly heated continuous conveyor belt, with direct heating from burning methane gas.

Drying technologies of food was also studied by (Ahmed, Singh, Chauhan, Anjum, & Kour, 2013; Chen & Mujumdar, 2009; Xiao & Arun, 2008). In their study, various characteristics of food are discussed. These include physical and chemical changes experienced during drying. The effect of moisture popularly known as water activity is explored in detail. Various drying technologies and dehydration processes are discussed. The various modes of heating explored include; convectional heating, radiative heating, microwave. Radio frequency and joule heating are explored.

The fundamental equations used to model the drying process are essential for understanding and predicting the behavior of moisture removal from food products during the drying process. These equations are derived from fundamental principles of heat and mass transfer and are employed to characterize the dynamics of moisture movement within the food material as it undergoes drying. Some of the key equations commonly used in modeling the drying process include:

1. Fick's second law of diffusion: This partial differential equation describes the transient diffusion of moisture within the food material as it moves from the interior to the surface during drying (Guenneau & Puvirajesinghe, 2013). Fick's second law describes how moisture content within a food product changes over time and space, offering valuable insight into the rate and pattern of moisture diffusion during the drying process. This law is fundamental for modeling and predicting moisture migration, which is critical for optimizing drying efficiency and ensuring uniform product quality.

2. Drying kinetics equations: These equations—including empirical models like the Page model, Logarithmic model, and others (Azzouz, Guizani, Jomaa, & Belghith, 2002)—characterize the drying rate based on variables such as moisture content, drying

time, and temperature. They provide valuable tools for predicting drying behavior and optimizing process parameters to enhance efficiency and product quality.

These kinetics equations provide a quantitative representation of the drying process and are used to characterize the drying behavior of specific food products under varying drying conditions.

3. Heat and Mass Transfer Equations: Heat and mass transfer equations—such as the energy balance equation, mass conservation equation, and Darcy's law for porous media permeability—are fundamental tools for simulating the movement of heat and moisture within food materials during the drying process (Azzouz et al., 2002; Danilov, Maslov, & Volosov, 2012). These equations provide a framework for understanding and optimizing the drying dynamics in food systems. These equations account for the convective, conductive, and evaporative heat and mass transfer mechanisms that occur as moisture is removed from the food.

4. Equilibrium moisture content models: These models describe the relationship between moisture content and relative humidity at equilibrium conditions (Oyelade, 2008). They are used to characterize the moisture sorption properties of the food material, providing valuable insights into the interaction between the food product and the surrounding drying environment.

5. Shrinkage and Porosity Equations: Shrinkage and porosity equations characterize the physical transformations that food materials undergo during drying, including reductions in volume, changes in porosity, and modifications to internal structure (Madiouli et al., 2007). Grasping these alterations is vital for accurately forecasting the mechanical behavior and texture of the final dried products.

By applying these core equations, researchers and food engineers are able to construct detailed mathematical models and simulations that effectively describe and enhance the food drying process. These models support the prediction of quality attributes in dried products and aid in the design of energy-efficient, high-performance drying systems tailored to specific food types and operational conditions.

These models are valuable tools for enhancing the understanding and control of the complex phenomena involved in the drying of food materials.

A mathematical model of the drying process of skin and hides was studied by (Haghi, 2001). Two fundamental equations on heat and mass transfer were used to model the drying process. It was found that transient distribution of moisture and heat in leather can be predicted and therefore optimized to conserve energy.

Studies on drying process of vegetables was done by (Iguaz, Esnoz, Martínez, López, & Vırseda, 2003) using a rotary dryer. Air and product temperature and humidity was determined and compared with actual data measurement and significant correlation was found. Six differential equations were analyzed to solve and determine the optimal ranges of six parameters, which include inlet temperature, air flow rate, moisture loss rate, outlet air temperature and humidity. From dynamic simulation, it was shown the temperature and moisture content of the products and the drying air can be predicted and therefore determine the drying time required for each product. According to Iguaz et al. (2003), inlet air temperature has a greater influence on the drying process than air flow rate in parallel flow configurations. However, in concurrent flow systems, air flow rate emerges as a more critical factor affecting the drying efficiency.

The big question which this research study is trying to answer is, for how long, at what temperature, at what air flow rate and velocity, and what initial moisture content of a product is required to dehydrate high quality final product to desired moisture content, and at what cost of energy. Is the cost minimal? These are answered from the model to be formulated, and simulations to be run.

2.7 Neural Networks and Energy Optimization

Neural networks have been widely used in optimization problems across various fields due to their ability to model complex relationships and learn from data. Optimization involves selecting the best possible solution from a set of alternatives by either maximizing or minimizing a specific objective function, all while satisfying predefined constraints. This process is fundamental in engineering and decision-making, where efficiency, cost-effectiveness, and performance must be balanced within given limitations.

Neural networks, with their ability to approximate complex functions and adapt to non-linear relationships, have proven to be effective tools for solving optimization problems.

One common application of neural networks in optimization is in the field of operations research, where they are used to solve complex scheduling, routing, and resource allocation problems. For example, neural networks have been employed to optimize production schedules in manufacturing, vehicle routing in logistics, and workforce scheduling in service industries. By training neural networks on historical data and using them to predict optimal schedules or resource allocations, organizations can improve efficiency and reduce costs. In engineering and design, neural networks are applied to enhance the efficiency and functionality of intricate systems and operations. For example, in structural engineering, neural networks are employed to enhance building design by analyzing factors like material characteristics, load dynamics, and budget limitations. In aerospace engineering, they assist in refining aircraft design elements—such as wing geometry and engine positioning—to boost fuel efficiency and overall performance. In finance, neural networks are utilized for optimizing investment portfolios, managing risk, and executing algorithmic trading strategies. By analyzing historical market data and learning patterns from financial markets, neural networks can assist in constructing optimized investment portfolios that balance risk and return.

Additionally, neural networks are employed in fraud detection and credit scoring, where they help financial institutions optimize decision-making processes by identifying fraudulent activities and assessing creditworthiness.

Furthermore, neural networks play a crucial role in supply chain management and inventory optimization. By leveraging neural network models, companies can forecast demand, optimize inventory levels, and improve supply chain efficiency.

Neural networks can detect complex patterns in demand data and external factors—like economic indicators and weather patterns—enabling more precise inventory management. This helps minimize the risks of stockouts and overstocking, ensuring a more balanced and efficient supply chain.

In the domain of energy systems and renewable energy, neural networks are used to optimize power generation, distribution, and consumption. For example, neural networks can be leveraged to forecast energy consumption trends, optimize the functioning of power generation facilities, and enhance the efficiency of renewable energy technologies such as solar and wind systems. Through neural network-based optimization, energy providers can reduce operational costs and improve the seamless incorporation of renewable energy into the electrical grid.

In the context of environmental science and climate modeling, neural networks are utilized to optimize environmental monitoring and resource management. Neural networks can analyze large-scale environmental data, such as satellite imagery and climate model outputs, to optimize the monitoring of natural resources, predict environmental changes, and support decision-making related to conservation and sustainable resource management.

Neural networks, a fundamental concept in the field of artificial intelligence and machine learning, are structured to mimic the workings of the human brain and process complex patterns and data in a manner akin to human cognition. Made up of interconnected nodes, often referred to as "neurons," these networks are built to identify hidden relationships and patterns in data, enabling them to perform a wide range of tasks including pattern recognition, classification, regression analysis, and informed decision-making. The basic building block of a neural network is the artificial neuron, also known as a node or perceptron. These neurons receive input data, perform computations using weighted connections, and produce an output signal. Through the collective behavior of interconnected neurons arranged in layers, neural networks can effectively process and learn from data. Neural networks typically consist of multiple layers, including an input layer to receive data, one or more hidden layers to process information, and an output layer to produce the network's prediction or decision. The power of neural networks stems from their capacity to learn and evolve through data—a process known as training. During this phase, the network fine-tunes the weights of its connections based on input data and desired outcomes, enhancing its accuracy in making predictions or classifications. A widely used architecture is the feedforward neural network, where information flows in a single direction from the input layer through hidden layers to the output layer. This kind of neural network is commonly used in domains such as image recognition, speech analysis, and natural language processing, where it excels at identifying patterns and making sense of complex, high-dimensional data. Another significant class of neural networks is recurrent neural networks (RNNs), which are designed to process sequences of data and have feedback loops that allow them to retain information from previous inputs. RNNs are well-suited for applications involving time-series data, language modeling, and speech recognition, due to their ability to capture temporal dependencies and contextual information. Convolutional neural networks (CNNs) are particularly well-suited for processing grid-structured data like images. They utilize convolutional layers to automatically extract features and build hierarchical representations, which makes them highly effective for tasks such as image classification, object detection, and segmentation—core components of modern computer vision systems. Recent progress in neural network design, training methodologies, and parallel computing has fueled the rise of deep neural networks, distinguished by their multiple hidden layers that enable the modeling of complex patterns and relationships in data. This advancement has greatly improved neural networks' ability to extract complex patterns and abstract features from vast datasets, leading to major breakthroughs in areas like natural language processing, medical diagnostics, autonomous driving, and beyond. Ultimately, neural networks offer a robust and adaptable foundation for machine learning, fueling innovation and reshaping numerous industries and technological domains. By leveraging their capacity to learn from data, recognize patterns, and make informed decisions, neural networks continue to push the boundaries of what is possible in artificial intelligence and contribute to advancements that are reshaping our interactions with technology and the world around us.

In this section, the neural network discussed refers to artificial neural networks and not the human body neural networks. This is denoted by ANN for (Artificial Neural Networks). This is discussed in terms of its application in energy control systems. Artificial neural networks are

Computer networks or programming structures made in likeness of the brain neural architecture. They typically consist of many hundreds of simple decision-making units which are connected in a circuit into a complex network. Each unit of ANN represents a real neuron which is responsible of making a decision or classification between two options; A or B, Yes or No, Right or Wrong, Up or Down, left or right, true or false among others. Two signals are input, and basing on the bias, the output will either be any one of the two options. This is in form of a simplified neuron which fires if it receives depending on the nature of the input stimuli. A significantly strong input signal from the other nodes to which it is connected, will yield an equivalent output signal to the next connected node.

An Artificial Neural Network is an information processing paradigm that is motivated by

biological nervous systems, which is responsible in processing information and giving back the desired response to the input stimulus. The key element of this methodology is the unique structure of the input stimuli processing system. A neural network consists of numerous intricately connected neurons that operate collectively to solve specific problems. Each neuron processes input and contributes to the overall output, enabling the network to learn patterns, make predictions, and perform complex tasks through coordinated computation. Artificial Neural Networks, much like humans, adapt and refine their responses when exposed to repeated stimuli. This learning process involves comparing the input, actual output, and the desired output to assess and reduce errors in future predictions. These networks are architected to handle complex tasks such as nonlinear Bayesian classification, along with a wide range of other mathematical computations.

The basic unit of a neural network is the single-input neuron, as illustrated in Figure 2.2. This neuron performs three key operations. First, the scalar input is multiplied by a scalar weight, resulting in a scalar product. Next, this weighted input is combined with a scalar bias to produce the net input. The bias, which can be thought of as a weight with a constant input of 1, effectively shifts the function horizontally. Finally, the net input is passed through a transfer function to generate the scalar output. These operations are referred to as the weight function, the net input function, and the transfer function, respectively (Marvin, 2016).

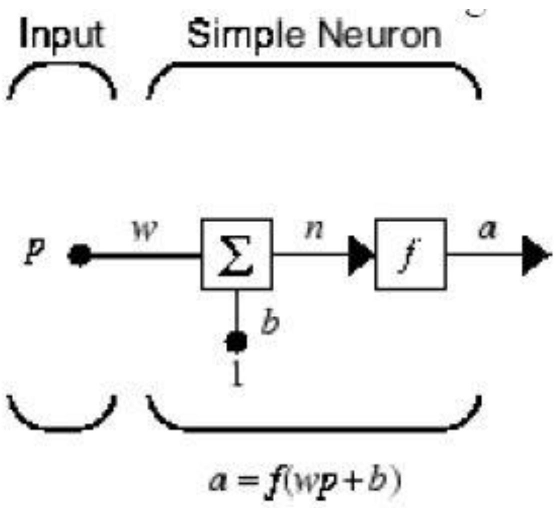

Figure 2-2 A Perceptron, as a unit of a Neural Network. Source:(Marvin, 2016)

A neuron could be a single layer, or multiple layers with a single input or a vector if inputs. It can be instantaneous or with delay. Some of the transfer functions include linear, threshold function or the sigmoid function is expressed as:

$$f(x)=\frac{1}{1+e^{-mx}}$$

where m is the slope parameter, and x is the variable representing the input.

Once the neural network architecture has been built, a set of learning algorithm is passed, through a process called training, so as to enable the network respond to inputs as desired. The training process is designed to enhance the system's responsiveness to repeated inputs, mirroring how the human brain adapts to stimuli through learning (Jones, 2014).Using a multi-layered neural network, training is defined as a process of selecting appropriate values of parameters (weights and biases) which best approximates a given function. By analyzing personal energy consumption data—presumed to follow a consistent pattern—a neural network can be trained to replicate that pattern. Once trained, the network can autonomously regulate energy flow to the individual, optimizing usage based on predicted demand and enhancing overall efficiency. This approach enables smart energy management tailored to individual consumption habits. This is an application of neural network in control systems (Hagan, Demuth, & Jesús, 2002).

In conclusion, neural networks serve as highly effective optimization tools across a wide array of disciplines. Their ability to model complex, nonlinear relationships and learn from data makes them invaluable in fields such as operations research, engineering design, financial forecasting, supply chain optimization, energy management, and environmental modeling. By harnessing their predictive and adaptive capabilities, professionals can enhance decision-making, improve system performance, and drive innovation across these diverse domains. By leveraging the ability of neural networks to learn from data and approximate complex functions, organizations and researchers can address complex optimization problems and improve decision-making processes. As neural network research and applications continue to advance, their role in optimization is expected to expand, offering new opportunities to enhance efficiency, sustainability, and innovation in various fields.

Mathematical optimization methodologies encompass a diverse set of techniques and algorithms designed to identify the best solution from a range of feasible options, subject to specific constraints and objectives. These approaches are widely applied across disciplines such as operations research, engineering, economics, finance, and machine learning to tackle intricate decision-making challenges and improve both efficiency and overall system performance.

One prevalent optimization methodology is linear programming, which is employed to address problems characterized by linear relationships and constraints. Linear programming focuses on finding the optimal value of a linear objective function while adhering to a series of linear equality and inequality constraints. By utilizing techniques such as the simplex method and interior-point methods, linear programming facilitates the allocation of resources, production planning, supply chain optimization, and other decision-making processes in diverse applications. Another prominent optimization technique is nonlinear programming, which addresses problems with nonlinear objective functions and constraints. Nonlinear programming utilizes a range of optimization strategies—such as gradient-based methods, genetic algorithms, and simulated annealing—to find optimal solutions in cases where variable relationships are nonlinear. These techniques are crucial for addressing complex challenges that lie beyond the scope of linear models, allowing for more precise and effective decision-making across a variety of fields.

Nonlinear programming is instrumental in optimizing complex systems, including engineering designs, financial modeling, and parameter estimation in machine learning. Integer programming and mixed-integer programming techniques are used to solve optimization problems in which some or all decision variables must assume integer values. This constraint introduces greater complexity than standard linear programming, as it transforms the solution space into a discrete set, often requiring more advanced algorithms to find optimal or near-optimal solutions. These methods are particularly valuable in applications involving scheduling, resource allocation, and logistics, where decisions are inherently indivisible. These methodologies are crucial in addressing optimization challenges related to discrete decision-making, such as resource allocation, scheduling, and combinatorial optimization problems in logistics, transportation, and telecommunications. Furthermore, optimization methodologies extend to stochastic programming, which accounts for uncertainty and risk in decision-making processes. Stochastic programming models incorporate probabilistic distributions and scenarios to address optimization problems under uncertainty, making them essential in risk management, portfolio optimization, and decision-making in the presence of random variables and fluctuations. In addition, metaheuristic optimization techniques—like genetic algorithms, particle swarm optimization, and simulated annealing—offer robust solutions for addressing complex optimization problems. These methods rely on population-based search strategies and iterative improvement mechanisms to explore large, nonlinear, and multimodal solution spaces efficiently, often outperforming traditional optimization approaches in challenging scenarios.

These methodologies are particularly effective in addressing combinatorial optimization, global optimization, and multi-objective optimization challenges in diverse domains. Moreover, convex optimization methodologies are pivotal in addressing optimization problems characterized by convex objective functions and constraints. Convex optimization techniques, such as interior-point methods and gradient descent algorithms, enable efficient and scalable solutions for a wide range of applications, including machine learning, signal processing, and control systems. In conclusion, mathematical optimization methodologies encompass a rich array of techniques and algorithms that play a critical role in addressing complex decision-making problems across diverse domains. By leveraging linear programming, nonlinear programming, integer programming, stochastic programming, metaheuristic optimization, and convex optimization methodologies, researchers, engineers, and decision-makers can derive optimal solutions, enhance efficiency, and make informed decisions that drive progress and innovation in a wide range of industries and applications.

2.8 Laplace transform and Transfer functions

The Laplace transform is a powerful mathematical tool used in engineering, physics, and mathematics to simplify the analysis of linear time-invariant systems and functions. It converts a time-dependent function, typically represented as f(t), into a function of a complex variable F(s) . The transform is defined by the integral:

$$F(s) = \int_0^\infty e^{-st} * f(t)\ dt$$

where e^{-st} is the exponential kernel and s is a complex frequency parameter. By applying Laplace transform allows differential equations to be transformed into algebraic equations, simplifying the analysis and solution of problems in areas such as control systems, electrical circuits, and signal processing. This transformation facilitates easier manipulation and solution of complex dynamic systems by working in the frequency domain rather than the time domain. The Laplace transform provides a method to analyze the behavior and response of linear systems to different inputs and disturbances. The inverse Laplace transform, denoted as

$$f(t) = \mathrm{L}^{-1}[F(s)],$$

This enables the reconversion of the transformed function into the time domain, facilitating the analysis of the system's response or behavior over time (Guenneau & Puvirajesinghe, 2013).

The Laplace transform also offers the benefits of linearity and time-shifting, making it a valuable tool for solving differential equations, convolution integrals, and initial value problems. Additionally, it is widely used in the analysis of stability, transient response, and frequency response characteristics of systems. In summary, the Laplace transform serves as a fundamental tool for simplifying the analysis of linear time-invariant systems, enabling the representation and solution of complex problems in a more manageable mathematical framework .

As a powerful mathematical technique used to solve complex differential equations, Laplace transform involves converting differential equations to algebraic equations, which can then be solved algebraically and inversely transformed back to original variables so as to obtain the solution of the differential equation.

The transfer function offers a streamlined depiction of a system's input-output dynamics within the frequency domain, serving as a crucial instrument for analyzing and designing systems. The relationship between the Laplace transforms and transfer functions is fundamental in the study of linear systems and control theory. Transfer functions are used to characterize the dynamic behavior of systems, and the Laplace transform provides a mathematical framework for their analysis. By representing systems in the frequency domain, engineers and researchers can analyze stability, transient response, frequency response, and other key system properties (Hsu, Peng, & Chang, 1997).

2.9 Feedback Mechanism and Optimal Controls

Feedback mechanisms are a fundamental concept in various fields, including biology, engineering, business, and social sciences. A feedback mechanism involves the process of using information about the output of a system to influence the operation of the system itself. This loop of information allows a system to adjust its behavior based on the output, thereby regulating its performance, stability, and response to external stimuli.

In biological systems, feedback mechanisms are vital for maintaining homeostasis—the process of preserving internal equilibrium. For instance, the human endocrine system relies on feedback loops to control hormone secretion, blood glucose levels, body temperature, and other physiological parameters. Negative feedback loops stabilize conditions by correcting deviations from a target value, whereas positive feedback loops can intensify changes, potentially causing instability (Cosentino & Bates, 2011).

Similarly, in engineering and control systems, feedback plays a crucial role in managing the behavior of dynamic systems. These systems utilize feedback to compare actual output with a desired set point, enabling adjustments that correct errors and respond to disturbances. This enhances both performance and stability. Common examples include thermostats in heating and cooling systems, cruise control in vehicles, and automatic voltage regulators in electrical grids (Thompson & Stewart, 2002).

In business and economics, feedback mechanisms are integral to performance management, decision-making, and market dynamics. Feedback from customers, employees, and stakeholders provides valuable information that organizations use to adapt their strategies, products, and operations. In financial markets, feedback mechanisms influence price dynamics, investment decisions, and market efficiency, shaping the behavior of investors and market participants (Goncharenko, Sharko, Sybachin, Khachaturyan, & Prokopenko, 2020).

In social and behavioral sciences, feedback mechanisms are involved in processes such as learning, communication, and social interaction. Feedback serves a vital function in education by offering students insights into their performance, helping to steer their learning process and foster the development of essential skills. In interpersonal relationships and group dynamics, feedback mechanisms influence communication, cooperation, and the evolution of social norms and behaviors (McLeod & Mortimer, 2012).

Optimal control is a field of mathematics focused on determining control strategies for dynamic systems to achieve a desired outcome or follow a specified trajectory. It involves finding the control inputs that optimize a performance criterion—such as minimizing energy use or maximizing efficiency—while ensuring the system behaves according to its governing equations and constraints. This control of a system is done over an interval of time to get the optimal solution with minimum errors (Lenhart & Workman, 2007). Optimization is applicable in engineering, biology, social and environmental realms, with the use of solar power not exceptional.

Formulation of optimal control function involves the description of a set of state equations which describes the dynamical system (plant), to be controlled. In this study, the focus is on regulating the drying process of food particles. Given the physical constraints of the processing plant, it is crucial to consider both control and state variables when establishing the system's operational boundaries. These variables play a key role in ensuring the drying process remains efficient, consistent, and within safe operating limits. The performance index measure which is either time, energy, fuel consumption, or a state regulator problem is modelled in different ways (Lin, 2007).

