NUTRITIVE AND PHYSICAL QUALITY ANALYSIS OF BLACK PEPPER DRIED WITH OPTIMIZED-HYBRID SOLAR DRYING SYSTEMS

GAN ZHI YING

SCHOOL OF HEALTH SCIENCES

UNIVERSITI SAINS MALAYSIA

January 2025

NUTRITIVE AND PHYSICAL QUALITY ANALYSIS OF BLACK PEPPER DRIED WITH OPTIMIZED-HYBRID SOLAR DRYING SYSTEMS

by

GAN ZHI YING

Dissertation submitted in partial fulfilment of the requirements for the degree on Bachelor in Nutrition with Honours

January 2025

CERTIFICATE

This is to certify that the dissertation entitled “NUTRITIVE AND PHYSICAL QUALITY ANALYSIS OF BLACK PEPPER DRIED WITH OPTIMIZED-HYBRID SOLAR DRYING SYSTEMS” is the bona fide record of research work done by GAN ZHI YING, MATRIC NUMBER 159918 during period record of August 2024 until January 2025 under my supervision. I have read this dissertation and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation to be submitted in partial fulfilment for the degree of Bachelor of Health Science (Honours) (Nutrition).

Main supervisor,

…………………………………

Prof. Dr. Wan Rosli Binti Wan Ishak
Dean
School of Health Sciences
Universiti Sains Malaysia
Health campus
16150 Kubang Kerian
Kelantan, Malaysia

Date: Jan 12, 2025

DECLARATION

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated and duly acknowledged. I also declare that it has been previously or concurrently submitted as a whole for any other degrees at Universiti Sains Malaysia or other institutions. I grant Universiti Sains Malaysia the right to use the dissertation for teaching, research and promotional purposes.

……………………………….

GAN ZHI YING

Date: 12 January 2025

ACKNOWLEDGEMENT

First and foremost, I would like to express my deepest gratitude to my dedicated supervisor, Prof Dr. Wan Rosli Bin Wan Ishak and my co-supervisor Dr Majid, in recognition of their patience, willingness to sacrifice their precious time for supervision, idea contribution, insightful guidance, and invaluable advice throughout the research project. In addition, I would like to extend my heartfelt appreciation to all lab assistants of the Analytical Laboratory in School of Health Sciences, USM for the invaluable cooperation and support. Their assistance included providing all the necessary apparatus and chemicals, offering briefings on imperative laboratory protocols as well as generously sharing their expertise on operating sophisticated instrument and providing help when challenges arose.

Moreover, I am deeply grateful to all my colleagues and senior sisters, especially Fatihah, Asma, Kak Lina and Kak Jessy for their contribution of time, as well as their invaluable assistance, advice and support throughout the research project. Special thanks to all my friends and lab mate who provide assistance and encouragement throughout the research project. Furthermore, I would also like to express my sincere gratitude to all of my lecturers who have taught us over the past four years, equipping me with the knowledge and skills necessary to complete this research project successfully.

Last but not least, I would like to acknowledge my beloved family members and friends for their endless support and encouragement throughout my study. In conclusion, I greatly appreciate the goodwill and support extended by all parties involved.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

a or L	Major axis
a*	Redness coordinate to greenness coordinate
b or T	Medium axis
b*	Yellowness coordinate to blueness coordinate
c or W	Minor axis
dE*ab	Total colour differences
dL	L* difference
D_g	Geometric mean diameter
g	Gram
g/g	Grams per gram
L*	Brightness coordinate
ml	Milliliter
mm	Millimeter
nm	Nanometer
m/m	Mass per mass
N	Normality
w/v	Weight per volume
°	Degree
℃	Degree Celcius
%	Percentage
Φ	Sphericity

LIST OF ABBREVIATIONS

AOAC	Association of Official Agricultural Chemists
CAGR	Compound Annual Growth Rate
CHO	Carbohydrate
DOSM	Department of Statistics Malaysia
EMC	Equilibrium Moisture Content
HCl	Hydrochloric Acid
HSD	Hybrid Solar Dryer
HSDS	Hybrid Solar Drying System
MPB	Malaysia Pepper Board
NaOH	Sodium Hydroxide
OSD	Open Air Sun Drying
P	Vapor Pressure
POD	Peroxidase
PPO	Polyphenol Oxidase
RH	Relative Humidity
UV	Ultraviolet
v-GHSD	v-Groove Hybrid Solar Drier
w/b	Wet basis