In this study, the solar food dryer challenge is approached as a state regulation problem, where optimization focuses on minimizing the elements of the state vector and aligning the output vector components with a predefined trajectory (Lewis, Vrabie, & Syrmos, 2012).

2.10 Model Linearization and Stability

Every model formulated has discrepancies between the actual model and the mathematical representation. This is due to assumptions and rounding off effects of the model. It is for this reason that every model is checked for its stability and sensitivity to small perturbations. The process of linearizing a state space system entails approximating the nonlinear dynamics of the system around an equilibrium point with a linear model. This linear model provides a simplified representation that can be utilized for analysis, stability assessment, and controller design.

Linearization is a fundamental concept in control theory and engineering that plays a crucial role in analyzing and understanding the behavior of complex systems. In this discussion, we will explore the process of linearization and its relationship to the stability of a system. We will delve into the underlying principles, mathematical techniques, and practical implications of linearization, with a focus on its significance in assessing system stability. Linearization is a method used to approximate the behavior of a nonlinear system around an operating point by constructing a linear model. Nonlinear systems, which are common in various engineering applications, exhibit complex and often unpredictable behaviors. However, by linearizing these systems, engineers can simplify their analysis and design processes, enabling the application of well-established linear control techniques. The process of linearization involves determining the linear approximation of the system's dynamics near a specific operating point. This is typically achieved through the use of Taylor series expansion, where the nonlinear system equations are approximated by a linear model that captures the system's behavior in the vicinity of the operating point. The linearized model provides a simplified representation of the system's dynamics, often in the form of state space equations or transfer functions, which are easier to analyze and manipulate mathematically. One of the key motivations for linearizing a system is to assess its stability. The stability of a system refers to its ability to return to a desired equilibrium or operating point following a disturbance. In control theory, stability is a critical property that directly impacts the performance and safety of engineered systems. Linearization allows engineers to assess the stability of nonlinear systems by examining the characteristics of their linear approximations near a specific operating point. This approach simplifies complex dynamics, offering critical insights into system behavior in localized regions. Common techniques used in the stability analysis of linearized models include eigenvalue analysis, frequency domain approaches, and Lyapunov stability methods. These approaches help engineers assess whether a system is stable, marginally stable, or unstable, and identify the key factors affecting its stability. By analyzing the eigenvalues of the system’s linearized state matrix or transfer function, engineers can extract critical insights into stability margins, transient behavior, and frequency response—information that is vital for developing robust and efficient control strategies.

Furthermore, linearization facilitates the application of well-established stability criteria, such as the Routh-Hurwitz criterion, the Nyquist stability criterion, and the root locus method, which are widely used in control system design. These stability criteria rely on the linearized model of the system to assess its stability properties and guide the selection of control parameters to achieve desired performance objectives. In practical engineering applications, linearization and stability analysis are essential steps in the design and implementation of control systems for a wide range of physical and technological systems. For example, in aerospace engineering, the stability of an aircraft's flight dynamics is critically important for ensuring safe and reliable operation. By transforming the nonlinear equations of motion that describe an aircraft's dynamics into a linearized form, engineers can evaluate the system's stability properties more effectively. This simplification enables the development of control algorithms aimed at improving the aircraft's stability and maneuverability, particularly around a specific operating point or flight condition.

Similarly, in robotics and mechatronics, the stability of robotic manipulators and automated systems is crucial for achieving precise and reliable performance. By linearizing the nonlinear dynamics of these systems, engineers can analyze their stability properties and design feedback control strategies to regulate their behavior and achieve desired performance specifications. In summary, linearization serves as a valuable technique that empowers engineers and researchers to examine the dynamics and stability of intricate nonlinear systems. Through the development of linearized models, they can uncover critical stability characteristics and formulate robust control strategies to meet specific performance goals. The application of linearization and stability analysis extends across diverse engineering disciplines, making it an indispensable tool for understanding and manipulating the behavior of complex systems.

2.11 Stability of Step Response function

The step response function is a fundamental tool used in control system analysis and design to evaluate the dynamic behavior and stability of a system. By subjecting a system to a sudden change or step input and observing its response over time, engineers can gain valuable insights into the system's stability, transient response, and performance characteristics. In this discussion, we will explore various methods for analyzing the stability of a step response function, including time-domain analysis, frequency-domain analysis, and stability criteria commonly used in control system engineering. Time-Domain Analysis of Step Response One of the primary methods for analyzing the stability of a step response function involves time-domain analysis, which focuses on examining the system's behavior in the time domain. The step response function offers a clear depiction of how a system's output changes over time when subjected to a step input. By analyzing key time-domain metrics such as rise time, settling time, overshoot, and steady-state error, engineers can assess the stability and performance of the system. For example, the settling time of a step response function reflects how rapidly the system attains and stays within a defined range near its final output value.

A system with a fast-settling time is often indicative of good stability characteristics, while a prolonged settling time may suggest instability or sluggish response. Similarly, overshoot and oscillations in the step response can be indicators of instability, as they reflect excessive or uncontrolled behavior in the system's response. Frequency-Domain Analysis of Step Response In addition to time-domain analysis, frequency-domain analysis provides a powerful method for evaluating the stability of a step response function by examining the system's behavior in the frequency domain can be analyzed using methods like the Fourier transform, Laplace transform, and Bode plots. These techniques provide engineers with valuable insights into the system's frequency response and stability traits. Through frequency-domain analysis, engineers can evaluate key stability metrics such as gain and phase margins, which are essential for ensuring reliable system performance. Gain margin reflects how much the system's gain can increase before it reaches instability, serving as an indicator of tolerance to gain fluctuations. Phase margin, on the other hand, measures the system's resilience to phase shifts within the feedback loop, providing insight into its overall robustness and stability. Systems with adequate gain and phase margins are generally considered stable, while insufficient margins may indicate instability and the potential for oscillations or instability. Stability Criteria and Methods Several stability criteria and methods are commonly employed to analyze the stability of a step response function and evaluate the system's stability margins. The root locus method, for example, provides a graphical technique for determining the poles and zeros of the system's transfer function and visualizing how changes in system parameters affect stability. Analyzing the root locus plot enables engineers to pinpoint areas of stability and instability, as well as evaluate how changes in system parameters influence overall stability. Another commonly applied method is the Nyquist stability criterion, which utilizes the system's frequency response to assess its stability. Through the construction of a Nyquist diagram and examination of the open-loop frequency response, engineers can determine key indicators such as gain and phase margins, and forecast the system's stability performance across different operating scenarios.

Additionally, the Bode stability criterion and the Routh-Hurwitz stability criterion serve as valuable analytical tools for assessing the stability of a system's step response. By examining the system's transfer function and frequency response, these methods help determine key stability characteristics. This analysis supports the formulation of effective control strategies that enhance both the stability and overall performance of dynamic systems. Practical Applications and Engineering Significance The analysis of the stability of a step response function is critically important in various engineering applications, including aerospace, automotive, robotics, and industrial control systems. For example, in aerospace engineering, the stability of an aircraft's response to pilot commands and external disturbances is essential for safe and reliable flight operations. By analyzing the stability of the aircraft's control system using step response functions, engineers can fine-tune control algorithms and autopilot systems to ensure stable and predictable behavior under diverse operating conditions. Similarly, in industrial control systems, the stability of feedback loops and regulatory control systems directly impacts the performance and reliability of manufacturing processes and equipment. Stability of step response helps in identifying stability issues, optimize control parameters, and enhance the stability and robustness of industrial control systems to achieve precise and consistent operation. In conclusion, the analysis of the stability of a step response function is a multifaceted and essential aspect of control system engineering. By utilizing both time-domain and frequency-domain analysis methods, along with established stability criteria and techniques, engineers can obtain critical insights into a system's stability properties and develop robust control strategies to meet specific performance goals. The application of stability analysis extends across diverse engineering disciplines, making it an indispensable tool for understanding and manipulating the behavior of complex control systems.

Analyzing the stability of a step response function is a critical aspect of control system engineering, as it provides insights into the dynamic behavior and stability of a system. According to Ogata (2010), time-domain analysis and frequency-domain analysis of step response functions are essential methods for evaluating the stability and performance characteristics of control systems. The step response function enables engineers to evaluate critical performance metrics—including rise time, settling time, overshoot, and steady-state error—which serve as important indicators of a system's stability (Ogata, 2020). Moreover, frequency-domain techniques like Bode plots and the Nyquist stability criterion are commonly used to analyze system stability by examining gain and phase margins (Ogata, 2020).These methods enable engineers to assess the robustness and stability of control systems, guiding the design of effective control strategies to achieve desired performance objectives. Moreover, the root locus method, as described by (Bishop, 2011), provides a graphical approach for analyzing the stability of step response functions by visualizing the pole-zero locations and their impact on system stability. By applying stability criteria and analytical methods, engineers can obtain meaningful insights into the stability features of step response functions, which in turn support the development of control strategies aimed at improving system stability and performance (Bishop, 2011). In practical engineering applications, the stability analysis of step response functions plays a crucial role in various domains, including aerospace, automotive, robotics, and industrial control systems. For instance, in aerospace engineering, the stability of aircraft control systems and autopilot response to step inputs is essential for ensuring safe and reliable flight operations. By analyzing the stability of step response functions, engineers can optimize control algorithms and autopilot systems to achieve stable and predictable behavior under diverse operating conditions. In essence, analyzing the stability of step response functions is a core component of control system engineering, empowering engineers to comprehend and influence the dynamics of complex systems to attain targeted stability and performance outcomes.

CHAPTER THREE

DRYER MODEL EQUATIONS

This chapter deals with the methods used to achieve the desired objective of designing an optimal solar food dryer. The chapter consists of a brief description of the solar dryer, a set of equations describing the food drying process and a set of equations describing the heat and fluid flow in the fluid circuit. Parameters controlling the efficiency of the solar dryer are also discussed in this chapter. This includes the methods of analysing the equations and simulation techniques.

3.1 Solar Dryer Components

A solar dryer is a type of device used to dry food products using solar energy as a source of heat. The solar collector harnesses the energy from the sun to create an environment that facilitates the removal of moisture from food items, thereby preserving them and extending their shelf life. Solar dryers are popular in locations with abundant sunlight and are valued for their energy efficiency, cost-effectiveness, and environmentally friendly operation. The basic principle behind a solar dryer involves capturing solar radiation and converting it into heat for the drying process (Amer et al., 2010). Solar dryers are designed to maximize solar exposure and heat retention while providing adequate airflow to facilitate moisture evaporation.

There are several configurations of solar dryers, including direct, indirect, and mixed-mode designs, each with unique features and applications. In a direct solar dryer, food products are exposed directly to sunlight, allowing solar radiation to heat the air inside the drying chamber, promoting moisture evaporation from the food. Indirect solar dryers utilize a separate solar collector to absorb solar energy and transfer it to the drying chamber through a heat exchange mechanism, preventing direct exposure of the food to sunlight. Mixed-mode solar dryers combine both direct and indirect heating methods to optimize the drying process under varying environmental conditions. Key components of a typical solar dryer include a collector, absorber, drying chamber, and ventilation system. The collector, often integrated with a transparent cover or glazing, captures solar radiation, while the absorber absorbs the solar energy and transfers it to the drying chamber. The drying chamber houses the food products and provides a controlled environment for the drying process, while the ventilation system facilitates airflow, promoting moisture removal and preventing overheating. Solar dryers offer several advantages, such as reduced energy costs, minimal environmental impact, and suitability for off-grid and remote locations. They are commonly used for drying a variety of agricultural products, including fruits, vegetables, grains, spices, and herbs, as well as fish and meat in some applications. Solar dryers are also favored for their ability to preserve the quality and nutritional integrity of the dried products compared to traditional sun drying methods. Solar dryers therefore harness solar energy to facilitate the drying of food products, offering an efficient and sustainable approach to food preservation. Their versatility, energy efficiency, and low operational costs make them a valuable tool for small-scale food processing, agricultural activities, and community-based initiatives aimed at enhancing food security and livelihoods (Amer et al., 2010).

Solar dryer under study in this research work is composed of four compartments, namely; the solar collector, the closed fluid pipe circuit, the heat exchanger, and the heating/drying chamber. The four components are interconnected and their operations controlled from one point. The first component of the solar collector picks the solar irradiation and heat water which is channelled through it. The fluid properties, flow rate and the number of solar irradiations together with the efficiency of the solar collector determine the temperature range of the fluid. The second component of closed fluid circuit consists of insulated pipes, water reservoir and water pump. This ensures continued flow of fluid and regulates the flow rate and fluid volume in the circuit. The third component is the heat exchanger. This component transforms the heat in the fluid to hot air. It consists of a set of air fans and a radiator. The fans extract the heat from the radiator and channels regulated hot air to the fourth chamber. The last chamber is the heating compartment. It is an open space where food is placed to dry. It may have shelves or trays holding food. In this compartment, a dehumidifier, a set of thermometers and air circulation controls are placed to monitor the temperature of the chamber.

The Figure 3.1 below is a flow chart describing the major components of the proposed solar dryer and how the components are inter-connected.

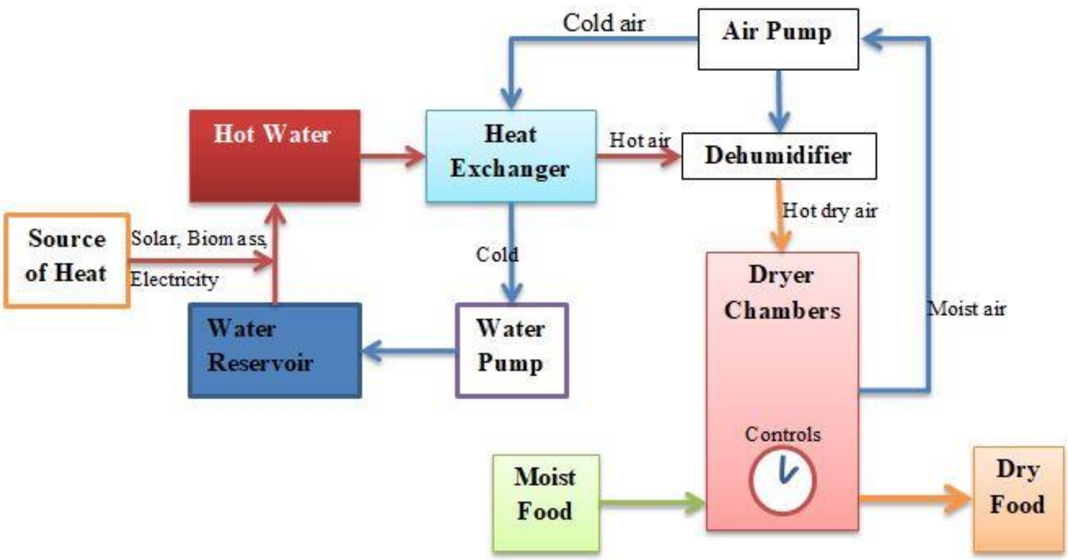

Figure 3-1 Compartmental Flow Chart of a Solar Drier. Source: Author

A simplified diagram showing the major components of the dryer is presented in Figure 3.2. The mathematical model is formulated to represent the four components; that is, the solar collector, fluid flow and heat transfer, the drying process of the food particles and the controls. The description of the detailed components was described in the next section. The alternative source of heat is not shown in the illustration, but can be placed to replace the solar collector.

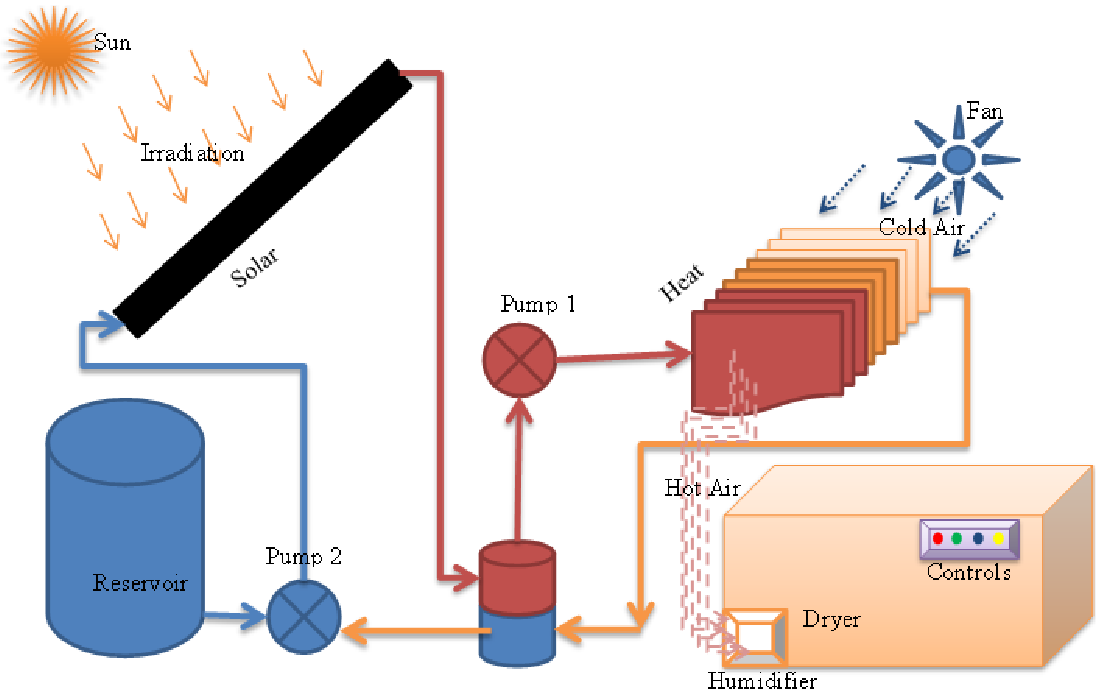

Figure 3-2 Conceptual Model of a Complete Solar Dryer. Source: Author

3.2 Model Formulation and Equations

The dryer model is subdivided into four sections, namely; the solar collector system; the piping system; the heat exchanger system; and the drying compartment. Mathematical equations are formulated for each section of the model, and coupled to give the state of the entire system. However, model equations representing the solar, and other alternative heat sources are analysed separately because of their independence from the other compartments. Once the optimal solution is achieved, the output solution is used as the input temperature to the piping compartment. After considering losses, the output of piping system becomes the input to the heat exchanger. This chain continues to finally reach the drying compartment.

3.2.1 Model Equations of a Solar Collector

In this subsection, model equations describing the working and the efficiency of the solar collector is formulated and analyzed. The components of this subsystem include the solar irradiation, solar collector panel, and the flow rate, input and output temperatures of the fluid together with the ambient temperature of the solar collector.

A solar collector is made up of several glass tubes arranged and interconnected to form a rectangular shaped solar collector, where water flows in, get heated by the heat from the sun, and hot water flow out at a given flow rate determined by a water pump connected to the source. Each solar collector is made up of a system of glass evacuated tubes, with water circulation loop as shown in Figure 3.3. The collector is made up of 400 tubes measuring 32mm diameter and 4000mm long, with a capacity of approximately 1,286,796 liters.

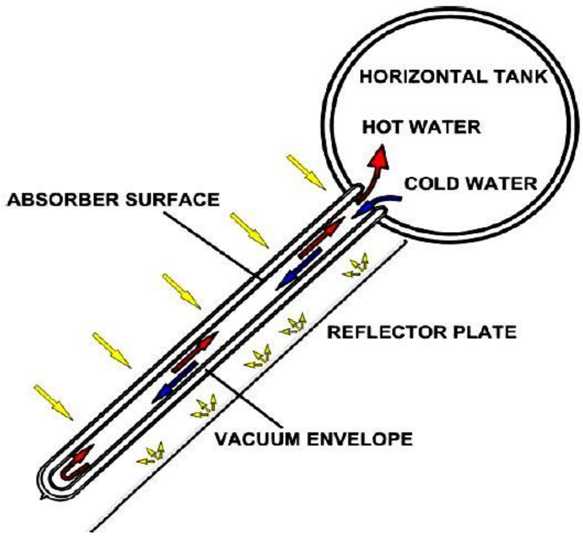

Figure 3-3 Solar Collector Glass evacuated tube. Source: (Budihardjo & Morrison, 2009)

A metal frame to hold solar collectors measuring 13m by 4m is estimated to hold and the support solar collectors which cover an approximate area of $52m^2$. Two sets of solar collectors were arranged to be inclined at 45^0 degrees, one set facing eastwards, and another set facing westwards, so as to collect as much radiation from the sun as possible, from morning to afternoon.

3.2.2 Solar Collector Model Equations

From the law of conservation of mass or energy, the fundamental relation of input, output and accumulation of energy or matter is given by;

$$Accumulaton\ of\ Matter\ = Input - Output + Internal\ Created\ - \ Loss \quad (3.1)$$

A schematic representation of a solar collector is shown in Figure 3.4(a), while a typical picture of vacuum tube solar water heater is shown in Figure 3.4(b)

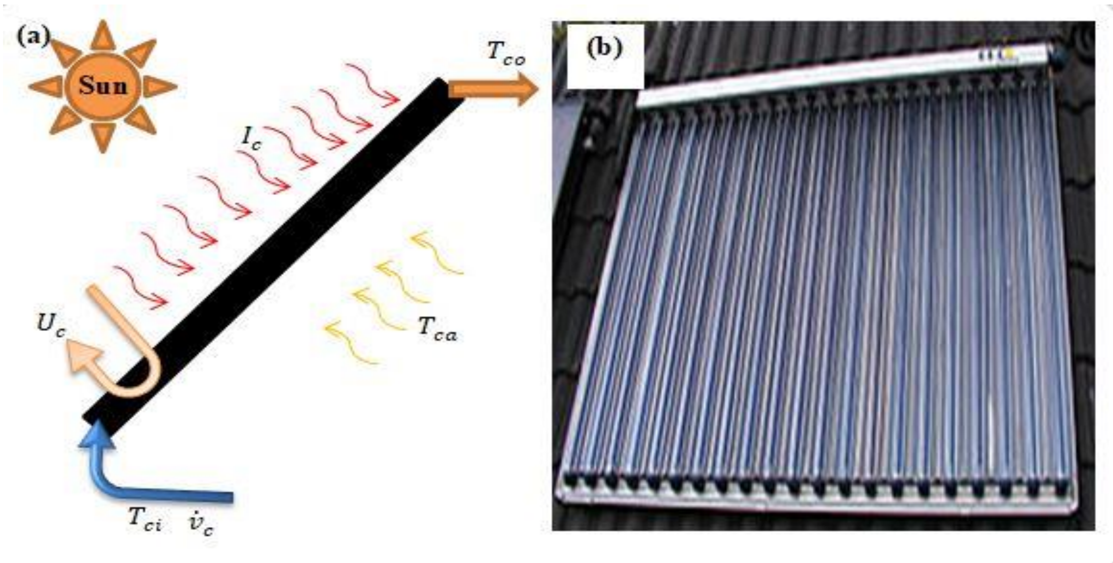

Figure 3-4 Solar (Water heater) collector (a) schematic diagram (b) Picture of solar collector installed in the roof of a building. Source: Author

In order to formulate a mathematical differential equation accounting for the net change in heat energy in the solar collector, let the input flow rate of water into the collector at a temperature of T_{ci} degrees Celsius be given $\dot{v}_{ci}$, let the flow rate out of the collector be $\dot{v}_{co}$, with the assumption that $\dot{v}_{ci} = \dot{v}_{co} = \dot{v}_c$ and let the output water temperature be T_{co} and let T_{ca} be the ambient air temperature around the collector, while I_c and U_c be the irradiance on the collector plate and overall heat loss coefficient respectively. From the conservation equation (3.1), we derive the differential equation

$$\frac{dT_{co}}{dt} = \frac{A_c \eta_c I_c}{\rho_c c_c V_c} - \frac{U_c A_c}{\rho_c c_c V_c}(T_{av} - T_{ca}) + \frac{\dot{v}_c}{V_c}(T_{ci} - T_{co}) \qquad (3.2)$$

where, the solar collector efficiency is given by η_c, the aperture surface of the collector is A_c, density of the collector fluid is ρ_c, volume of the collector fluid V_c, the average fluid temperature in the collector is $T_{av} = 0.5(T_{ci} + T_{co})$ (Patterson & Miers, 2010).

According to the analysis of performance of solar collector done by (Budihardjo & Morrison, 2009), the solar collector efficiency η_c is evaluated as

$$\eta_c = \eta_0 - a\frac{(T_{av} - T_{ca})}{G} - b\frac{(\bar{T} - T_a)^2}{G} \qquad (3.3)$$

where η_0 is the manufacturer's rated efficiency, a, b are solar collector constants, T_{av} is the average temperature in the collector, T_{ca} ambient temperature of the collector in degrees Celsius and I_c is the incident solar radiation on the aperture in W/m^2. From the experimental analysis, the efficiency of the glass evacuated vacuum tube was found to be (Budihardjo & Morrison, 2009)

$$\eta_c = 0.536 - 0.8240\frac{T_{av} - T_{ca}}{I_c} - 0.0069\frac{(T_{av} - T_{ca})^2}{I_c} \qquad (3.4)$$

3.2.3 Solar Irradiation

The average solar radiation emitted by the sun is known to reach the outer atmosphere at the rate of about 1.367 kW/m^2, the value is called the *solar constant (Carbonell, Cadafalch, & Consul, 2013)*. Total emission of the sun is about $3.7 \times 10\ W/s$. This radiation may be divided according to its spectral distribution into UV, visible and near IR, the latter two accounts for about 90% of the total emission (Eltbaakh et al., 2011). The atmosphere distorts the solar radiation and alters the wavelength distribution; also, the solar energy actually reaching the ground varies with latitude, season, time of day and other factors such as topography, meteorological elements, atmospheric dust and contamination. The radiation available on the ground is composed of beam or direct radiation and diffuse radiation, producing half of the available energy. There is also solar reflected by the earth's surface, and long-wave re-radiation such as nocturnal radiation which is particularly significant for some cooling purposes.

Heat source comprises a set of equations representing the drying process of the food particle, the solar hear collection at the solar collector, the hydrodynamics of the fluid flow in the closed fluid chamber, and the mass transfer equations of hot air in the drying chamber. Irradiation data for the region under study, that is Nairobi, Thika, and Dagoreti was acquired from (Ng'ethe, 2019; Wasike, 2015).

3.2.4 Analytic Solution of Solar Equation

The solution of the solar collector equation (3.1) is obtained as follows;

$$\frac{dT_{co}}{dt} = \frac{A_c\eta_c I_c}{\rho_C c_c V_c} - \frac{U_c A_c}{\rho_C c_c V_c}(T_{av} - T_{ca}) + \frac{\dot{v}_c}{V_c}(T_{ci} - T_{co})$$

$$= \frac{A_c\eta_o I_c}{\rho_C c_c V_c} - \frac{U_c A_c}{2\rho_C c_c V_c}(T_{ci} + T_{co}) + \frac{U_c A_c}{\rho_C c_c V_c}T_{ca} + \frac{\dot{v}_c}{V_c}T_{ci} - \frac{\dot{v}_c}{V_c}T_{co}$$

$$= \frac{A_c\eta_o I_c}{\rho_C c_c V_c} - \frac{U_c A_c}{2\rho_C c_c V_c}T_{ci} - \frac{U_c A_c}{2\rho_C c_c V_c}T_{co} + \frac{U_c A_c}{\rho_C c_c V_c}T_{ca} + \frac{\dot{v}_c}{V_c}T_{ci} - \frac{\dot{v}_c}{V_c}T_{co}$$

$$= \frac{A_c\eta_o I_c}{\rho_C c_c V_c} - \frac{U_c A_c}{2\rho_C c_c V_c}T_{ci} + \frac{U_c A_c}{\rho_C c_c V_c}T_{ca} + \frac{\dot{v}_c}{V_c}T_{ci} - \left[\frac{U_c A_c}{2\rho_C c_c V_c}T_{co} + \frac{\dot{v}_c}{V_c}\right] T_{co}$$

Let $\alpha = \frac{A_c\eta_o I_c}{\rho_C c_c V_c} - \frac{U_c A_c}{2\rho_C c_c V_c}T_{ci} + \frac{U_c A_c}{\rho_C c_c V_c}T_{ca} + \frac{\dot{v}_c}{V_c}T_{ci}$, $\beta = \left[\frac{U_c A_c}{2\rho_C c_c V_c}T_{co} + \frac{\dot{v}_c}{V_c}\right]$, then the equation above reduces to;

$$\frac{dT_{co}}{dt} = \alpha - \beta T_{co}$$

Whose solution by separation of variables is

$$T_{co}(t) = \alpha\beta + (T_{ci} - \alpha\beta)e^{-\beta t}$$

or this can be written as;

$$T_{co}(t) = \alpha\beta\left(1 - e^{-\beta t}\right) + T_{ci}e^{-\beta t} \qquad (3.5)$$

Note that the limit as $t \to \infty$ equation (3.5) yields $T_{co}(t) = \alpha\beta$, the steady state temperature at prolonged exposure of the solar collector to constant irradiation.

3.3 Piping System Mathematical Model Equations

Heat transfer along pipes occurs through conduction, convection, and radiation. In many engineering applications, heat transfer through pipes is a critical consideration for the efficient operation of systems such as industrial boilers, and process piping. The heat transfer rate along a pipe is influenced by factors such as the thermal conductivity of the pipe material, the fluid flow inside the pipe, and the surface area available for heat transfer. Understanding and optimizing heat transfer along pipes is essential for designing energy-efficient systems and ensuring the proper functioning of industrial processes.

In order to describe the dynamics of heat transfer along the pipes, it is necessary to consider the effect of parameters like insulation, type of material, length of pipes, diameter, mass flow rate among others. The temperature of the water from the collector is taken to be T_{co} while the inlet temperature is given by T_{ci}. As water flows through pipes, the heat may be lost through two processes, conduction and/or convection or both. The mathematical equations describing the conductive and convective heat loss are explained below.

Conductive heat loss is experienced when the pipe, which is in contact with the water is heated, and thus the water loses heat energy to the pipe material, as it flows along the pipe. This heat loss can be reduced by using a material with less heat conductivity coefficient or by thickening the walls of the pipes. From experimental tests, some materials have a known conductivity coefficient, for example steel has 45W/mK, while copper has 398W/mK, Aluminium 205W/m-K, Glass 0.8W/mK and Polystyrene 0.03W/mK. This means that copper conducts heat faster and more effectively than steel (Patterson & Miers, 2010).

The purpose of this analysis is to ensure that heated water from the solar collector reaches the heat exchanger when still hot, so that maximum heat is extracted from the water to the drying air. The following are the mathematical equations describing the heat loss through conduction and convection.

Conductive heat transfer refers to the movement of heat through a substance or between substances that are in direct physical contact. This process happens via particle collisions and the exchange of kinetic energy. Materials with high thermal conductivity, like metals, facilitate efficient heat flow, whereas insulators such as wood or plastic resist heat transfer due to their low conductivity. Conductive heat transfer is given by the formula;

$$Q_{cond} = \frac{kA(T_{ci} - T_{\infty})}{d}$$

where k is the thermal conductivity, A is the surface area of the material, T_{∞} is the temperature of the surrounding environment and d is the thickness of conducting material. When conductive heat transfer of a material is known, the final temperature can be determined as;

$$T_\infty = T_{ci} - \frac{dQ_{cond}}{kA} \tag{3.6}$$

On the other hand, convective heat loss occurs when heat is transferred away from an object through the movement of fluids or gases. This process involves the flow of a fluid, such as air or water, carrying heat away from the object's surface. For example, when a hot cup of coffee cools down because the steam rising from the cup carries heat away, that's an example of convective heat loss. Convective heat loss is defined by the formula;

$$Q_{conv} = h_{conv}A(T_p - T_\infty)$$

where h_{conv} is the convective heat transfer coefficient, and T_p is the temperature of the pipe surface and T_∞ is the temperature of the surrounding environment.

A measure of all the components contributing to heat loss is represented by the ability of the material to resist heat loss. Thermal resistance refers to the property of a material or an object to resist the flow of heat through it. It is a measure of how much a material impedes the transfer of heat and is typically quantified in terms of its thermal conductivity. Materials with high thermal resistance are poor conductors of heat and are often used as insulators, while materials with low thermal resistance are good conductors and are used for heat transfer purposes.

Conductive thermal resistance refers to the resistance to heat flow through a material or between materials in direct contact with each other. It is related to the material's thermal conductivity and the thickness of the material. Convective thermal resistance, on the other hand, refers to the resistance to heat transfer due to the movement of fluids or gases. It is associated with the fluid's velocity and the surface area over which the heat transfer occurs.

Radiative thermal resistance refers to the resistance to heat transfer through electromagnetic radiation. It is a measure of the ability of a material to block or resist the transfer of heat through thermal radiation. Materials with low radiative thermal resistance are good emitters and absorbers of thermal radiation, while materials with high radiative thermal resistance are poor emitters and absorbers.

The formula for conductive thermal resistance of a circular pipe is given by;

$$R_{cond} = \frac{\ln\left(\frac{r_0}{r_i}\right)}{2\pi kL} \tag{3.7}$$

where R_{cond} (in K/W) is the thermal resistance of the pipe, r_0 is the outer radius of the pipe, r_i is the inner radius of the pipe, L is the length of the pipe and k is the thermal conductivity.

Similarly, the convective heat resistance R_{conv} (in K/W) is given by;

$$R_{conv} = \frac{1}{kA} \tag{3.8}$$

While the radiative thermal resistance is also given by

$$R_{rad} = \frac{T_p - T_\infty}{\varepsilon A\sigma\left(T_p^4 - T_\infty^4\right)} \tag{3.9}$$

The total resistance of the material is therefore given by

$$R_{tot} = R_{cond} + R_{conv} + R_{rad}$$

From the total heat resistance as the sum of equation (3.7), (3.8) and (3.9), the total heat loss in the piping system is computed as;

$$Q_{tot} = \frac{\mathrm{T_{in}} - T_{\infty}}{R_{tot}} = \frac{\Delta T}{R_{tot}} = UA\Delta T \qquad (3.10)$$

where $U = \frac{1}{R_{tot}A}$ is the total thermal coefficient, and ΔT is the temperature difference between the fluid and the surrounding environment.

From the above formula definitions, the output temperature T_{co} can be calculated at the end of the pipe system, to determine the input temperature at the point where the pipe enters the heat exchanger. The output temperature of the thermal liquid is given by;

$$T_{out} = T_{in} - \frac{Q_{tot}}{\rho c_c A \dot{v}_c}$$

where Q_{tot} is the amount of heat transferred with units (J) and c_c is the specific heat capacity of the collector's thermal fluid, $A = \pi r^2$ the surface area per unit length and ρ is the density of the thermal fluid.

3.4 The Heat Exchanger

The heat exchanger is a device used to transfer heat energy from one system of a closed loop of fluid, to another system of fluid at different temperature. The original source of heat could be from a closed loop of water or coolant in a piped network, to the surrounding air blown through by fans. This system is composed of radiators with thin pipes which circulates hot water, whose heat is lost to the environment through radiation to the surrounding air. The target of this heat exchange system is to lose as much of the heat energy as possible in the hot water closed loop to the surrounding environment. This is facilitated through a design of fins, which extends the radiated heat as surface heat exchangers, and which acts as a barrier between the inner fluid and the outer fluid. The system is designed to have fans, which directs cold air through the heat exchanger, to heat the air and to control the flow rate of heat into the drying compartment.

There are two types of exchangers, depending on the relative arrangement of hot and cold fluid flow direction. If both of the fluids flow in the same direction, this is called parallel flow heat exchanger, and if the fluids flows in parallel but opposite directions, the heat exchanger is called counter flow (Boda, Deshetti, & Gavade, 2017; Kim, Baik, Jeon, Jeon, & Byon, 2017). Each heat exchanger has three parts, namely, the inlet hot fluid tubes, the outlet hot fluid tube and the coiled tube with fins, where cold air is blowing across to collect/acquire as much heat as possible from the radiating hot fluid as illustrated in Figure 3.4.

3.4.1 Parallel Flow (Concurrent) Heat Exchanger

A parallel flow heat exchanger is a type of heat exchanger where the hot and cold fluids flow in the same direction, parallel to each other. This design allows for a high log mean temperature difference between the two fluids, resulting in efficient heat transfer. In a parallel flow heat exchanger, the hot and cold fluids enter the exchanger at the same end and exit at the same end, running parallel to each other throughout the process. The hot fluid interacts with the cold fluid continually as the flow along the tube. This implies that the overall heat exchange efficiency is low, but provides uniform temperature distribution in the exchanger. The temperature profile of the concurrent heat exchanger is illustrated in Figure 3.5(a) and it is noted that, the output temperature of the cold fluid is always less than the output temperature of the hot fluid, as is always limited by it.

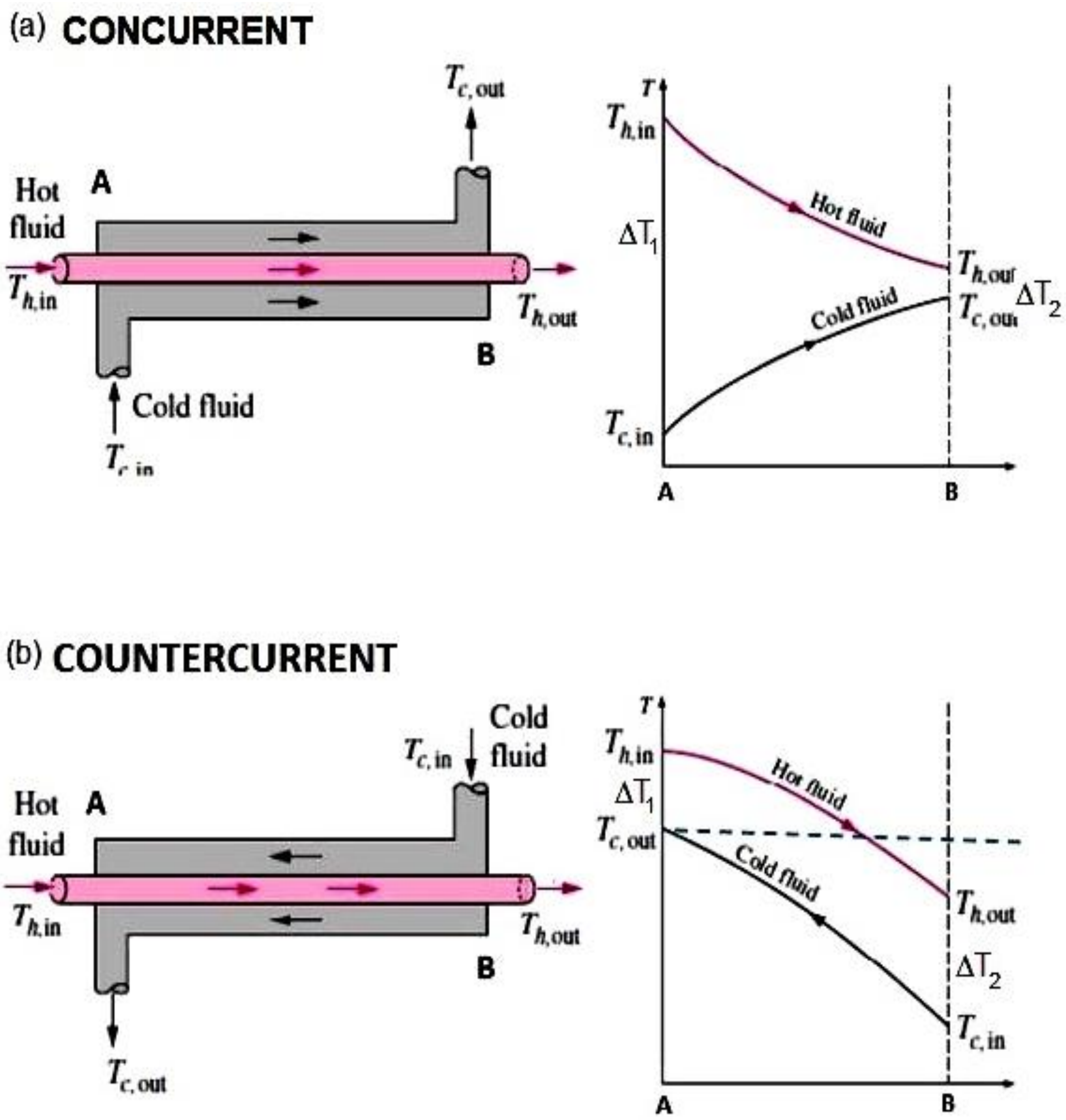

Figure 3-5 Parallel and Counter Flow Heat Exchanger Configuration, and Temperature Distribution profile. Source: (Sachdeva, 2006)

3.4.2 Counter Flow Heat Exchanger

A counter flow heat exchanger is a type of heat exchanger in which the hot and cold fluids flow in opposite directions. This design maximizes the temperature difference between the two fluids, leading to efficient heat transfer. In a counter flow heat exchanger, the hot fluid enters at one end while the cold fluid enters at the opposite end, and they flow in opposite directions through the exchanger. This allows for a more uniform temperature difference across the exchanger, resulting in improved heat transfer efficiency. This arrangement is depicted in Figure 3.5(b). In this configuration, the overall heat transfer is more efficient than that of parallel flow, with the maximum output temperature of the cold fluid restricted by the input temperature $T_{c,in}$.

3.4.3 Heat Exchanger Mathematical Model

The mathematical model of a heat exchanger typically involves equations that describe the heat transfer and fluid flow characteristics within the exchanger. The calculation of heat transfer across the exchanger is derived from the first law of thermodynamics, which depend on the surface area of the exchanger and the flow rates of the fluid, together with the temperature difference of the two fluids. These equations can include principles of thermodynamics, fluid mechanics, and heat transfer, and are used to analyze and predict the performance of the heat exchanger under different operating conditions. The model may incorporate parameters such as heat transfer coefficients, fluid properties, flow rates, and temperature differentials to simulate the behavior of the heat exchanger and optimize its design and operation.

The calculations used in this research assumes that the heat exchanger is of a single-phase type, implying that the entering fluid remains in the same phase as in the outlet.

The energy balance equation is a fundamental principle in thermodynamics that states that the energy entering a system must equal the energy leaving the system, plus any energy accumulated within the system less energy lost in the system. It is expressed mathematically as:

$$Energy\ In = Energy\ Out + Accumulation - Loss$$

This equation is commonly used to analyze and quantify energy transfers in various systems, including heat exchangers, chemical processes, and thermal systems. It provides a basis for understanding the flow and transformation of energy within a system and is essential for evaluating system performance and efficiency.

The energy balance over the hot and cold fluids for a differential element of length dx given by,

$$\begin{aligned} dQ_h &= -\dot{m}_h c_{p_h} dT_h \\ dQ_c &= -\dot{m}_c c_{p_c} dT_c \end{aligned} \tag{3.11}$$

Where $\dot{m} = \rho A \dot{v}$ is the mass flow rate and c_p the specific heat capacity of the fluid while the subscripts h, c denotes the hot and the cold fluid respectively. Integrating equation (3.11) and finding the temperature difference $d(\Delta T) = dT_h - dT_c$ yields the relation equivalent to the formula in equation (3.10) represented as;

$$Q = UA\Delta T_m \tag{3.12}$$

where ΔT_m is the (mean) average effective temperature difference for the entire heat exchanger, A is the surface area and U is the heat transfer coefficient which depends on thermal resistance defined depending on the nature of the exchanger walls as;

$$U = \frac{1}{\frac{1}{h_o} + \frac{L}{k} + \frac{1}{h_i}}$$

For a plane wall and

$$U = \frac{1}{\frac{1}{h_o} + \frac{r_o}{K} \ln\left(\frac{r_o}{r_i}\right) + \left(\frac{r_i}{r_o}\right)\frac{1}{h_i}}$$

for a cylindrical wall. The subscripts o, i are used to denote inside and outside surfaces of the heat exchanger walls respectively. The entire temperature difference ΔT_m of a heat exchanger is also defined as;

$$\Delta T_m = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$$

where $\Delta T_1 = T_{h,i} - T_{c,i}$ and $\Delta T_2 = T_{h,o} - T_{c,o}$ for a parallel flow configuration and $\Delta T_1 = T_{h,i} - T_{c,o}$ and $\Delta T_2 = T_{h,o} - T_{c,i}$ for a counter current flow configuration as shown in Figure 3.4.