ABSTRAK

Lada hitam mempunyai kepentingan komersial yang penting di Malaysia. Keutamaan pengguna didorong oleh sifat pemakanan dan fizikalnya. Walaupun pengeringan di bawah matahari terbuka (OSD) digunakan secara meluas di negara tropika berdasarkan keberkesanan kosnya, ia mempunyai beberapa kelemahan, termasuk intensif buruh, memakan masa pengeringan, kebergantungan cuaca, dan risiko pencemaran. Sistem pengeringan solar hibrid (HSDS) telah muncul sebagai alternatif untuk menangani masalah ini. Oleh itu, kajian ini bertujuan untuk menilai kecekapan HSDS berbanding OSD dan menilai komposisi nutrisi serta kualiti fizikal lada hitam yang dikeringkan menggunakan HSDS berbanding lada hitam komersial. Kecekapan HSDS mengeringkan lada hitam dinilai dengan memplotkan graf penyingkiran kelembapan dan menganalisis kandungan kelembapan keseimbangan (EMC) pada lengkung tersebut. Komposisi nutrisi (kelembapan, abu, protein, minyak, gentian kasar, dan karbohidrat) bagi sampel yang dikeringkan menggunakan HSDS dan sampel komersial ditentukan menggunakan kaedah standard. Sifat fizikal termasuk warna, ketumpatan, diameter purata geometri, dan sferisiti juga dianalisis. Kinetik pengeringan menunjukkan bahawa HSDS lebih cekap daripada OSD dalam menyingkirkan kelembapan daripada lada hitam. Analisis proksimat menunjukkan kandungan minyak yang jauh lebih tinggi (6.23%) dan kandungan abu yang lebih rendah (3.08%) dalam lada yang dikeringkan menggunakan HSDS berbanding lada komersial (masing-masing 4.71% dan 3.70%, $p < 0.05$). Tiada perbezaan signifikan diperhatikan dalam kandungan kelembapan, protein, gentian kasar, karbohidrat, ketumpatan, diameter purata geometri, sferisiti, dan nilai a* antara lada hitam yang dikeringkan menggunakan HSDS dan lada hitam komersial. Perbezaan signifikan diperhatikan dalam nilai L* dan b*, menunjukkan lada hitam yang dikeringkan menggunakan HSDS mempunyai warna yang lebih gelap dan rona kebiruan berbanding

lada hitam komersial, yang meningkatkan nilai pasaran. Nilai dE*ab sebanyak 4.50 menunjukkan perbezaan warna yang ketara antara lada hitam yang dikeringkan menggunakan HSDS dan lada hitam komersial. Sebagai kesimpulan, hasil ini menekankan keberkesanan HSDS dalam mengekalkan kualiti melalui keadaan pengeringan terkawal, meminimumkan kemerosotan warna, dan memastikan pemeliharaan ciri-ciri utama dengan lebih baik.

ABSTRACT

Black pepper holds significant commercial importance in Malaysia. Consumer preference is driven by its nutritional and physical properties. While open sun drying (OSD) is widely used in tropical countries by virtue of its cost effectiveness, it presents several limitations, including labour intensive, time consuming, weather dependency and contamination risks. Hybrid Solar Drying System (HSDS) have emerged as an alternative to address these limitations. Hence, this study aims to evaluate the efficiency of HSDS compared to OSD and assess the nutritional composition and physical quality of HSDS-dried black pepper relative to commercial black pepper. The efficiency of HSDS drying the black pepper was evaluated by plotting a moisture removal graph to analyse the equilibrium moisture content (EMC) in the curve. Nutritional composition (moisture, ash, protein, oil, crude fiber and carbohydrate (CHO)) of HSDS-dried and commercial samples were determined using standard methods. Physical properties including colour, density, geometric mean diameter, and sphericity, were also analyzed. Drying kinetics demonstrated that HSDS was more efficient than OSD in removing moisture from black pepper. Proximate analysis revealed significantly higher oil content (6.23%) and lower ash content (3.08%) in HSDS-dried pepper compared to commercial pepper (4.71% and 3.70% respectively, $p < 0.05$). No significant differences were observed in moisture, protein, crude fiber, carbohydrate, density, geometric mean diameter, sphericity and a* value between HSDS-dried and commercial black pepper. Significant differences were observed in L* and b* values, indicating that HSDS-dried pepper exhibited a darker colour and a bluish hue compared to commercial black pepper which increase the market value. dE*ab value of 4.50 represented significant colour difference between HSDS-dried black pepper and commercial black pepper. In conclusion, these outcomes highlight the effectiveness of