3.4.4 Effectiveness of Heat Exchanger

The effectiveness of a heat exchanger is a measure of how well it is transferring heat between the hot and cold fluids. It is defined as the ratio of the actual heat transfer in the heat exchanger to the maximum possible heat transfer if the fluids were completely mixed. The effectiveness of a heat exchanger provides insight into its performance and efficiency, and it is a key parameter in the analysis and design of heat exchangers.

The general effectiveness of heat exchanger is determined by the ratio of the actual heat transfer to the maximum possible heat transfer, given as,

$$Effectiveness = \frac{Actual\ heat\ Transfer}{Maximum\ possible\ heat\ transfer}$$

In order to express this effectiveness mathematically, let the number of transfer units (NTU) be denoted by N and let $T_{\min}$ and $T_{\max}$ denote the minimum and maximum temperatures respectively. Then the effectiveness of a heat exchanger is a function of heat exchanger surface area A and the heat transfer coefficient U only given by;

$$\epsilon = \frac{Q}{Q_{max}} = \epsilon\left(N,\ \frac{T_{min}}{T_{max}}\right) \tag{3.13}$$

where $Q = C_c(T_{co} - T_{ci})$ and $Q_{max} = C_c(T_{hi} - T_{ci})$, while $N = \frac{UA}{T_{min}}$.

Once the effectiveness of a heat exchanger is known, its actual rate of heat transfer can be determined. The rate of heat transfer in a heat exchanger is the amount of heat transferred per unit time between the hot and cold fluids flowing through the exchanger. It is a measure of the heat exchange efficiency and is typically quantified in terms of energy per unit time (e.g., watts or BTU per hour). The rate of heat transfer depends on factors such as the temperature difference between the hot and cold fluids, the surface area available for heat transfer, and the overall heat transfer coefficient of the exchanger. This rate of heat transfer can therefore be described by;

$$Q = \epsilon T_{max} = \epsilon T_{min}\left(T_{h,i} - T_{c,i}\right),$$

where the specific effectiveness of a parallel flow heat exchanger and that of a counter flow heat exchanger are given respectively as (Boda et al., 2017),

$$\epsilon_{parallel} = \frac{1-\exp[-N(1-C)]}{1+C} \tag{3.14}$$

And

$$\epsilon_{counter} = \frac{1-\exp[-N(1-C)]}{1-C\exp[-N(1-C)]} \tag{3.15}$$

From the description of the heat exchanger and heat transfer has been done using equations (3.10) – (3.15). The output hot air is from the exchanger is then channeled through the dehumidifier, so as to remove any moisture in the air, and the hot dry air is directed to the food drying chamber, through temperature and humidity regulators, where desired dry air temperature and flow rate is controlled.

3.5 Food drying chamber Model

A hot air food drying chamber is a section of the food dryer, where moist food products are placed for dehydration by circulating hot air around them. The chamber typically consists of a heat source, a fan for air circulation, and trays or racks for holding the food items. The hot air removes moisture from the food, slowing down the growth of bacteria and mold, and extending the shelf life of the food products. This method is commonly used for drying fruits, vegetables, herbs, and meats to create shelf-stable products. Food drying chamber is made of a heat insulated container, with specialized shelves and trays, where food slices are placed. The trays are perforated to allow air circulation from beneath and from top. These trays are also designed to vibrate or rotate, so that food products do not stick to the walls as they are dried, and at the same time to expose all faces of the food particle to hot air.

The power supplied to controls and for the mechanical movement of trays and shelves is generated by photovoltaic solar cells placed adjacent to solar water heaters in the roof of the drying chamber.

In order to analyse the functionality of the drying chamber, mathematical formulas describing the air mass flow, drying air temperature, loss of moisture in the food particles and humidity mass flow are formulated. The necessary mathematical model equations are discussed in the subsequent subsections.

3.5.1 Model Assumptions and Equations of Food Mass Transfer

The food particle is hereby assumed to be made up of a rigid skeletal material filled with moisture. For convenience, the food particle is geometrically defined as spherical and uniformly sized. Other geometrical shapes of food particles were considered in chapter four. Other assumptions include homogeneity and isotropic property of the food particles.

Mass transfer in the food drying process involves the movement of moisture from the interior of the food product to the surface, where it evaporates into the surrounding air.

This process occurs due to differences in vapor pressure between the food and the surrounding air. As moisture evaporates from the surface of the food, more moisture diffuses from the interior to replace it, resulting in a continuous mass transfer process. The rate of mass transfer is influenced by factors such as air temperature, humidity, airflow velocity, and the properties of the food product.

The process of mass transport and energy transfer in this research study is assumed to be unidimensional, while diffusion and conduction of heat between the food particles is neglected. That means all food particles are dehydrated from the hot air in the drying chamber and no heat from the neighbouring food particles. It is also assumed that the water in the closed fluid circuit is never depleted nor generated. This will ensure that the flow dynamics is maintained. Only moisture and temperature are the physical properties of the food particle that varies. The moisture in the food particle is hereby assumed to migrate from the centre of the particle to the surface only through molecular diffusion. The drying process of the food particle is illustrated in Figure 2.2 in section 2.1 above.

3.5.2 Major Dryer Compartment Model Equations

The following are the mathematical model equations of various processes in the solar dryer. The equations will then be solved and analyzed for parameter significance and their values simulated to determine the optimal threshold values.

Mass Conservation of the Food Particle

The conservation of mass of a food particle refers to the principle that states that the mass of a food particle remains constant unless there is a net mass transfer into or out of the particle. This principle is fundamental in food processing and preservation, as it governs the changes in moisture content and overall mass of food products during various processing operations such as drying, freezing, and heating. By understanding and applying the conservation of mass principle, the stability and shelf life of food can be predicted and the effects of mass transfer can be controlled.

Model equation describing conservation of mass of a food particle, during drying is given by

$$\frac{\partial(\rho X)}{\partial t} = \frac{1}{r^n}\frac{\partial}{\partial r}\left[r^n D(X,T)\frac{\partial(\rho X)}{\partial r}\right] \tag{3.16}$$

where X, ρ, t, r, n, D, T denotes the volume of moisture content, food particle density, time, dimension, shape, (where, $n = 0$ denotes rectangular or disc geometric shape, $n = 1$ represents cylindrical shape, and $n = 2$ denotes spherical shape), diffusion coefficient and temperature respectively (Neto, 1997).

Heat Energy Balance

The heat energy balance in drying food involves accounting for all incoming and outgoing heat energy during the drying process. This includes the heat input to the food from the drying air, the heat used to evaporate moisture from the food, the sensible heat of the dried product, and any heat losses from the system. By maintaining a heat energy balance, it is possible to understand and optimize the energy requirements for the drying process, leading to improved efficiency and reduced operational costs.

The heat energy balance equation describing the temperature profile is given by the equation

$$\frac{\partial Q}{\partial t} = \frac{\partial\left[\overline{\rho}.\overline{c_p}.(T-T_0)\right]}{\partial t} = k\frac{\partial^2 T}{\partial x^2} \tag{3.17}$$

where Q, x, c_p, k, T_0 denotes Energy, the spatial dimension, specific heat capacity, thermal conductivity and initial temperature respectively, and the bar ($\bar{}$) denotes average value.

The Drying Air Mass Balance

The drying air mass balance in food drying involves accounting for the mass of air entering and leaving the drying chamber, as well as the changes in moisture content of the air during the drying process. This includes considering the mass of dry air, the mass of water evaporated from the food, and the mass of moisture-laden air leaving the chamber. By maintaining a drying air mass balance, it is possible to optimize the drying conditions, ensure proper moisture removal from the food, and improve the overall efficiency of the drying process.

The drying air mass balance equation is described by the partial differential equation

$$\frac{\partial[\rho_{air}.v_{air}.Y_{air}]}{\partial y'} = \left\{(1-\varepsilon)\frac{A_p}{V_p}\left[-D\frac{\partial(\rho.X)}{\partial r}\right]_{r=R}\right\} \qquad (3.18)$$

where $\rho, v, Y, \varepsilon, A, V, R$ denotes the air density, velocity, moisture content, porosity, area, volume and Radius of the particle respectively. The subscript air denotes drying air.

Analyzing these equations at different parameter values and conditions, yields the temperature profile and drying rates of various food particles.

3.6 Sensitivity Analysis and Significant Parameter Identification

Sensitivity analysis is a mathematical operation of determining the effect of varying parameters on the overall change in the main variable. For a model differential equation with various parameters, sensitivity analysis involves examining how variation in a parameter in a differential equation affects the overall behaviour and outcome of the model.

In this study, we have six model equations, three describing the heat collection and transfer in the solar dryer, and three describes the mass transfer and energy balance on the food particles in the drying chamber. For the purpose of optimization of the solar dryer, this section analyses the sensitivity of the solar dryer model equation only, which will guide the choice of the parameters for effective operation of the solar dryer.

Sensitivity analysis of this model is done following the same procedures defines by (Savatorova, 2023) as follows:

Consider the system of differential equations

$$\begin{gathered} \dot{x_1} = f_1(x_1, x_2, \dots, x_n, a_1, a_2, a_3, \dots, a_m) \\ \dot{x_2} = f_2(x_1, x_2, \dots, x_n, a_1, a_2, a_3, \dots, a_m) \\ \dot{x_3} = f_3(x_1, x_2, \dots, x_n, a_1, a_2, a_3, \dots, a_m) \\ \vdots \\ \dot{x_n} = f_n(x_1, x_2, \dots, x_n, a_1, a_2, a_3, \dots, a_m) \end{gathered} \tag{3.19}$$

Which is expressed in vector form as;

$$\frac{d\boldsymbol{Z}}{dt} = F(\boldsymbol{Z}, \boldsymbol{p}); \boldsymbol{p} = a_i, i = 1,2,3, \dots, m$$

where $\boldsymbol{Z} = (x_1, x_2, \dots, x_n)$ is a vector of variables and $\boldsymbol{p} = a_i$ is set of parameters.

The sensitivity vector $\boldsymbol{s}_j$ of the system $F(\boldsymbol{Z}, \boldsymbol{p})$ with respect to variations in the parameters $\boldsymbol{p}$ is determined by the equation;

$$\boldsymbol{S} = \left[\frac{\partial x_j}{\partial a_i}\right] = \begin{pmatrix} \frac{\partial x_1}{\partial a_1} & \frac{\partial x_1}{\partial a_2} & \cdots & \frac{\partial x_1}{\partial a_m} \\ \frac{\partial x_2}{\partial a_1} & \frac{\partial x_2}{\partial a_2} & \cdots & \frac{\partial x_2}{\partial a_m} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial x_n}{\partial a_1} & \frac{\partial x_n}{\partial a_2} & \cdots & \frac{\partial x_n}{\partial a_m} \end{pmatrix} \tag{3.20}$$

If the exact values of the variables x_j are known, then the elements of the sensitivity matrix $\boldsymbol{S}$ can be determined. In our case, we consider the evolution dynamics of each sensitivity measures in equation (3.19) as;

$$\frac{ds_j}{dt} = \frac{d}{dt}\left(\frac{\partial Z}{\partial p}\right) = \frac{\partial f_i}{\partial x_1}.\frac{\partial x_1}{\partial a_j} + \frac{\partial f_i}{\partial x_2}.\frac{\partial x_2}{\partial a_j} + \frac{\partial f_i}{\partial x_3}.\frac{\partial x_3}{\partial a_j} + \cdots + \frac{\partial f_i}{\partial a_j}$$

where $i = 1,2, \dots, n$ is the number of equations in the system and $j = 1,2, \dots, m$ is the number of parameters. Using this concept, the sensitivities of the model equations (3.2), (3.10) and (3.11) is evaluated for the following parameters.

Table 3-1 Relative Analytic Sensitivity for various parameters

	Solar collector Parameters	**Symbol**	**Sensitivity of the Parameter**
1	Area of the collector	A_c	$s_A \coloneqq \frac{A_c\eta_c I_c}{\rho_c c_c V_c} - \frac{U_c A_c}{\rho_c c_c V_c}(T_{av} - T_{ca})$
2	Collector’s efficiency	η_c	$s_\eta \coloneqq \frac{A_c I_c}{\rho_c c_c V_c}$
3	Density of the fluid	ρ_c	$s_\rho \coloneqq -\frac{A_c\eta_c I_c}{\rho_c^2 c_c V_c} + \frac{U_c A_c}{\rho_{c\,c}^2 c_c V_c}(T_{av} - T_{ca})$
4	Specific heat capacity	c_c	$s_c \coloneqq -\frac{A_c\eta_c I_c}{\rho_c c_c^2 V_c} + \frac{U_c A_c}{\rho_c c_c^2 V_c}(T_{av} - T_{ca})$
5	Volume of the thermal fluid	V_c	$s_V \coloneqq -\frac{A_c\eta_c I_c}{\rho_c c_c V_c^2} + \frac{U_c A_c}{\rho_c c_c V_c^2}(T_{av} - T_{ca}) - \frac{\dot{v}_c}{V_c^2}(T_{ci} - T_{ca})$
6	Ambient Temperature	T_{ca}	$s_{T_{ca}} \coloneqq \frac{U_c A_c}{\rho_c c_c V_c} - \frac{\dot{v}_c}{V_c}$
7	Heat Exchanger change in energy	Q_h	$dQ_h = -\rho A \dot{v} c_p dT_h$
7	Density of the fluid	ρ	$s_\rho \coloneqq -A\dot{v}c_p(\Delta T)$
8	Area of cross section of tubes	A	$s_A \coloneqq -\rho \dot{v} c_p(\Delta T)$
9	Flow velocity of the fluid	$\dot{v}$	$s_{\dot{v}} \coloneqq -\rho A c_p(\Delta T)$

3.7 Optimization of Food drying process

Optimization of the food drying process involves maximizing the efficiency and quality of the drying operation. This can be achieved through various methods such as controlling the drying air temperature, humidity, and airflow velocity, as well as adjusting the thickness and arrangement of the food layers. Additionally, optimizing the food drying process may involve minimizing the drying time while ensuring that the food retains its nutritional value, flavor, and texture. By fine-tuning these parameters, food processors can improve productivity, reduce energy consumption, and maintain the overall quality of the dried food products.

In a drying process, it is desirable to produce a solid product of a specified quality at minimum cost, making use of the maximum efficiency/capacity of the available dryer. It is possible to have several operating conditions where the product quality and production specifications are met. Several optimization techniques are available such as direct search methods, and gradient-based methods, but due to the many degrees of freedom there are complex trade-offs, which offers scope for optimization.

Direct search methods, such as linear interpolation methods (Powell, 1994), are easy to apply, but can solve only simple optimization problems. The complexity of energy transfer, pressure requirements, flow rate, temperature, and fluctuations of irradiation, the drying process optimization was analyzed using advanced methods (Augustis, Juozas, Linas, & Ricardas, 2015).

In this research study, the optimization, method chosen involves the use of differential neural networks system, where the model parameters are suitably placed in a mathematical equation formulated using differential equations (Awodele & Jegedo, 2009). The model equations are then transformed to obtain transfer functions, which can be coupled to build optimization control functions (Atwa, El-Saadany, Salama, & Seethapathy, 2010; Augustis et al., 2015).

The optimization and Neural network model, are then developed using MATLAB - SIMULINK, and used to simulate various model parameters, in order to determine their sensitivity, stability and their respective threshold ranges (Ascione et al., 2016; Awodele & Jegedo, 2009).

The SIMULINK model formulated, receives feedback signals from energy utility terminals, which were optimized, and used to adjust the desired energy input from solar panel heat collector or other heat sources. (Ben, 2010). The link between energy production and energy consumption points and all the processes involved were synchronized for optimality.

The Neural Network optimization model, describes a set of technological gadgets, which analyzes and sends feedback to energy production points, on the intensity of use and volume of energy required by each consumer. Synchronization of the fluctuating heat demands and moisture content in the food particle were adjusted so that each food type is dried at optimal temperature ranges as needed (Carlo, Massimo, Thomas, & Fiacomo, 2014).

The parameters of interest in this research study include fluid velocity, temperature, humidity, discharge rate, pressure, food type, moisture content, among others are incorporated in the model equations for analysis. The analytic solution of the mathematical model is then evaluated and tested for stability, while simulation results were analyzed using SIMULINK.

3.7.1 Optimization Decision Variables

An optimization problem involves finding the best solution from all feasible solutions. It typically involves maximizing or minimizing a certain objective function while satisfying a set of constraints. Optimization problems can be solved using mathematical techniques such as linear programming, nonlinear programming, and evolutionary algorithms. The goal of solving an optimization problem is to identify the most efficient or effective solution given a specific set of constraints and objectives.

The optimization problem in this research involves finding the minimum life cycle cost of solar food drier and the cost of the strategic plan to maximization of drying benefits. The formulation of the optimal control involves including in the objective function the sum of costs of the state variables to be minimized and the cost of implementing the optimal control variables.

Minimization of the cost of drying food particles both in terms of energy consumed and time taken yields an objective function as the sum of the costs of the state variables to be minimized together with the costs of implementing the control variables. In this study, our desire is to minimize the cost of drying food particles. This is achieved through minimization of the cost of solar panels (solar heat collectors), and maximize the heat energy output to the fluid closed circuit, which then maximizes the heat output in the drying air mass, thus minimizing the time of drying, and related costs.

3.7.2 Objective function

The design is made to minimize the costs of the major components, the cost of auxiliary heat source and the time taken to dry food. Let $x(t)$ be the total cost of solar collectors, the cost of water pumps, cost of pipes, cost of heat exchanger system, drying chamber and the cost of clarifier, and let $u_i(t)$ be the cost of achieving the i^{th} control variable, where $i = moisture,\ heat,\ solar$ then, the objective function is;

$$x(t) = C_{col} + C_{pip} + C_{ex} + C_{dry} + C_{tank} = \sum_i x_i(t) \qquad (3.21)$$

where C_{col} is the cost of solar collector, C_{pip} is the cost of closed loop piping system, C_{ex} is the cost of heat exchanger system, including the fans, C_{dry} is the cost of the dryer compartment and C_{tank} is the cost of water tank and associated peripherals and pumps.

The component targeted are grouped using the variable $u_i(t)$ defined as;

$$u(t) = u_{mc} + u_q + u_{mfr} + u_{afr} + u_{ac} = \sum_i u_i(t) \qquad (3.22)$$

where u_{mc} is the minimum targeted moisture content, u_q is the targeted heat minimum energy, u_{mfr} is the target fluid mass flow rate, u_{afr} is the target minimum air flow rate in the drying chamber and u_{ac} is the aperture area of the solar panel.

3.7.3 Constraint Conditions

In optimization, constraint conditions are essential for defining the boundaries or limitations within which the optimization problem must be solved. These constraints can be classified into equality constraints, inequality constraints, and bound constraints. Equality constraints ensure that certain variables are equal to specific values, while inequality constraints impose restrictions on the variables' values. Bound constraints, on the other hand, define the permissible ranges for the variables. By incorporating these constraint conditions into optimization problems, engineers and researchers can effectively model real-world scenarios and find optimal solutions that satisfy the specified constraints.

The objective of interest is restricted by constraints with maximum and minimum attainable values. These constraints include the pump speed, aperture area size of the solar collectors, solar irradiation limits, total cost of investment, limited temperature for drying different food products among others. These restrictions can be expressed on $u(t) \in K \in R^m$ and the state equation completed by the initial and/or boundary conditions

$$x(0) = x_0,\ x(T) = x_T$$

where T is the final time.

3.7.4 Optimization Algorithm

The Pontryagin's Minimum Principle is a key concept in the field of optimal control theory, particularly in the context of continuous-time systems. It provides necessary conditions for optimality in problems involving the minimization of a cost function, subject to differential equations that describe the dynamics of the system. The associated optimization algorithm, known as the Pontryagin's Minimum Principle, is used to solve such optimal control problems by determining the control inputs that minimize the specified cost function while satisfying the system dynamics (Pontryagin, 1987).

The study proposes to use the Pontryagin's maximum principle to solve the optimal control problem involving the decision variables $x(t)$ and the objective variable $u(t)$. This involves the process of determining control and state trajectories for a dynamic system over a period of time in order to minimize a performance index.

Consider a system of dynamical systems which evolve according to the state/plant equation

$$x'(t) = f\big(t, x(t), u(t)\big) \tag{3.23}$$

where $u = (u_1, u_2, u_3, \dots, u_m)$ and $x = (x_1, x_2, x_3, \dots, x_n)$ represents the control variables exercised on the system, and the state variables respectively. Using the restrictions in section 3.3 above, the objective cost function measuring the performance index on how good a given control $u(t)$ is, is of the form

$$J(x, u) = h(x(t_0), T) + \int_{t_0}^{T} g\big(t, x(t), u(t)\big)\, dt \tag{3.24}$$

Where h and g are scalar functions, while t_0 and T are initial and final time and J describes the performance index, which n this case describes how best is the supply of heat fits the requirements of the food particles during drying. The main objective of this Optimal Control problem is finding the piecewise continuous control $u(t)$ and the associated state variable $x(t)$ to maximize the given objective functional $J(x, u)$.