HSDS in maintaining quality through controlled drying conditions, minimizing colour degradation and ensuring better preservation of key characteristics.

CHAPTER 1

INTRODUCTION

1.1 Background of Research Study

Black pepper, with the scientific name *Piper nigrum* L. is an annual vine that belongs to the family Piperaceae and is cultivated for its peppercorns. Its dried fruits, known as "King" of spices are widely used globally as a well-known spice with a long history due to their pungent aroma, serving as a natural food enhancer to elevate the flavour of dishes. Other than that, *Piper nigrum* are also widely researched for its pharmacological activities, such as radical scavenging, antioxidant, anti-insecticidal, anti-inflammatory, anticonvulsant, allelopathy as well as anti-microbial effect. Researchers found that the genus Piper has a rich phytochemistry and they showed that the terpenoids, amides, and alkaloids such as piperine are abundantly present (Hammouti *et al*., 2019). Due to its significant commercial, medicinal and economic value, Piper nigrum stands as the most prominent species within the Piper genus. The specific cultivation requirements of black pepper have led tropical countries that meet these conditions to become the world's leading exporters of peppercorns (Sen and Rengaian, 2021).

The black pepper is the most important and most widely used spice in the world, accounting 34% of the total market (Mayr *et al*., 2021 as cited in Nunes Pinto Paracampo *et al*., 2022). The global black pepper market is poised for significant growth, with a projected CAGR of 5.37% from 2022 to 2027, driven by its culinary applications and recognized pharmacological benefits (Nunes Pinto Paracampo *et al*., 2022). Malaysia, endowed with a tropical and humid climate, possesses the potential to generate substantial national income from black pepper cultivation. In 2020, Malaysia ranked among the top five black pepper producers globally, following Vietnam, Brazil, Indonesia, and India (International Pepper Community, 2020, as cited in Khew *et al*., 2022). In 2017, Malaysia produced 23,500 metric tons of black pepper (Malaysian Pepper Board, 2018). Sarawak emerged as the leading producer within Malaysia, contributing approximately 23,780 tonnes in 2018 (Izzah & Asrina, 2019). According to Department of Statistics Malaysia (DOSM) and Malaysia Pepper Board (MPB), Malaysia exported a total of 5,530,000 tonnes of black pepper, generating a value of RM138.29 million in 2022 (Ministry of Plantation and Commodities, 2022), creating significant economic opportunities and employment prospects within the country.

However, the commercialization of black peppers is generally regulated by its quality which involving the pungency, colour, fresh aroma and the nutritive values. One of the most imperative factors that can affect the quality of black pepper is the processing of black pepper such as drying. According to Shango (2021), starch content in black pepper may subject to mould attack and insect infestation due to its hygroscopic nature. Hence, drying is critical stage to decide pepper quality as it determines the storage water content to inhibit the mould growth and prolong their storability (Shango, 2021a & Paul *et al*., 2021b). Hence, it is imperative to determine EMC of the black pepper. The EMC is reached when the amount of water molecules on the surface is equal to amount of water molecules leaving the surface, so the material will not gain or lose water vapor (Sweygers *et al*., 2022). According to Kusuma *et al*., (2023), the higher and faster the EMC value is achieved, the quicker the material reaches its equilibrium point, indicating ease of evaporation. The drying rate decrease as drying time increases or moisture content decreases. Initially, water evaporates rapidly, but as the process progresses, the remaining water molecules, bound to the material's structure, become increasingly resistant to evaporation. The drying rate provides insights into the drying behavior and helps assess the quality of the final product. A very rapid drying rate can potentially damage the product's tissue, resulting in undesirable colour changes. Drying typically occurs in two stages: an initial rapid drying phase where water evaporates quickly, followed by a slower drying phase as the moisture content approaches the EMC. During the final equilibrium phase, the moisture ratio and drying rate gradually declined until they stabilizing with minimal changes (Kusuma *et al*., 2023). To ensure quality preservation and suitability for commercialization, the final moisture content of black pepper should be reduced to 12% (w/b) from an initial moisture content of approximately 65% (w/b) (Sousa *et al.*, 2023).