The desired Optimal Control problem is in the form

$$\max_{\mathrm{u}} J(x, u) \tag{3.25}$$

Such that the following constraints hold

$$x'(t) = g\big(t, x(t), u(t)\big) \tag{3.26}$$

$$x(t_0) = x_0, (x(T) = x_T) \tag{3.27}$$

where the final condition on x is written in brackets to mean that sometimes it is omitted when the final value is not restricted. Considering a weight parameter b to show different efforts on the application of a control variable, we represent the optimal control problem in the form

$$J(u) = \int_0^T x(t)\, dt + b \int_0^T u^2(t)\, dt \tag{3.28}$$

where b is the weight parameter describing the importance of implementing the control variable $u(t)$.

In this study, since partial differential equations in equations (3.1 – 3.4) are used to formulate the model, we intend to develop an algorithm for efficient solution of partial differential equations constrained optimization, identification and control problems sensitivity analysis of the optimal solar heater variables by considering an objective form which describes the distribution of irradiation intensity and output temperature. In order to solve this optimal control problem in equation (3.25 – 3.28), where Pontryagin's Maximum Principle was applied.

Pontryagin's Maximum Principle is a mathematical theory used to solve optimization problems for dynamic systems, particularly in control theory and optimal control. In this problem, we define the adjoint functional H here referred to as Hamiltonian.

The Hamiltonian, named after the Irish mathematician William Rowan Hamilton, is a fundamental concept in classical mechanics and mathematical physics (Yang, Rahmani, Shabani, Neven, & Chamon, 2017). It is a scalar function that summarizes the dynamics of a physical system, particularly in the context of conservative systems. In classical mechanics, the Hamiltonian is defined as the sum of the kinetic and potential energies of the system, expressed in terms of the generalized coordinates and momenta. The Hamiltonian provides a powerful framework for analyzing the behavior of dynamical systems and is extensively used in various branches of physics and engineering (Yang et al., 2017). In this research study, the Hamiltonian is given by;

$$H\big(t, x(t), u(t), \lambda(t)\big) = f\big(t, x(t), u(t)\big) + \lambda(t) g\big(t, x(t), u(t)\big) \quad (3.29)$$

with $\lambda(t)$ as the multiplier of the state variable. Solving to minimize the Hamiltonian in equation (3.27) is done by evaluating the condition which satisfies the equations

$$\frac{\partial H}{\partial u} = 0; \tag{3.30}$$

$$\lambda'(t) = -\frac{\partial H}{\partial x} \tag{3.31}$$

The solution of equation (3.30) and equation (3.31) yields the optimum function with respect to all admissible control vectors given by

$$u^* = u^*(x, \lambda, t) \tag{3.32}$$

The next step is to find the Pontryagin's function

$$\mathcal{H}^*(x, \lambda, t) =, \min_{u \in U} \mathcal{H}(x, \lambda, t) \tag{3.33}$$

Whose solution gives a set of $2n$ equations define as;

$$\dot{x}(t) = \frac{\partial \mathcal{H}^*(x,\lambda,t)}{\partial \lambda} \text{ (representing the state equation)} \tag{3.34a}$$

$$\dot{\lambda}(t) = -\frac{\partial \mathcal{H}^*(x,\lambda,t)}{\partial x} \text{ (representing the co-state equation)} \tag{3.34b}$$

subject to the boundary conditions which are derived from equation (3.30 – 3.31) and arising from the problem where the initial time $t_0 = 0$ is given and the final time $T = t_f$ is free. These conditions are stated as;

$$\begin{gathered} x(t_0) = x_0 \\ \left[\frac{\partial h(x,t)}{\partial x} - \lambda(t)\right]\Big|_{t_1} = 0 \end{gathered} \tag{3.34c}$$

The results of equation (3.33) are substituted back into the expression for $u^* = u^*(x, \lambda, t)$ in equation (3.31) to obtain the desired optimal control.

From the formulation of the food drying process as a dynamic system with the objectives function and constraints presented in sections 3.6.3 and 3.6.4 respectively, Pontryagin's Maximum Principle is utilized to derive optimal control policies that minimize energy consumption, maximize drying efficiency, or achieve other specified goals within the constraints of the drying system. This analysis is carried out and discussed explicitly in the chapter four.

The desired control function $u^* = u^*(x, \lambda, t)$ describes the measure and level of heat, mass flow rate, temperature of hot air and the time of drying desired to optimize drying cost and time.

CHAPTER FOUR

MODEL SIMULATION RESULTS

This chapter presents detailed analytic and numerical results of the model equations of the study. These are presented in various sections, subdivided into three categories, namely; Solar Drier model and mathematical model equations and their analysis; Food particle equations and their analysis; and Optimization equations and their analysis. All the analysis is done both analytically and using MATLAB – SIMULINK, where Simulink block is created and joined together to represent the model equations, then parameters are inserted in the workspace and simulation run. The variables are adjusted in the process, so that the optimal values are obtained. A summary of data collected were presented for the purpose of simulations and comparison of numerical and analytic results.

4.1 Solar Drier Model equations

A solar dryer model is a mathematical or computational representation of a solar drying system used to predict and optimize its performance. The model typically incorporates parameters such as solar radiation, ambient temperature, air velocity, humidity, and the geometry of the drying chamber. By simulating the heat and mass transfer processes within the solar dryer, the model can predict the drying kinetics, energy consumption, and the quality of dried products. It can also be used to optimize the design and operating conditions of the solar dryer to achieve efficient and effective drying of agricultural produce or other materials.

The solar drier as discussed in chapter three is composed of various compartments, which were analyzed individually and later combined to form a system. The parts which are of central focus are the solar collector subsystem, the pipe network subsystem, the heat exchanger subsystem and the drying chamber system. These together form a solar drier system. The solar collector mathematical equations, describing the collection of radiation from the sun, and heating the fluid in the solar collector pipe loop was presented in chapter three, in equation (3.2). The simulation of solar collector model depends on the input temperature which is represented by the radiation data collected. The data used was obtained as secondary data from (Ng'ethe, 2019; Schafer et al., 2002) and (Wasike, 2015).

4.1.1 Solar insolation in Kenya

Solar insolation in Kenya is abundant due to its location near the equator, which results in consistently high levels of solar radiation throughout the year. The country receives an average of 4-6 kWh per square meter per day, with certain regions experiencing even higher levels. This makes Kenya an ideal location for solar energy generation and has led to the widespread adoption of solar power as a renewable energy source for both urban and rural areas. The high solar insolation in Kenya presents significant opportunities for the development of solar energy projects and has the potential to contribute to the country's energy security and sustainability.

The sun rises from the East on average from sunrise time of around 6.30am and sets in the West at sunset time of around 6.30pm, approximately 12 hours sunshine in a day. Because of geographical location of Kenya, most of the time of the year, the sun is not far from directly above the surface, and thus placing the solar collector with a tilt to face the East or the West will pick maximum sunrays.

The average radiation from the sun reaches the atmosphere at a constant solar rate of $4.367 kW/m^2$. This radiation energy is subdivided into three: Ultra Violet (UV) light, Visible light and near Infra-Red (IF) light (Wasike, 2015). The solar radiation from the sun is distorted by atmospheric conditions, and depends on other factors like latitude, topography, climatic conditions, atmospheric contamination, among others. The average radiation reaching the earth surface in a sunny day is approximately $3.14 \times 10^7 W/m^2/day$ (Schafer et al., 2002).

Diffuse solar radiation refers to solar energy that reaches the Earth's surface after being scattered by the atmosphere. Unlike direct solar radiation, which comes in a straight line from the sun, diffuse solar radiation is diffused or scattered in different directions by atmospheric particles and gases. This type of solar radiation can contribute to overall solar energy collection, especially on cloudy or overcast days when direct sunlight is limited. Diffuse solar radiation plays a significant role in the generation of solar power and can be harnessed through the use of solar panels and other solar energy technologies. Diffuse solar radiation can be estimated by the empirical formula given by (Fu & Rich, 2000). It is defined as;

$$H_d = H(1.00 - 1.13K_T) \quad (4.1)$$

where H_d is the mean daily solar diffuse to the earth, H is the total global solar radiation and K_T is the sky clarity index or transmissibility.

The following data related to average received and extractable energy at 90% efficiency of the thermal system in $KWhr/m^2/day$ as recorded by (Wasike, 2015) for the period January – December, 2000 at Dagoreti, Thika and at Jomo Kenyatta International Airport (JKIA) – Nairobi, Kenya recorded at an interval of 10 minutes in a span of 12 hours in a day, from 6.am to 6.pm.

Table 4-1 Solar Radiation measurements obtained in a sunny day at Thika, JKIA Nairobi and Dagoreti,(Wasike, 2015).

DAGORETI		JKIA NAIROBI		THIKA		DAGORETI		JKIA NAIROBI		THIKA	
TIME	kWhr/m^2	TIME	kWhr/m^2	TIME	kWhr/m^2	TIME	kWhr/m^2	TIME	kWhr/m^2	TIME	kWhr/m^2
6:00 AM	6.80	6:00 AM	5.90	6:00 AM	6.35	12:40 PM	18.90	12:40 PM	10.60	12:40 PM	14.75
6:10 AM	6.60	6:10 AM	5.70	6:10 AM	6.15	12:50 PM	18.00	12:50 PM	10.30	12:50 PM	14.15
6:20 AM	6.70	6:20 AM	5.70	6:20 AM	6.20	12:55 PM	17.20	12:55 PM	10.20	12:55 PM	13.70
6:30 AM	6.60	6:30 AM	5.70	6:30 AM	6.15	1:00 PM	16.90	1:00 PM	9.80	1:00 PM	13.35
6:40 AM	6.30	6:40 AM	5.80	6:40 AM	6.05	1:05 PM	16.20	1:05 PM	9.50	1:05 PM	12.85
6:50 AM	6.00	6:50 AM	5.40	6:50 AM	5.70	1:10 PM	15.60	1:10 PM	9.50	1:10 PM	12.55
7:00 AM	6.00	7:00 AM	5.40	7:00 AM	5.70	1:15 PM	15.30	1:15 PM	9.20	1:15 PM	12.25
7:10 AM	5.80	7:10 AM	5.40	7:10 AM	5.60	1:20 PM	14.00	1:20 PM	9.10	1:20 PM	11.55
7:20 AM	5.90	7:20 AM	5.30	7:20 AM	5.60	1:25 PM	13.60	1:25 PM	8.70	1:25 PM	11.15
7:30 AM	5.80	7:30 AM	5.50	7:30 AM	5.65	1:30 PM	13.20	1:30 PM	8.90	1:30 PM	11.05
7:40 AM	5.60	7:40 AM	5.80	7:40 AM	5.70	1:35 PM	13.00	1:35 PM	8.40	1:35 PM	10.70
7:50 AM	5.70	7:50 AM	6.60	7:50 AM	6.15	1:40 PM	12.60	1:40 PM	8.50	1:40 PM	10.55
8:00 AM	5.80	8:00 AM	7.50	8:00 AM	6.65	1:45 PM	11.80	1:45 PM	8.20	1:45 PM	10.00
8:10 AM	5.80	8:10 AM	11.00	8:10 AM	8.40	1:50 PM	11.40	1:50 PM	8.00	1:50 PM	9.70
8:20 AM	5.30	8:20 AM	12.50	8:20 AM	8.90	1:55 PM	10.80	1:55 PM	7.80	1:55 PM	9.30
8:30 AM	5.60	8:30 AM	15.00	8:30 AM	10.30	2:00 PM	10.60	2:00 PM	7.70	2:00 PM	9.15
8:40 AM	5.30	8:40 AM	16.60	8:40 AM	10.95	2:05 PM	10.60	2:05 PM	7.30	2:05 PM	8.95
8:50 AM	5.50	8:50 AM	17.60	8:50 AM	11.55	2:10 PM	10.20	2:10 PM	7.50	2:10 PM	8.85
9:00 AM	6.30	9:00 AM	18.60	9:00 AM	12.45	2:20 PM	9.70	2:20 PM	7.10	2:20 PM	8.40
9:10 AM	6.90	9:10 AM	19.50	9:10 AM	13.20	2:30 PM	9.40	2:30 PM	6.80	2:30 PM	8.10
9:20 AM	8.40	9:20 AM	19.80	9:20 AM	14.10	2:40 PM	9.20	2:40 PM	6.70	2:40 PM	7.95

9:30 AM	11.10	9:30 AM	20.30	9:30 AM	15.70	2:50 PM	8.50	2:50 PM	6.60	2:50 PM	7.55
9:40 AM	13.30	9:40 AM	20.40	9:40 AM	16.85	3:00 PM	8.20	3:00 PM	6.50	3:00 PM	7.35
9:50 AM	15.50	9:50 AM	20.10	9:50 AM	17.80	3:10 PM	7.80	3:10 PM	6.50	3:10 PM	7.15
10:00 AM	16.60	10:00 AM	20.50	10:00 AM	18.55	3:20 PM	7.20	3:20 PM	6.50	3:20 PM	6.85
10:10 AM	17.70	10:10 AM	20.30	10:10 AM	19.00	3:30 PM	7.00	3:30 PM	6.20	3:30 PM	6.60
10:20 AM	18.80	10:20 AM	20.30	10:20 AM	19.55	3:40 PM	7.30	3:40 PM	6.30	3:40 PM	6.80
10:30 AM	19.20	10:30 AM	20.20	10:30 AM	19.70	3:50 PM	6.80	3:50 PM	6.00	3:50 PM	6.40
10:40 AM	20.00	10:40 AM	20.00	10:40 AM	20.00	4:00 PM	6.80	4:00 PM	6.00	4:00 PM	6.40
10:50 AM	20.20	10:50 AM	19.70	10:50 AM	19.95	4:10 PM	6.60	4:10 PM	6.00	4:10 PM	6.30
11:00 AM	20.10	11:00 AM	19.50	11:00 AM	19.80	4:20 PM	6.70	4:20 PM	5.80	4:20 PM	6.25
11:10 AM	20.20	11:10 AM	19.30	11:10 AM	19.75	4:30 PM	6.60	4:30 PM	5.80	4:30 PM	6.20
11:20 AM	20.40	11:20 AM	18.90	11:20 AM	19.65	4:40 PM	6.30	4:40 PM	5.70	4:40 PM	6.00
11:30 AM	20.40	11:30 AM	18.40	11:30 AM	19.40	4:50 PM	6.60	4:50 PM	5.70	4:50 PM	6.15
11:40 AM	20.30	11:40 AM	17.00	11:40 AM	18.65	5:00 PM	6.50	5:00 PM	5.80	5:00 PM	6.15
11:50 AM	20.20	11:50 AM	15.90	11:50 AM	18.05	5:10 PM	6.50	5:10 PM	6.10	5:10 PM	6.30
12:00 PM	19.90	12:00 PM	14.60	12:00 PM	17.25	5:20 PM	6.50	5:20 PM	6.60	5:20 PM	6.55
12:10 PM	19.70	12:10 PM	13.40	12:10 PM	16.55	5:30 PM	6.30	5:30 PM	6.10	5:30 PM	6.20
12:20 PM	19.40	12:20 PM	12.60	12:20 PM	16.00	5:40 PM	6.00	5:40 PM	6.30	5:40 PM	6.15
12:30 PM	19.20	12:30 PM	11.50	12:30 PM	15.35	5:50 PM	6.10	5:50 PM	6.40	5:50 PM	6.25

The data presented in Table 4.1 indicates an increase in received and extractable energy as the day grows, and drops again in the evening, as plotted in Figure 4.1.

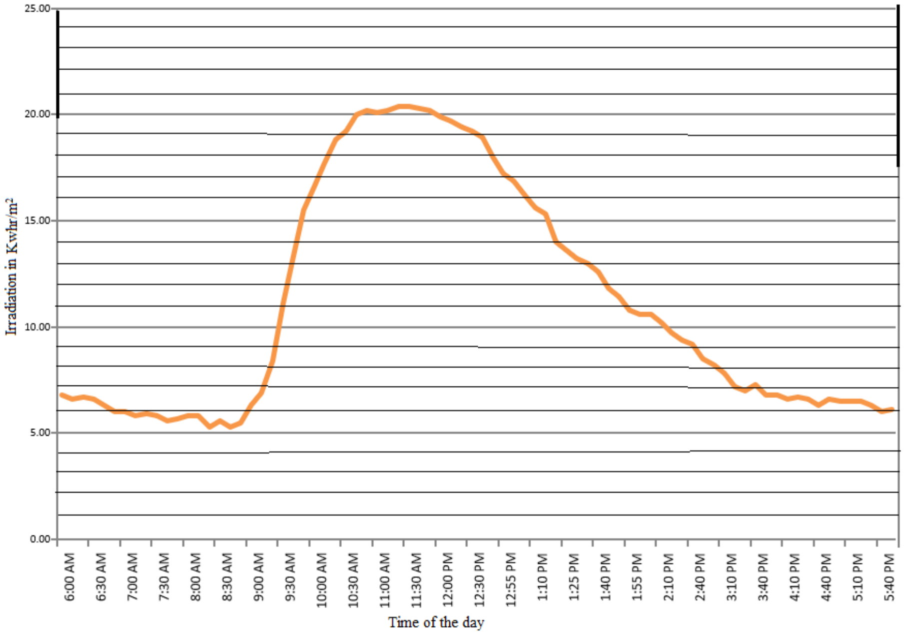

Figure 4-1 Solar Irradiation Energy received and extractable in a 12 hours sunny day in Kenya. (Wasike, 2015)

4.1.2 Solar Collector Equations and Simulink Model

In order to carry out simulation of the performance of a solar collector, as modelled in equation (3.2), SIMULINK building blocks are arranged to represent the equation, and parameter values inserted for simulation. These equations are fundamental to understanding the heat transfer and energy conversion processes within a solar collector. The parameters involved in equation (3.2) include; area of the solar collector (A_c), fluid temperature into and out of the solar collector T_{ci} and T_{co} respectively, ambient temperature T_{ca}, mass flow rate $\dot{v}_c$, volume of the fluid in the collector V_c, irradiance data I_c,and heat loss U_c. Their values are listed in Table 4.2, as provided by the manufacturer, with a variable fluid velocity, depending on the pump attached.

Table 4-2 Parameters of Solar Collector Heat Simulation

	Symbol	Parameter name	Value
1	A_c	Aperture area of the Solar collector	1.2m^2 – 14m^2
2	V_c	Volume of the fluid in the solar collector	500
3	$\dot{v}_c$	Velocity or mass flow rate of fluid into the collector	variable
4	T_{ci}	Input temperature of fluid into the collector	22ºC
5	T_{co}	Output fluid temperature from the collector	Simulated
6	T_{ca}	Ambient temperature around the collector	27ºC
7	U_c	Average heat loss in the collector	7W/m^{2}K
8	I_c	Irradiance data of solar energy	See Table 4.1
9	ρ_c	Density of the fluid in the solar collector	1000
10	C_c	Specific heat capacity of the fluid in the solar collector	997
11	η_c	Solar collector efficiency	0.87
12	T_{av}	Average temperature, $\frac{1}{2}(T_{ci} + T_{co})$	Calculated
13	C	Heat capacity of the fluid given by $C = \rho_c c_c V_c$	4.985e+08

The SIMULINK model for a solar collector is presented in Figure 4.2. Irradiation data in Table 4.2 is fed through a vector labelled Irradiation and with variation of the velocity $\dot{v}_c$, area A_c and the volume of the collector, the maximum output temperature T_{co} is obtained to be 101.54ºC as shown in the digital display block.

Three inputs, namely; input temperature, ambient temperature and solar irradiation are fed into the SIMULINK model, and one output; of the fluid output temperature is measured. The temperature output is captured and plotted in the scope and digital display. The output temperature measured just at the solar collector output pipe keeps on increasing because of continued heating of the fluid. Putting into consideration the heat loss in the pipe system through convection and radiation, the final heat energy reaching the heat exchanger is lower than that recorded as discussed in the piping system in the next section. The output heat energy in the water is sufficient to be transferred to drying air via the heat exchanger.

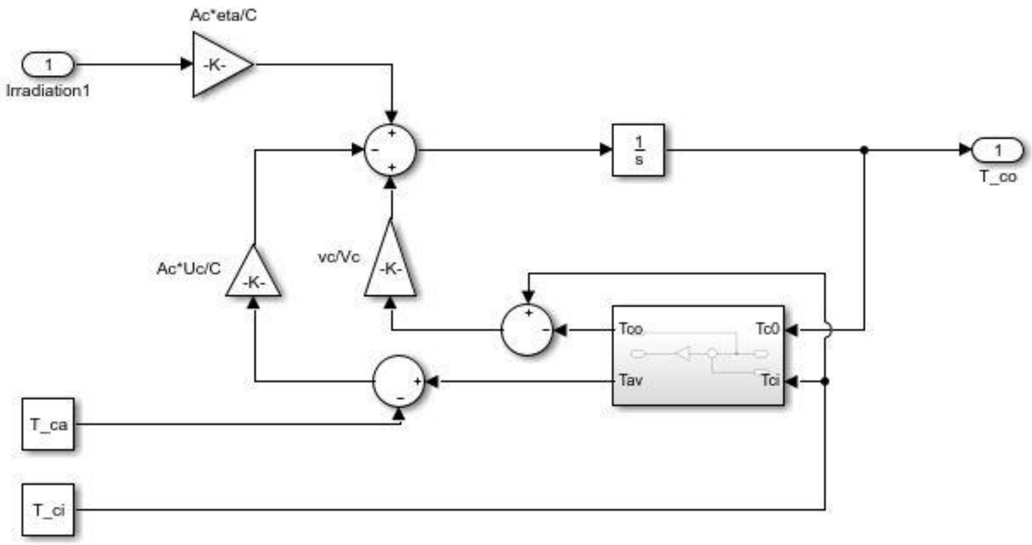

Figure 4-2 Design of a SIMULINK model of a Solar Collector in equation (3.2)

The solar network shown in figure (4.2) is masked in the final model by the image of a vacuum tube solar collector for easy understanding of the flow diagram of the model.

4.1.3 Solar Collector Simulation

Using the data provided in Table 4.1, the simulation results of the solar collector is presented below. It is noted that as the velocity of the fluid is varied, the output temperature is also varied. Similarly, the surface area of the collector is directly proportional to the output temperature of the fluid. In this research, only velocity is varied and the graph n Figure 4.3 shows the temperature variations as the velocity is varied. The desired output temperature is between $343K$ (70^0C) and $423K$ (150^0C), and for this, the optimal mass flow rate is $[500 - 1025]cm^3/s$. Note that the fluid output temperature reaches 60^0 C after 1 day and keep increasing to a stable temperature of approximately 130^0C after 10 days.

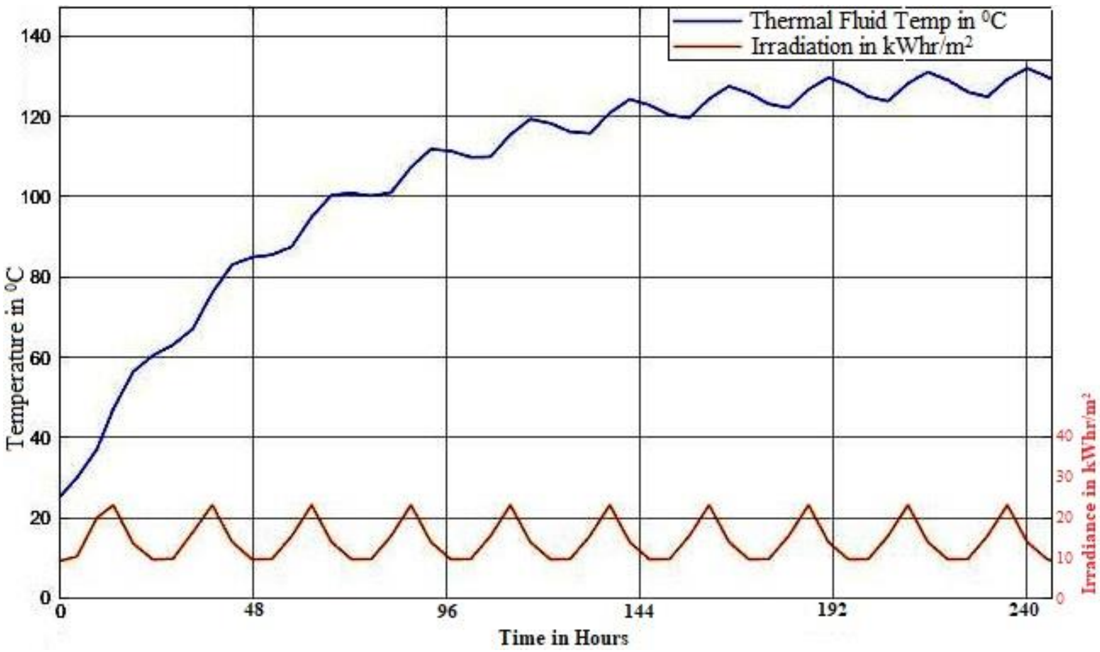

Figure 4-3 Solar irradiation energy and cumulative fluid temperature out of collector. Source: Author

4.2 The Piping System

Modelling the piping system involves specifying parameters that describe the pipes used in the model. These include the pipe length, diameter, internal and external surface area, insulation, heat conductivity across the pipe, among others. The SIMULINK block that models pipe flow dynamics in a thermal liquid network due to viscous friction losses and convective heat transfer with the pipe wall is presented in **Error! Reference s ource not found.**.

The pipe may be composed of one or more segments. Each segment contains a fixed volume of liquid whose pressure and temperature evolve based on its dynamic compressibility and thermal capacity as well as mass and energy exchanges with adjacent segments. The ports A and B are the thermal liquid conserving ports associated with the pipe inlet and outlet. Here, it is assumed that all segments have the same pipe wall temperature.

4.2.1 Piping system SIMULINK network

The piping system is modelled using a connection of pipe components with characteristics of heat loss, heat transfer rate, insulation, dimensions and velocity of fluid inside the pipe. Figure 4.4 below shows the schematic representation of the pipe network in a Solar heat dryer. In this study, a total of 30m length of pipe is used, with diameter of 0.021m and length of 30m, with zero inclination.

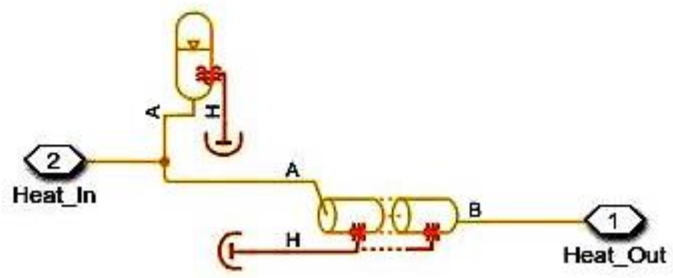

Figure 4-4 SIMULINK Pipe Network in the Dryer Model. Source: Author

The port 2 indicated as Heat_in in Figure 4.4 joins the outlet T_{co} in Figure 4.2, where hot water from the Solar collector is received. The Heat_out port connects to the heat exchanger discussed in the next subsection. The total heat loss along the pipe network is evaluated as the sum of heat loss due to conduction and heat loss due to convection, but the pipe is insulated so that heat loss is minimized. The piping network is also connected to an insulated gas filled accumulator, which acts as a pressure balancing mechanism to minimize the possibility of pipes bursting due to build in pressure as a result of heating. When the pressure is increased, the gas chamber is compressed, and when the pressure reduces, the compressed gas is expanded, thus ensuring a smooth flow of the hot water in the pipe throughout.

Conductive heat loss is calculated using given by the equation,

$$Q_{cond} = \frac{kA\Delta T}{d} \tag{4.2}$$

Where; Q_{cond} is the conductive heat loss in watts (W), k is the thermal conductivity of the pipe material in Wats per meter Kelvin (W/mK), A is the surface area in m^2, ΔT is the change in temperature in Kelvin (K) and d is the diameter, distance or thickness of the pipe in meters (m).

The choice of the material to be used for piping will depend on their thermal conductivity. The interest is to have a poor conductor of heat, so that all the heat in the liquid is reserved throughout the pipe length from the input to output, that is $T_i \approx T_o$ (temperature in equals to temperature out). Examples of materials and their thermal conductivity include; steel $45W/mK$, copper $398W/mK$, silver $406W/mK$, Aluminum $205W/mK$, Glass $0.8W/mK$, polystyrene $0.03W/mK$, among others.

In absence of suitable material, there is always an option of insulation, where heat is protected from loss using suitable jacket covering the pipe to insulate from loss of heat to the environment.

4.2.2 Pipe network mathematical equations

Convective heat loss along the pipe is given by,

$$Q_{conv} = h_{conv} A_s \left(T_p - T_\infty\right) \tag{4.3}$$

Where, Q_{conv} is the convective heat loss, A is the surface area, T_P is the pipe temperature and T_∞ is the environmental temperature.

The total thermal loss is evaluated as the ratio

$$Q_{loss} = \frac{\Delta T}{R_{tot}} = UA\Delta T \tag{4.4}$$

Where Q_{loss} heat loss, ΔT change in temperature and R_{tot} total thermal resistance, with $R_{tot} = R_{cond} + R_{rad} + R_{conv}$ defined as;

$$R_{cond} = \frac{\ln\left(\frac{r_0}{r_i}\right)}{2\pi kL} \quad (4.5)$$

and

$$R_{rad} = \frac{(T_p - T_\infty)}{\varepsilon A_s \sigma(T_p^4 - T_\infty^4)} \quad (4.6)$$

Where r_0 and r_i denotes the outer and inner radius of the pipe respectively, k thermal conductivity and L is the diameter of the pipe, ε denotes the radiative coefficient, σ conductivity and A_s is the surface area.

Temperature profile $T_m(x)$ along a pipe is determined as follows;

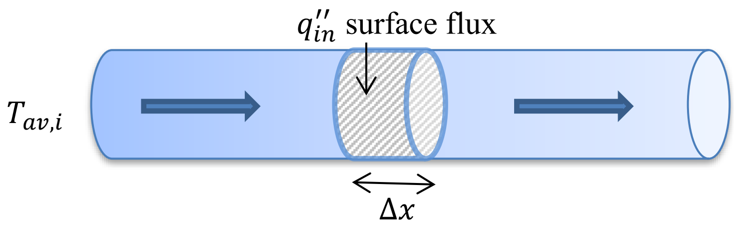

Figure 4-5 Temperature profile along a pipe. (Source: Author)

The thermal flux into the pipe is given by

$$q_{in} = \dot{m}c_p(T_o - T_i)$$

And the rate of change of the flux

$$\frac{dq_{in}}{dt} = \dot{m}c_p\frac{dT_{av}}{dt}$$

$$q''A_s = q''2\pi r\Delta x$$

Equating the last two expressions and integrating both sides yields;

$$\int_{T_{av,i}}^{T_{av,o}} dT_{av} = \int_0^x \frac{q''2\pi r\Delta x}{\dot{m}c_p}$$

These yields

$$T_{av}(x) = \frac{q''2\pi r\Delta x}{\dot{m}c_p}x + T_{av,i} \tag{4.7}$$

For plug flow, where $\dot{m} = \frac{\pi D^2 \rho v}{4}$ and the temperature out of a pipe T_o can be expressed as;

$$T_o = T_t + (T_o - T_t)e^{-\frac{4h}{c_p \rho v D}x} \tag{4.8}$$

The SIMULINK pipe network illustrated in Figure 4.3 is masked with a diagram of an insulated pipe, for easy understanding of the diagrammatic flow of the final model.

The temperature of fluid inside the pipe in simulation results remains constant throughout as per the input temperature. This means that the temperature is increasing if the source is increasing, and dropping if the source is declining. This is a condition of perfect insulation.

4.3 Heat Exchanger

As described in section 3.4, the heat exchanger is the device which aids in the exchange of heat energy between two fluids. In this study, the heat exchanger is the third component of the solar dryer, which extracts heat in the fluid inside the closed loop pipe network, out onto the drying air in the drying chamber. The physical diagram of the two types of heat exchangers is shown in the Figure 4.6 below.

In the SIMULINK network, a mask of a radiator is used to show the location of the heat exchanger. The heat exchanger used in this research is the one where heat is transferred from a closed loop of hot water, to air through forced convection, where fans blow air through thin fins in the heat exchanger, extracting heat. The cold air is obtained from the environment, but first passed through a humidifier, to make it dry. This will help increase the temperature of the hot drying air, and help fasten the drying process of the food particles.

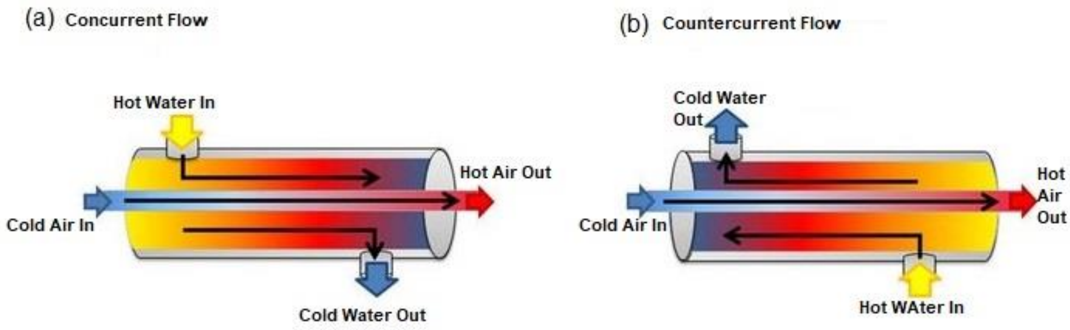

Figure 4.6 Concurrent and Counter flow Heat Exchangers. (Source: Author)

4.3.2 Heat Exchanger Mathematical Model Equations

This section deals with the analysis of heat transfer and mass flow equations necessary in describing the drying process of food particles in the dryer. This is done with a brief description and formulation of a set of equations describing the heat transfer in a heat exchanger, and a set of equations describing the mass flow and energy distribution in the drying chamber. Parameters controlling the efficiency of the heat exchanger and desired drying air characteristics are discussed. The dryer model is subdivided into two sections, namely; the heat exchanger subsystem, and the drying compartment.

The mathematical equations of the heat exchanger typically describe the heat transfer and fluid flow characteristics within the exchanger. The calculation of heat transfer across the exchanger is derived from the first law of thermodynamics, which depend on the surface area of the exchanger and the flow rates of the fluid, together with the temperature difference of the two fluids. These equations can include principles of thermodynamics, fluid mechanics, and heat transfer, and are used to analyze and predict the performance of the heat exchanger under different operating conditions. The calculations used in this research assumes that the heat exchanger is of a single-phase type, implying that the entering fluid remains in the same phase as in the outlet.

The energy (E) balance equation is a fundamental principle in thermodynamics that states that the energy entering a system must equal the energy leaving the system, plus any energy accumulated within the system less energy lost in the system. It is expressed mathematically as:

$$E_{In} = E_{Out} + E_{Accumulation} - E_{Lost} \tag{4.9}$$

This equation is commonly used to analyze and quantify energy transfers in heat exchangers. As the hot fluid transfers some of its energy to the cold fluid, this process is accompanied by respective changes in enthalpy, which can be expressed by the equations for the hot and cold fluids respectively as,

$$\begin{aligned} Q &= -\dot{m}_h c_h dT_h \\ Q &= -\dot{m}_c c_c dT_c \end{aligned} \tag{4.10}$$

Where $\dot{m} = \rho A \dot{v}$ is the mass flow rate and c the specific heat capacity of the fluid at constant pressure, $A = (width \times length\,)$ is the surface area of the heat exchanger, and the subscripts h, c denotes the hot and the cold fluid respectively. Using the notation U denoting the heat transfer coefficient, and $\Delta T = T_h - T_c$ for temperature difference, equation (2) for heat transfer can be expressed as,

$$Q = UA\Delta T \tag{4.11}$$

Where ΔT_m is the mean temperature difference, and U is the heat transfer coefficient given by,

$$U = \frac{1}{\frac{1}{h_o} + \frac{r_o}{K}\ln\left(\frac{r_o}{r_i}\right) + \left(\frac{r_i}{r_o}\right)\frac{1}{h_i}} \tag{4.12}$$

Heat transfer for a differential element of length, dx, is obtained by differentiating equation (2) and expressing the temperature difference $d(\Delta T) = dT_h - dT_c$. This yields the relation,

`

$$dQ = -\dot{m}_h c_h dT_h = -C_h dT_h$$
$$dQ = -\dot{m}_c c_c dT_c = -C_c dT_c \qquad (4.13)$$

where $\dot{m}_h c_h = C_h$ and $\dot{m}_c c_c = C_c$. With little algebra, integration and rearrangements using equation (3), equation (5) can be expressed as,

$$Q = UA\frac{(\Delta T_2 - \Delta T_1)}{\ln(\Delta T_2/\Delta T_1)} \qquad (4.14)$$

Where for counter current, the temperature differences ΔT_1 and ΔT_2 are indicated in Figure 1. and defined as,

$$\Delta T_1 = T_{h,i} - T_{c,o},\ \Delta T_2 = T_{h,o} - T_{c,i} \qquad (4.15)$$

4.3.3 Effectiveness of Heat Exchanger

The effectiveness of a heat exchanger is a measure of how well it is transferring heat between the hot and cold fluids. The general effectiveness of heat exchanger is determined by the ratio of the actual heat transfer to the maximum possible heat transfer, given as,

$$Effectiveness = \frac{Actual\ heat\ Transfer}{Maximum\ possible\ heat\ transfer}$$

In order to express this effectiveness mathematically, let the number of transfer units (NTU) be denoted by N and let $T_{\min}$ and $T_{\max}$ denote the minimum and maximum temperatures respectively. Then the effectiveness of a heat exchanger is a function of heat exchanger surface area A and the heat transfer coefficient U only given by;

$$\epsilon = \frac{Q}{Q_{max}} = \epsilon\left(N, \frac{T_{min}}{T_{max}}\right) \qquad (4.16)$$

where $Q = C_c(T_{c,o} - T_{ci})$ and $Q_{max} = C_c(T_{hi} - T_{ci})$, while $N = \frac{UA}{T_{min}}$.

The rate of heat transfer in a heat exchanger is the amount of heat transferred per unit time between the hot and cold fluids flowing through the exchanger. It is a measure of the heat exchange efficiency and is typically quantified in terms of energy per unit time (e.g., watts or BTU per hour). The rate of heat transfer depends on factors such as the temperature difference between the hot and cold fluids, the surface area available for heat transfer, and the overall heat transfer coefficient of the exchanger. This rate of heat transfer can therefore be described by;

$Q = \epsilon T_{max} = \epsilon T_{min}\left(T_{h,i} - T_{c,i}\right),$

where the specific effectiveness of a counter flow heat exchanger is given as in [22] by,

$$\epsilon_{counter} = \frac{1-\exp[-N(1-C)]}{1-C\exp[-N(1-C)]}\,;\, C = \frac{C_{min}}{C_{max}} \qquad (4.17)$$

From the description of the heat exchanger and heat transfer in equations (4.8) – (4.15). The output hot air is then channeled through the dehumidifier, (so as to remove any moisture), to the drying chamber, through temperature sensors and flow regulators, so that the desired dry air temperature and flow rate is obtained.

4.3.4 SIMULINK network of Heat Exchanger

The SIMULINK network flow of heat exchanger is represented in Figure 4.7 below. This SIMULINK block models a heat exchanger in a thermal liquid network, where the heat transfer rate is based on the number of transfer units (NTU). The model used supports both the concurrent and countercurrent flows on a concentric flow, shell and tube, cross flow, and generic heat exchanger configurations defined by tabular data. In our model, the two liquids used was water and air. Hot water from the solar heater passes through the heat exchanger, and transfer the heat to air, which is then channeled to the dryer to heat and dry the food particles.

Ports A2 and B2 in the SIMULINK network in Figure 4.6 are the thermal liquid inlet and outlet. The inlet A2 describes the flow of hot water from the solar collector, and the outlet B2 represents the flow out from the heat exchanger. The initial temperature of the liquid in the heat exchanger is 25^0 C, room temperature, and the flow rate depends on the speed of the pump connected to it through the solar collector. In this research study, it is assumed that the mass flow rate of fluid inside the model remains constant throughout from the water pump, solar collector, heat exchanger, and back to reservoir tank. The length of the pipe network in the heat exchanger is a total of 6m, of diameter 0.02m and cross-sectional area of $1.5\pi(0.01)^2m^2$, and with a flow rate of 1.128litres per second.

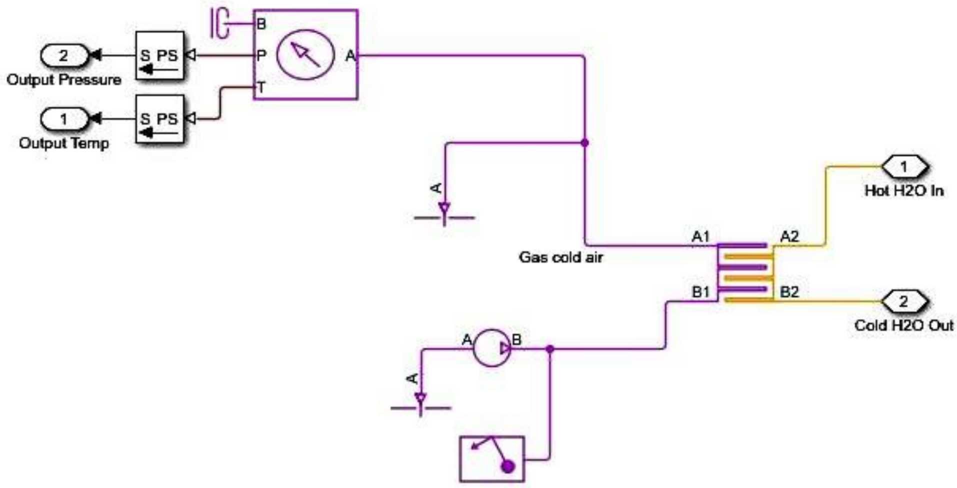

Figure 4-7 Heat Exchanger SIMULINK Network containing temperature and pressure sensors and measurements. Source: Author.

4.3.5 Simulation of temperature in a Heat Exchanger

Ports A1 and B1 is associated with the inlet and outlet of the controlled fluid, in this case cold air. The cold air flows from port B1 to A1, countercurrent to the flow of the hot liquid, so as to pick the maximum heat from the water. The source of the cold air is the environment, but passing through a humidifier to ensure that the inlet air is dry. This air is expected to be at environmental temperature, of 20^{0}C on average, and leaves the heat exchanger by a forced air mass flow using a fan, at a temperature higher, depending on velocity and temperature of the thermal liquid in the exchanger. This network is masked using a radiator in the final model flow.

The output temperature of air across the heat exchanger is plotted in Figure 4.8 below. The temperature is recorded without regulation at various air mass flow rate as indicated in the graph. The desired output temperature depends on the volume, time of drying and the requirements of the food products to be dried. The setting in the control unit controls the temperature in two ways; namely by connecting a bypass pipe to prevent flow of hot water through the heat exchanger, or by adjusting the mass flow rate of air in the dryer.

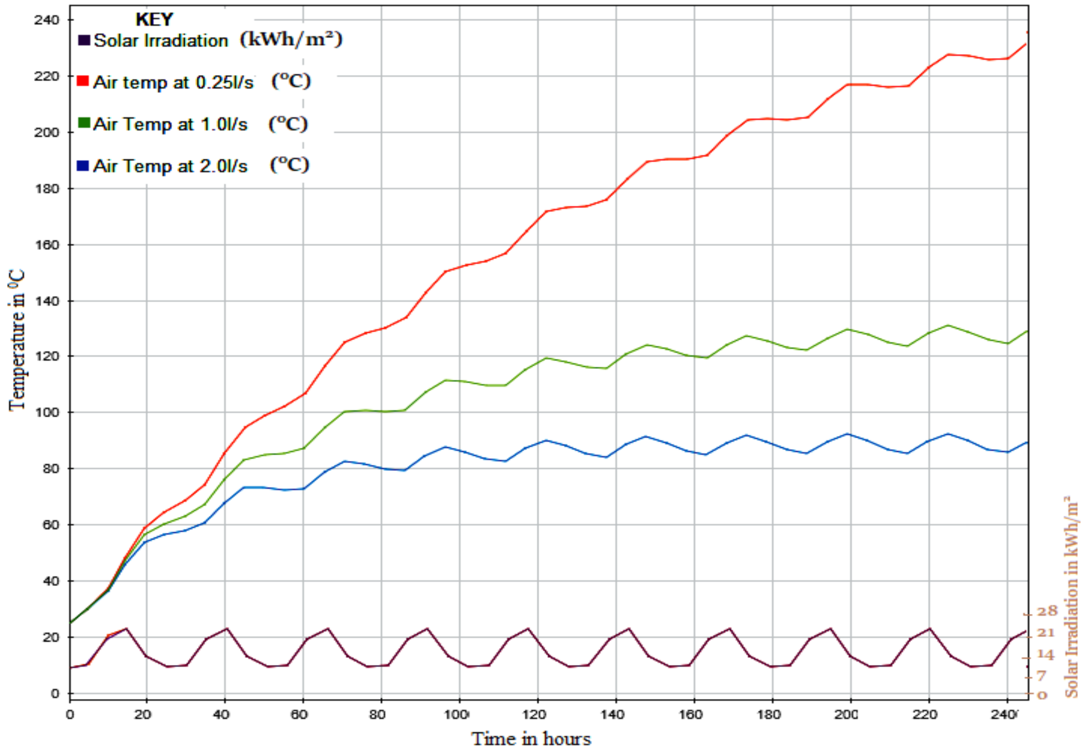

Figure 4-8 Output temperature of the hot air from the heat exchanger at different air mass flow rate

4.4. Food Drying Chamber

The next subsystem in the model is the Dryer. This is the final and major target of the entire model. The other subsystems are adjusted to suit the requirements of the dryer. It is in the drying chamber that food products are placed, and exposed to hot drying air for dehydration depending on their nature.

Various food products have their upper limit of maximum temperature that can be exposed to dehydrate, of which, beyond this limit, the food products will start getting cooked or roasted, thus spoiling their quality.

The process of dehydration as described in section. The food particles to be dried are placed in trays in the drying chamber, and once the door and windows are sealed appropriately, switched are put on to allow hot dry air in and to eliminate moist air in the dryer. Measuring devices are placed to monitor the temperature, time, mass flow rate, number of radiators switched on, etc.

4.4.1 Drying Chamber components

The drying chamber contains 5 heat exchangers placed on the walls of the drying chamber, each fitted with controlled fans, to regulate the air mass flow rate, and also fitted with thermometers and mass flow rate devices to control the drying parameters.

Depending on the type of food, amount of food to be dried, their initial moisture content, the required final moisture content, and the expected urgency of the drying process (or residence time), adjustment is made on the hot air mass flow rate, thermal liquid mass flow rate, number of radiators in use, and the amount of supplementary source of energy that can be allowed to heat the thermal liquid so that all the parameters are controlled and monitored.

The value of parameters that are used in the simulation process of the dryer are presented in Table 4.3 below. These parameters are indicated for the complete structure of the dryer.

Table 4-3 List of Dryer Simulation Parameters values

S.No	**Symbol**	**value**	**Description**
1	$h_{air,roof}$	$12W/m^2K$	Convective Air - Roof heat transfer coefficient
2	$h_{air,wall}$	$24\ W/m^2K$	Convective Air - Wall heat transfer coefficient
3	$h_{air,wind}$	$25\ W/m^2K$	Convective Air - Window heat transfer coefficient

4	$A_{s,wind}$	$0.25\ m^2$	Area of each window
5	$A_{s,roof}$	$14.4\ m^2$	Area of the roof
6	$A_{s,wall}$	$40.32\ m^2$	Area of the walls
7	c_{fuel}	$300.25\ Ksh$	Cost of gas fuel per liter
8	ρ_{roof}	$32\ kg/m^3$	Density of the roof
9	ρ_{wall}	$1920\ Kg/m^3$	Density of the wall
10	ρ_{wind}	$2700\ Kg/m^3$	Density of the window
11	wid	$2.4\ m$	Width of the dryer
12	$\hbar t$	$4\ m$	Height of the dryer chamber
13	$\hbar t$	$0.5\ m$	Height of the window
14	le	$6\ m$	Length of the dryer
15	No	3	Number of windows in the dryer
16	ε_{roof}	0.1	Percentage of heat leakage through the roof
17	ε_{wall}	0.15	Percentage of heat leakage through the wall
18	ε_{wind}	0.2	Percentage of heat leakage through the window
19	θ	0.070736	Pitch of the roof in radians
20	h_r	$100\ W/m^2K$	Radiative (radiator) heat transfer coefficient
21	$h_{air,roof}$	$38\ W/m^2K$	Convective air – roof heat transfer coefficient
22	L_{roof}	0.2	Roofing material thickness
23	$c_{p,air}$	1005.4	Specific heat capacity of air
24	$c_{p,wind}$	$840\ J/kgK$	Specific heat capacity of the window material
25	$c_{p,roof}$	$835\ J/kgK$	Specific heat capacity of the roofing material
26	$c_{p,wall}$	$835\ J/kgK$	Specific heat capacity of the wall material
27	$A_{s,radi}$	$5m^2$	Surface area of the radiator
28	k_{roof}	$0.038\ W/mK$	Thermal conductivity of the roof
29	k_{wall}	$0.038\ W/mK$	Thermal conductivity of the wall

30	k_{wind}	0.78 W/mK	Thermal conductivity of the window
31	$h_{air,wall}$	$34W/m^2K$	Convective air - wall heat transfer coefficient
32	L_{wall}	$0.2m$	Wall thickness
33	L_{wind}	$0.01m$	Window thickness
34	wid	0.5 m	Width of the window
35	$h_{air,wind}$	32 W/m^2K	Convective air - window heat transfer coefficient
36	N	[0 – 6]	Number of radiators
37	τ	[120 – 200]	Torque speed of the water pump

The complete dryer model is illustrated in Figure 4.9 below. It is noted that controls available include; thermal liquid collector output, radiator, drying chamber and temperature reading and controls, number of radiators, air mass flow rate control, water pump switch and speed control, water reservoir volume, level and temperature reading, irradiation threshold switch, alternative fuel valve level, fuel cost scope, among others.

4.5 Optimization

A simulation of the dryer at any time indicates the radiator temperature, dryer temperature, the solar irradiation, the alternative fuel flow and cost among others. It is noted that at the dryer setting of 80^0C, the temperature in the first four days is unstable, and this fluctuation can be supplemented by a release of alternative fuel energy to raise the temperature to the desired level. The alternative fuel can be set to automatic regulator, so that every night, the switch goes on, to substitute absence of solar irradiation, to endure optimal results.

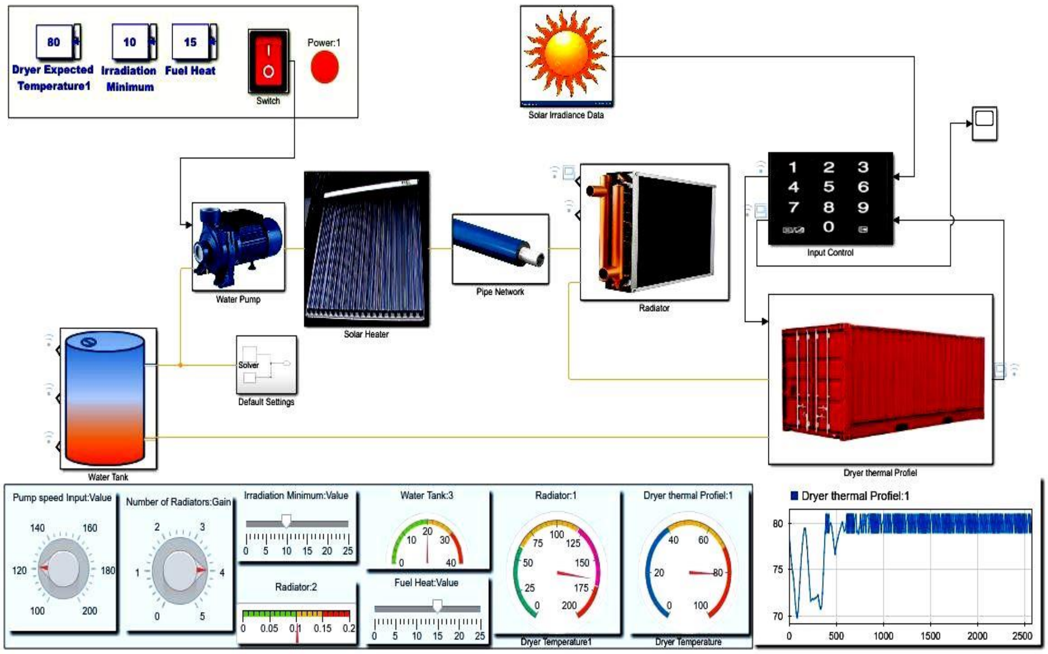

Figure 4-9 Complete Drier model showing all the components, controls and switches (Source: Author)

The graph showing the optimal fuel consumption and the cost is presented below in Figure 4.10. It is calculated that the flow of petroleum cooking gas is based on the current market values at Ksh 2800 per 7Kg gas cylinder, giving a rate of Ksh 400/kg or Ksh 0.4/g. This is multiplied by the amount of mass flow to determine the cost of fuel used.

It is noted that in absence of solar irradiation, the fuel cost curve increases exponentially but with automatic regulation, the fuel curve is a step function, with zero cost during the day as the dryer is fully operated by solar energy. It is noted that the cost is more than three times cheap when solar energy is used as compared to continuous alternative fuel source of energy which rises to over Ksh 5800 in 10 days unlike Ksh 1800 for intermittent scenario.

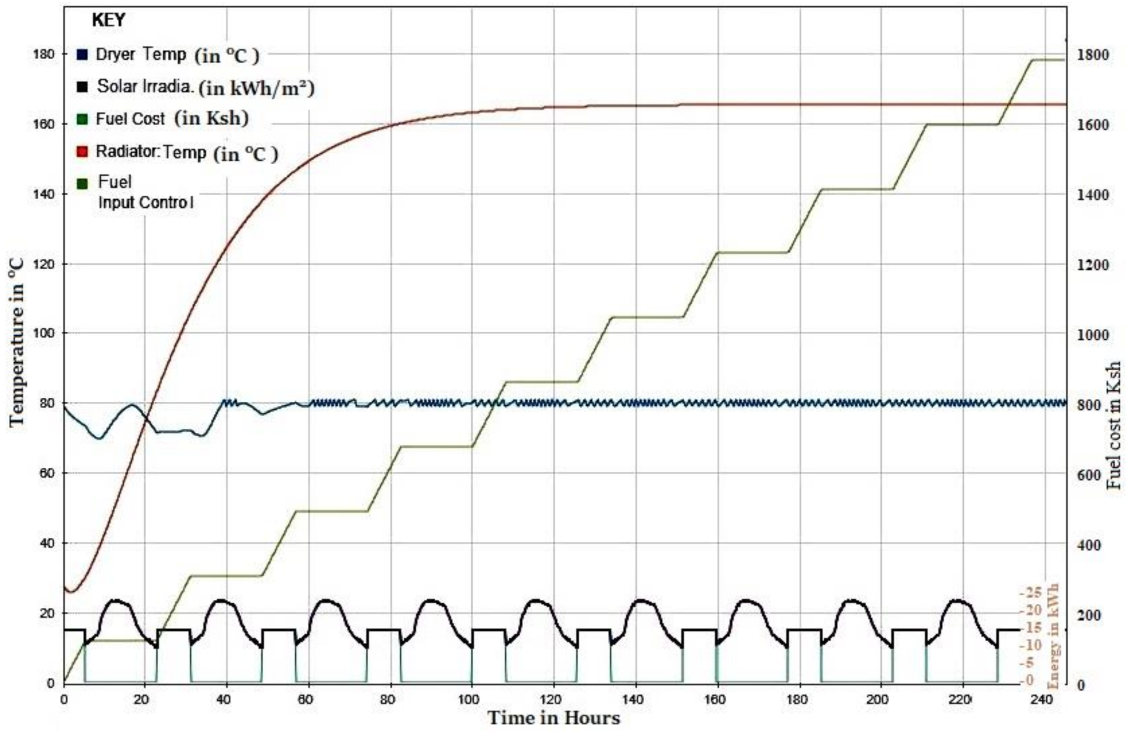

Figure 4-10 Complete Dryer Model simulation showing intermittent fuel and cost

Comparing the cost of energy from intermittent use of LPG gas to supplement solar energy, and the continuous use of LPG gas as presented in Figure 4.10, it is noted that the cost of fuel used to dry the same amount of food products at same moisture content hits Ksh 5600 in 10 days as opposed to Ksh 1800 when solar is used during the day and LPG gas used during the night.

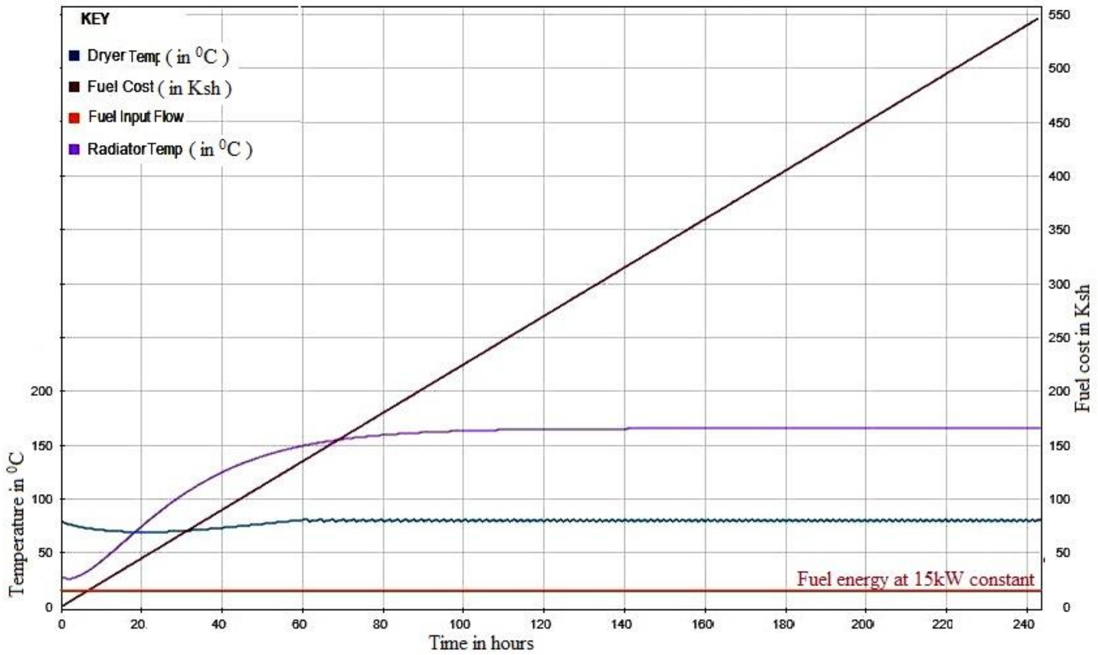

Figure 4-11 Complete dryer model simulation showing continuous fuel cost

This clearly justifies optimization of mixed energy sources, where the green energy is used as the main source of energy, in this case solar power, and the next less expensive energy (LPG) gas is used to supplement the times that solar power is insufficient, or during the night. Such a combination has the main advantage in terms of cost reduction. The use of biogas however can be explored to replace the LPG gas.

4.5.1 Drying Chamber and Water-to-Air Heat Exchanger's Output

The drying chamber is the final and major target of the entire food drying model. The other subsystems are adjusted to suit the requirements of the dryer. It is in the drying chamber that food products are placed, and exposed to hot drying air for dehydration depending on their nature. The drying chamber are equipped with heat exchangers placed on the walls of the drying chamber, each fitted with controlled fans, to regulate the air mass flow rate. Depending on the type of food, amount of food to be dried, their initial moisture content, the required final moisture content, and the expected urgency of the drying process (or residence time), adjustment is made on the hot air mass flow rate, thermal liquid mass flow rate. These parameters are continuously controlled using a feedback mechanism for the entire time that food products are undergoing dehydration process.

Various food products have their upper limit of maximum temperature that can be exposed to dehydrate, of which, beyond this limit, the food products will start getting cooked or roasted, thus spoiling their quality. The food particles to be dried are placed in trays in the drying chamber, and hot dry air is channeled from the heat exchangers through the trays to eliminate moist air in the dryer. Measuring devices are placed to monitor the temperature, time, mass flow rate, number of radiators switched on, among other variables.

For a water to air heat exchanger, the temperature of the extracted hot air from the heat exchanger depends on the variables which include; input temperature of thermal liquid $T_{h,i}$, air mass velocity through the fan v_a, sweep area of the fan A_f, water volumetric flow rate $\dot{V}_w$, heat transfer area of the exchanger A_e and heat exchangers' coefficient of heat transfer U. For a fixed area of heat exchanger, with fixed input thermal fluid temperature, and fixed fan area, the only variable used to control the output temperature, is the air mass flow rate through the fan v_a. Incorporating this into equation (4.14) and (4.15) yields,

$$N = \frac{UA}{\rho_a A_f c_a v} := \frac{K}{v} \text{ where } K = \frac{UA}{\rho_a A_f c_a} \tag{4.18}$$

And thus, the effectiveness as a function of air velocity is defines as,

$$\epsilon(v)_{counter} = \frac{1-e^{-\frac{K}{v}(1-C(v))}}{1-C(v)\, e^{-\frac{K}{v}(1-C(v))}} \tag{4.19}$$

Where $C(v) = \frac{C_{min}(v)}{C_{max}(v)}$, and if C_{min} is the air side, then $C(v) = \frac{\rho_a A_f v c_a}{\rho_h \dot{V}_h c_h}$ and the output temperature of air is given by

$$T_{a,o} = T_{a,i} + \epsilon(v)\left(T_{h,i} - T_{a,i}\right) \tag{4.20}$$

Where the subscript a- air, i – in, o- out and h for hot water. Using the food drier model data as presented in Table 4.4, the output temperature of hot air can be illustrated as shown in Figure 4.12.

Table 4-4 Concurrent Heat Exchanger Simulation Variables

Variable	**Symbol**	**Value**
Hot water inlet	$T_{h,i}$	100 ^{0}C
Hot water flow rate	$\dot{V}_h$	1.128 lit/s
Density of water	ρ_h	997 Kg/m^3
Specific heat capacity of water	c_h	4186 J/Kg-K
Air in temperature	$T_{a,i}$	25 ^{0}C
Fan area	A_f	0.05m^2
Air velocity	v_a	4.0m/s
Density of air	ρ_a	1005J/Kg-K
Heat transfer coefficient	U	100W/m^2-K
Exchanger heat transfer Surface area	A	2.827m^2
Cold air inlet temp	$T_{a,i}$	25^{9}C

From Figure 4.12, the temperature of the thermal fluid drops slightly, and the output air temperature is seen to increase from the initial input temperature of 25^{0}C to 75.6^{0}C as illustrated. This temperature however is obtained at constant air flow rate and constant fan revolution per minute. Any changes to these variables affect the output temperature of the drying air.

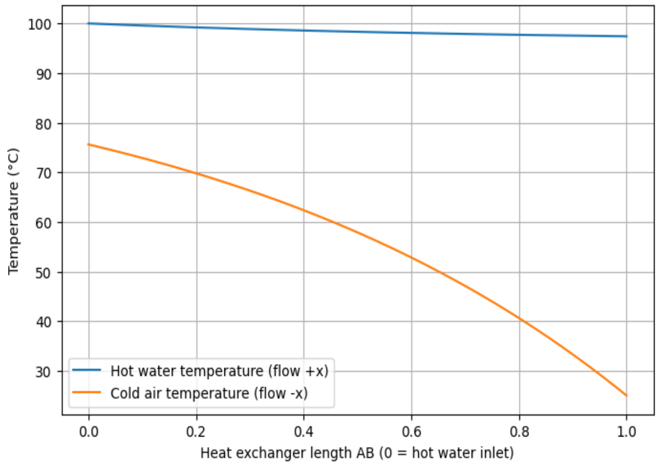

Figure 4-12 Concurrent Heat Exchanger Hot air output temperature Profile

The parameters related to the output in Figure 4.12 are presented in Table 4.5. These include; NTU of $N = 1.172$, capacity ratio $C = 0.051$, heat exchanger's effectiveness $\epsilon(v) = 0.6826$ and the maximum air temperature of $T_{a,o} = 75.6^0C$. These values are achieved using the input values presented in Table 4-5.

Table 4-5 Heat Exchanger simulation Output parameters

Variable	**Symbol**	**Value**
NTU	N	1.172
Capacity ratio	C	0.051
Effectiveness	$\epsilon(v)$	0.6826
Air outlet temperature	$T_{a,o}$	75.6 ^{0}C

4.5.2 Air Mass flow rate and Output Temperature

The optimal output temperature of the drying air is obtained by tunning the variables of the fan area, fan speed and air flow velocity. It is noted that these tree variables have inverse relationship with the output temperature as shown in Figure 4.13. Simulation of the effect of air velocity, fan area and fan rotation speed are presented in Figure 4.13.

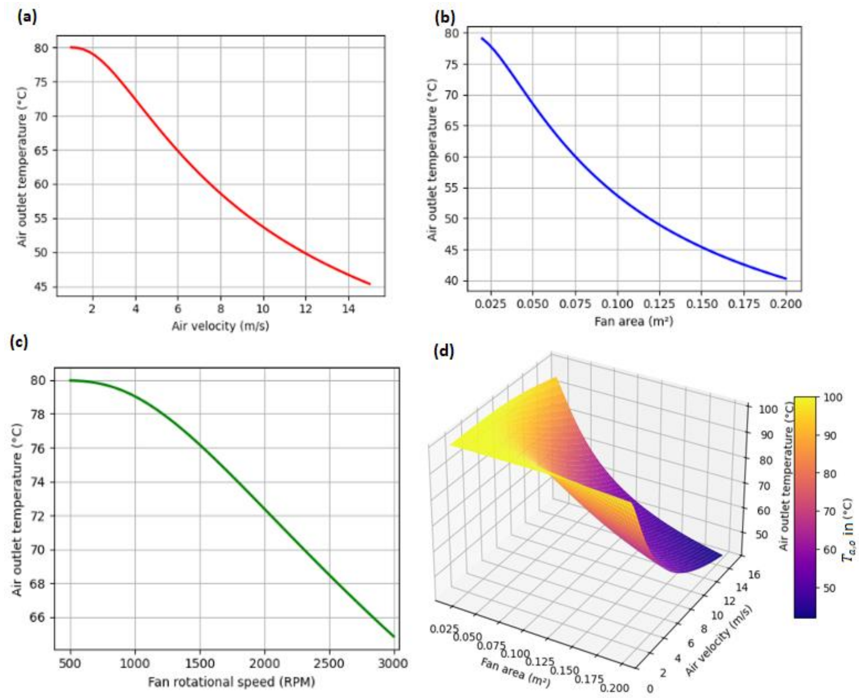

Figure 4-13 Effect of air velocity, fan sweep area and fan speed on output air temperature

It is noted that all the three variables are inversely proportional to the output temperature. At low air velocity, flowing air through the heat exchanger will have adequate time to pick heat from the hot pipes (heated by hot water) and therefore the lower the velocity, the higher the output temperature of the drying air as indicated in part (a) of Figure 4-13. Similarly, bigger diameter of a fan sweeps a larger area forcing more air through the heat exchanger, thus end up cooling the heat expected to be output. The smaller the amount of air flowing through the heat exchanger increases the enthalpy and thus brings out more heat. This is illustrated in part (b) of Figure 4-13. The third variable on fan rotation speed becomes obvious from the linear relation of fan speed and air velocity $v = k_n N$, where v denotes air velocity, N fan rotation speed and k_n variation constant, that increase in fan speed lowers the output air temperature as depicted in Figure 4-13(c). Putting all of them together, a surface plot representing the relation of all the three variables is presented in Figure 4-13(d).

4.5.3 Optimization of Drying Air Temperature

An optimization problem typically involves maximizing or minimizing a certain objective function while satisfying a set of constraints. Such a problem can be solved using mathematical techniques such as linear programming, nonlinear programming, and evolutionary algorithms, multi-objective particle swarm optimization, non-dominated sorting genetic algorithms, pareto-front based simulated annealing, Pontryagins' methods, among others. The goal of solving an optimization problem is to identify the most efficient or effective solution given a specific set of constraints (conditions are essential for defining the boundaries or limitations within which the optimization problem must be solved) and maximization or minimization of desired objective(s) of interest restricted by constraints with attainable values.

The Pontryagin's Minimum Principle (PMP) is a key concept in the field of optimal control theory, particularly in the context of continuous-time systems. It provides necessary conditions for optimality in problems involving the minimization of a cost function, subject to differential equations that describe the dynamics of the system. The associated optimization algorithm, known as the Pontryagin's Minimum Principle, is used to solve such optimal control problems by determining the control inputs that minimize the specified cost function while satisfying the system dynamics.

The study proposes to use the Pontryagin's maximum principle to solve the optimal control problem involving the decision variables $x(t)$ and the objective variable $u(t)$. This involves the process of determining control and state trajectories for a dynamic system over a period of time in order to minimize a performance index.

From equation (4.11), we have heat energy equal to the local heat flux through the wall, and thus in an infinitesimal length element dx, we have;

$$\delta\dot{Q} = UA(T_h - T_c)dx \tag{4.21}$$

Expressing equation (4.21) in terms of equation (4.11) yields;

$$\begin{aligned} \frac{dT_h}{dx} &= -K_h(T_h - T_c) \\ \frac{dT_c}{dx} &= -K_c(T_h - T_c) \end{aligned} \tag{4.22}$$

With the negative sign denoting that the heat is increasing in the opposite direction of the x – axis in a countercurrent heat exchanger arrangement, where $K_c = \frac{UA}{\dot{m}_c c_c}$ and $K_h = \frac{UA}{\dot{m}_h c_h}$, and other parameters carry the same meaning.

To maximize the outlet air temperature $T_{c,o}$, given inlet hot water temperature $T_{h,i}$, this forms an optimal control problem with the controls $u_1(t)$ denoting air velocity which affects the air mass flow rate $\dot{m}_a(u_1)$ and $u_2(t)$ denoting the fan speed which affects both air velocity and convective heat transfer coefficient $h_a(u_1, u_2)$. Define the constraint variables $x = (x_1, x_2)$ as,

$$x_1(t) = T_h(t),\ x_2(t) = T_c(t) \tag{4.23}$$

Representing the water temperature and air temperature respectively. The state equation is therefore presented as;

$$\begin{aligned} \dot{x_1}(t) &= -K_h(u_2)(x_1 - x_2) \\ \dot{x_2}(t) &= -K_c(u_2)(x_1 - x_2) \end{aligned} \tag{4.24}$$

The objective function of this optimal control problem is to maximize the output air temperature $T_{c,o}$ while penalizing the power used by the fan in terms of fan power u_2^2 and fan resistance u_1^2. This yields the objective function,

$$J(x, u) = x_2(t_f) - \int_o^{t_f} (c_1 u_1^2 + c_2 u_2^2)dt \tag{4.25}$$

Where t_f is the optimality feasible time limit, c_1, c_2 are arbitrary weighting constants representing energy cost coefficients. $J(x, u)$ describes the performance index, which in this case describes how best the controls can be manipulated to give the maximum temperature. The main objective of this Optimal Control problem is finding the piecewise continuous control $u(t) = (u_1, u_2)$ and the associated state variable $x(t) = (x_1, x_2)$ to maximize the given objective functional $J(x, u)$.

In order to solve this optimal control problem in equation (4.24 – 4.25), we will apply Pontryagin’s Maximum Principle.

Pontryagin's Maximum Principle is a mathematical theory used to solve optimization problems for dynamic systems, particularly in control theory and optimal control. In this problem, we define the adjoint functional H here referred to as Hamiltonian as;

The Hamiltonian, named after the Irish mathematician William Rowan Hamilton, is a fundamental concept in classical mechanics and mathematical physics [25]. It is a scalar function that summarizes the dynamics of a physical system, particularly in the context of conservative systems.

The Hamiltonian is hereby defined by;

$$H\big(t, x(t), u(t), \lambda(t)\big) = \lambda_1 \dot{x_1} + \lambda_2 \dot{x_2} - (c_1 u_1^2 + c_2 u_2^2) \qquad (4.26)$$

Here, the parameter $\lambda(t)$ denotes the multiplier of the state variable. Substituting equation (4.24) into equation (4.26) yields,

$$H\big(t, x(t), u(t), \lambda(t)\big) = -\lambda_1 K_h(u_2)(x_1 - x_2) - \lambda_2 K_c(u_2)(x_1 - x_2) - (c_1 u_1^2 + c_2 u_2^2) \qquad (4.27)$$

Which can be simplified to;

$$H = U(u_2)(x_1 - x_2)[-\lambda_1 A_1 + \lambda_2 A_2] - (c_1 u_1^2 + c_2 u_2^2) \tag{4.28}$$

Where $A_1 = \frac{A}{\dot{m}_h c_h}$, $A_2 = \frac{A}{\dot{m}_c(u_1) c_c}$ are redefined to emphasize the function of U and the effect of u_1 on $\dot{m}_c$.

Solving to minimize the Hamiltonian in equation (4.28) is done by evaluating the condition which satisfies the equations

$$\frac{\partial H}{\partial u} = 0 \tag{4.29}$$

That is,

$$\begin{aligned} \frac{\partial H}{\partial u_1} &= U(u_2)(x_1 - x_2)\lambda_2 \frac{\partial A_w}{\partial u_1} - 2c_1 u_1 \\ \frac{\partial H}{\partial u_2} &= (x_1 - x_2)[-\lambda_1 A_1 + \lambda_2 A_2] \frac{dU}{du_2} - 2c_2 u_2 \end{aligned} \tag{4.30}$$

Solving equation (4.29) in terms of equation (4.30) yields the optimal fan speed u_1^* and optimal air velocity u_2^* as,

$$\begin{aligned} u_1^* &= \frac{U(u_2)(x_1 - x_2)\lambda_2}{2c_1} \frac{\partial A_2}{\partial u_1} \\ u_2^* &= \frac{(x_1 - x_2)[\lambda_1 A_1 + \lambda_2 A_2(u_i)]}{2c_2} \frac{dU}{du_2} \end{aligned}$$

(4.31)

Where $U(u_2)$ is the relation between overall conductance and fan speed, which could be linear with k_u as the sensitivity of the slope. Using the data in Table 4.5. The simulation of optimal air velocity and optimal fan speed is illustrated in Figure 4.14.

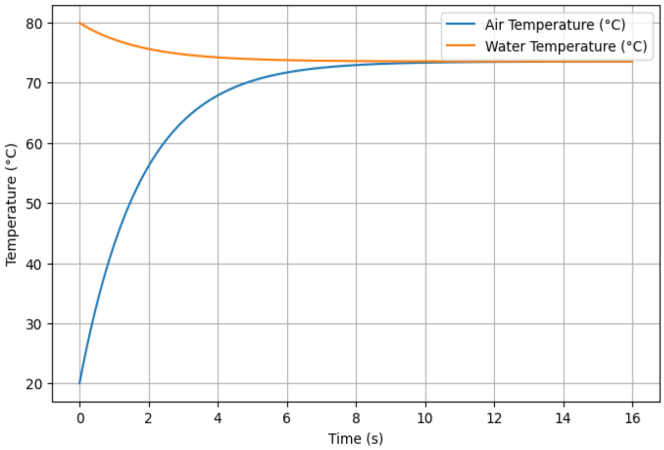

Figure 4-14 Optimal Control of Heat Exchanger (Pontryagin)

The optimal values are $v_{min} = 0.2m/s$ air velocity and using $v = k_n N$, with $k_n = 0.01$, the fan speed will be $N = 20\ RPS$. It in noted from Figure 4.14 that the optimal output temperature of hot drying air is 75.6^{0}C, achieved after 10 seconds of simulation. This is based on the condition that the input water temperature into the heat exchanger is maintained at 80^{0}C throughout the simulation process.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

In this chapter, a summary of the findings is presented, and recommendations, both for implementation and for further research are presented, in the following respective sections.

5.1 Conclusion

The use of solar energy is simulated in this research and found that with the Kenyan solar insolation of between $5.4KWhr/m^2$ and $20.50KWhr/m^2$, the use of solar collector with efficiency of $\eta_c = 80\%$ is able to collect heat of up to $1.367KW/m^2$ and heat water from 22^0C to 60^0C at a rate of $0.25l/s$. This is amazing energy that can be harvested and used for other purposes, including heating swimming pools, heating cooking water, heating water for domestic use, among others.

In this research, the same energy in the hot water was channeled to a heat exchanger, a set of radiators with a total length of 60m pipe, of radius $r = 0.02m$, connected to flowing hot water. If the heat transfer coefficient of the heat exchanger is $100W/m^2K$, it was found that the hot air blowing through the heat exchanger can pick heat from the radiator and dissipate between 90^0C and 230^0C depending on the velocity.

This heat is dried regulated and channeled to the food drying chamber, depending on the specification, time of residence, moisture content and volume of the food to be dried. The number of radiators working at once and the speed of the fan is varied to arrive at the desired temperature.

Alternative energy is used intermittently to supplement the solar insolation and the same results are achieved at a 67.86% reduction of cost. This makes the cost of drying ideal and affordable with the environmental conservation embraced by use of green energy.

5.2 Recommendations

In this research study, focus was on the dryer, parameter range and optimization of alternative source of energy. The following recommendations are made for implementation.

It is recommended that a prototype solar dryer is designed to allow fine tuning and additional adjustment for effective functioning of the dryer. In this study, food products drying rate and residence time was not simulated and further research can be done on the same. Also, in this research, it was assumed that water is used as the thermal liquid. Other fluids with higher specific heat capacities can be used in the model. It is also noted that humidifier specifications were not discussed and not simulated, but it is here assumed that a very efficient humidifier is connected to the dryer so that hot air into the drying chamber is always dry.

5.3 Recommendation for further research

In this research study, various aspects have been explored, including and more specifically on the solar collector, heat transfer along pipes, heat exchanger and hot air-drying chamber. These have been done with various assumptions and conditions which include constant water volume, constant irradiation, constant solar collector efficiency, absence of compression and expansion of thermal fluid, constant heat transfer conditions, absence of fouling among others.

These makes the order unrealistic and calls for the need to carry out further research in order to improve efficiency of the solar dryer. Some of the areas of research on solar dryers may include and not limited to:

Efficiency Improvement: Research aimed at enhancing the efficiency of solar dryers through design modifications, thermal storage integration, and optimization of heat transfer mechanisms. This is achieved by looking into the design of drying trays, air mass transfer, heat transfer in heat exchangers and the ambient conditions of the setup environment.

Material and Design Innovation: Exploring new materials and innovative design concepts for solar dryers to improve heat absorption, air circulation, and moisture removal. Considering the use of steel and optimal insulation as well as other material types yields a field of possible values that can be compared and analyzed for the best choice of materials to build the solar dryer.

Modeling and Simulation: Utilizing computational modeling and simulation techniques to analyze and optimize the performance of solar dryers under different operating conditions and environmental factors. The use of SIMULINK is limited to the choice of parameters in this research thesis, but additional parameters can be incorporated to yield a better approximation of the model.

Control and Automation: Researching control systems and automation technologies to enhance the operational control, monitoring, and performance optimization of solar dryers. It is noted here that a few measuring devices are placed on the dashboard which includes thermometer, number of radiators, and air mass flow rate. Other measurements like humidity, time, weight, moisture content among others is necessary for an ideal solar dryer.

Food Quality and Safety: Investigating the impact of solar drying on food quality, nutritional preservation, and food safety, as well as developing best practices for drying various food products. Laboratory tests on the quality of food and nutritive content need to be tested both before and after the drying process.

Integration with Other Technologies: Exploring the integration of solar drying with other renewable energy sources, energy storage technologies, or hybrid drying systems to improve overall performance and reliability. These include the use of electricity, fuel and cooking gas, and their comparison.

Socio-Economic Impact: Researching the socio-economic impact of solar drying technologies on local communities, including income generation, food security, and environmental sustainability. This aspect is very important for affordability and sustainability of the proposed prototype.

Scaling and Adoption: Studying strategies for scaling up the adoption of solar drying technologies, addressing barriers to implementation, and promoting knowledge transfer and capacity building in local communities. The use of National Cereals and Produce Board (NCPB), which is mandated to collect and store cereals from farmers and redistribute to millers in an attempt to control supply and demand forces in the marks.

Research in these areas can contribute to the development of more efficient, reliable, and sustainable solar drying technologies, with potential applications in agriculture, food processing, and resource-constrained regions. Despite the above recommendations, quality work has been done and contributions to new knowledge adequately done.

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APPENDICES

Appendix 1: Matlab Simulation Parameters

```
A_c = 12;

A_c1 = 12;

A_c2 = 12;

A_c3 = 12;

I_c = 5.5;

I_c1 = 5.5;

I_c2 = 5.5;

I_c3 = 5.5;

LRoof = 0.2;

LRoof1 = 0.2;

LWall = 0.2;

LWall1 = 0.2;

LWindow = 0.01;

LWindow1 = 0.01;

NG_density = 0.9;

S_radiator1 = 5;

S_radiator2 = 5;

S_radiator3 = 5;

S_radiator4 = 5;

S_radiator5 = 5;

S_radiator6 = 5;

S_radiator7 = 5;

S_radiator8 = 5;

S_radiator9 = 5;

T_ca = 27;

T_ca1 = 27;
```

```
T_ca2 = 27;

T_ca3 = 27;

T_ci = 22;

T_ci1 = 22;

T_ci2 = 22;

T_ci3 = 22;

T_co = 35;

T_co1 = 35;

T_co2 = 35;

T_co3 = 35;

U_l = 0.025;

U_l1 = 0.025;

U_l2 = 0.025;

U_l3 = 0.025;

Var = 0;

Vol_c = 500;

Vol_c1 = 500;

Vol_c2 = 500;

Vol_c3 = 500;

area_roof_room1 = 75.188023793574686;

area_roof_room2 = 75.188023793574686;

area_roof_room3 = 75.188023793574686;

area_roof_room4 = 75.188023793574686;

area_roof_room5 = 2.4;

area_wall_room1 = 95.666666666666671;

area_wall_room2 = 83.333333333333329;

area_wall_room3 = 72.666666666666671;
```

```
area_wall_room4 = 59.333333333333336;

area_wall_room5 = 11.52;

area_window_room1 = 3;

area_window_room2 = 2;

area_window_room3 = 2;

area_window_room4 = 2;

area_window_room5 = 0.25;

c_air = 1005.4;

c_air1 = 1005.4;

c_roof = 835;

c_roof1 = 835;

c_sp = 997;

c_sp1 = 997;

c_sp2 = 997;

c_sp3 = 997;

c_wall = 835;

c_wall1 = 835;

c_window = 840;

c_window1 = 840;

cost = 0.30024726245143063;

eta_0 = 0.8;

eta_1 = 0.8;

eta_2 = 0.8;

eta_3 = 0.8;

fuel_cost = saveVarsMat.fuel_cost; % <12406x1 double> too many
elements

h_air_roof = 12;

h_air_roof1 = 12;

h_air_wall = 24;
```

```
h_air_wall1 = 24;

h_air_window = 25;

h_air_window1 = 25;

h_radiator1 = 100;

h_radiator2 = 100;

h_radiator3 = 100;

h_radiator4 = 100;

h_radiator5 = 100;

h_radiator6 = 100;

h_radiator7 = 100;

h_radiator8 = 100;

h_radiator9 = 100;

h_roof_atm = 38;

h_roof_atm1 = 38;

h_wall_atm = 34;

h_wall_atm1 = 34;

h_window_atm = 32;

h_window_atm1 = 32;

htHouse = 2.4;

htHouse1 = 4;

htWindows = 0.5;

htWindows1 = 1;

kRoof = 0.038;

kRoof1 = 0.038;

kWall = 0.038;

kWall1 = 0.038;

kWindow = 0.78;
```

```
kWindow1 = 0.78;

leak_roof_percent = 0.1;

leak_roof_percent1 = 0.1;

leak_wall_percent = 0.15;

leak_wall_percent1 = 0.15;

leak_win_percent = 0.2;

leak_win_percent1 = 0.2;

lenHouse = 6;

lenHouse1 = 30;

n1_window = 1;

n1_window1 = 3;

n2_window = 1;

n2_window1 = 2;

n3_window = 1;

n3_window1 = 2;

n4_window = 1;

n4_window1 = 2;

n5_window = 1;

pitRoof = 0.070735530263064589;

pitRoof1 = 0.070735530263064589;

rho_w = 1000;

rho_w1 = 1000;

rho_w2 = 1000;

rho_w3 = 1000;

roofArea = 300.75209517429874;

roofDensity = 32;

roofDensity1 = 32;
```

```
simlog_sscfluids_house_heating_system =
saveVarsMat.simlog_sscfluids_house_heating_system; % <1x1
simscape.logging.Node> unsupported class

tout = [0; 8.96; 17.92; 26.880000000000003; 35.84;
44.800000000000004; ...
        53.760000000000005; 62.720000000000006; 71.68;
80.640000000000015; ...
        89.600000000000023; 98.560000000000031; 107.52000000000004;
116.48000000000005; ...
        125.44000000000005; 134.40000000000006; 143.36000000000007;
152.32000000000008; ...
        161.28000000000009; 170.24000000000009; 179.2000000000001;
188.16000000000011; ...
        197.12000000000012; 206.08000000000013; 215.04000000000013;
224.00000000000014; ...
        232.96000000000015; 241.92000000000016; 250.88000000000017;
259.84000000000015; ...
        268.80000000000013; 277.7600000000001; 286.72000000000008;
295.68000000000006; ...
        304.64000000000004; 313.6; 322.56; 331.52;
340.47999999999996; ...
        349.43999999999994; 358.39999999999992; 367.3599999999999;
376.31999999999988; ...
        385.27999999999986; 394.23999999999984; 403.19999999999982;
412.1599999999998; ...
        421.11999999999978; 430.07999999999976; 439.03999999999974;
448; ...
        ];

tout1 = saveVarsMat.tout1; % <12406x1 double> too many elements

vel_c = 2;

vel_c1 = 2;

vel_c2 = 2;

vel_c3 = 2;

wallDensity = 1920;

wallDensity1 = 1920;

widHouse = 2.4;

widHouse1 = 10;

widWindows = 0.5;

widWindows1 = 1;

windowDensity = 2700;

windowDensity1 = 2700;
```

Appendix II: Plagiarism Awareness Certificate

SR576

ISO 9001:2019 Certified Institution

THESIS WRITING COURSE

PLAGIARISM AWARENESS CERTIFICATE

This certificate is awarded to

Kenneth Korkoren

PHD/AM/02/15

In recognition for passing the University's plagiarism

Awareness test for Thesis **entitled: MATHEMATICAL MODELING AND PARAMETER ESTIMATION OF AN OPTIMAL SOLAR FOOD DRYER with** similarity index of 6% and striving to maintain academic integrity.

Word count:50509

Awarded by

Prof. Anne Syomwene Kisilu
CERM-ESA Project Leader Date: 04/07/2024