Solar energy is a permanent, renewable and eco-friendly energy source. To preserve the quality of the final products, most agriculture products for storage must first be dried. The matured green berries are typically sundried after harvested to produce black pepper. In black pepper cultivation, most tropical countries commonly employ open-sun drying methods (Fudholi *et al*., 2015). This approach is favoured by virtue of the intense sunlight available in these regions, its cost-effectiveness as well as the lower dry recovery observed in the samples (Hirko *et al*., 2022). Both of the studies show that this open-sun drying method required about 6 to 7 days to preserve the desired quality of black pepper. However, the main drawback for this open-sun drying method is that highly depend on the available of sunlight and is unable to proceed after sunset and during cloudy weather (Lakshmi *et al*., 2020). Additionally, rainy days pose challenges for producers, as they are unable to carry out drying processes under such conditions. The difficulty in controlling drying paramaters adversely affects the organoleptic properties of the grains and compromises the final product quality due to uneven grain moisture levels (Sousa *et al*., 2023). Besides, this prolong drying process in direct sunlight may also increase the susceptibility to contamination of the black pepper by soil, insects and microbes which may produce unattractive grayish products (Paul *et al*. 2021 & Sousa *et al*., 2023), lead to loss of flavour components (Shango, 2021) as well as may lead to degradation of quality due to the heat and moisture sensitivity of spices, with prolonged exposure to high temperatures and humid conditions during drying being the primary contributing factors (Majumder *et al*., 2021).

Since OSD is a climate-dependent traditional method that is uncontrolled, labour intensive, time consuming and unhygienic (Paul *et al*., 2021), need a large open space as well as susceptible to contamination, to address these limitations, hybrid solar drying system (HSDS) is developed as an alternative. Based on Tiwari (2016), hybrid solar dryer supply ample amount of heat, exceeding the ambient temperature under given humidity condition. It raises the vapour pressure of the moisture within the product and lowers the relative humidity of the drying air, enhancing the air's capacity to carry moisture.

Consumer preferences for black pepper are heavily influenced by its visible physical qualities, such as colour, and its nutritional value. However, research on the nutritional composition of black pepper dried using optimized hybrid solar drying systems is currently lacking. Hence, this study aims to investigate the efficiency of HSDS compared to OSD and whether the nutritional and physical qualities of black pepper dried by HSDS meet the standards of commercially available black pepper. To achieve this, the study will evaluate key parameters, including carbohydrates (CHO), protein, oil content, moisture content, total ash, crude fiber, as well as colour, diameter, and density.

1.2 Research Problem

One of the most imperative factors that can affect the quality of black pepper is the processing of black pepper such as drying. Black pepper, the world's most significant and widely used spice, comprising 34% of the global spice market (Mayr *et al*., 2021, as cited in Nunes Pinto Paracampo *et al*., 2022), is crucial for the global economy. According to Khew *et al.* (2022), Malaysia ranks among the top five black pepper producers globally, following Vietnam, Brazil, Indonesia, and India in black pepper production (International Pepper Community, 2020, as cited in Khew *et al*., 2022). The global black pepper market, valued at 4.1 billion US dollars in 2018, is projected to experience continued growth driven by increasing global consumption and demand. In Malaysia, black pepper is a significant cash crop and a major foreign exchange earner, primarily cultivated in regions like Kuching, Sarikei, Serian, and Bentong. Smallholder farmers dominate the sector, cultivating an estimated 7,414 hectares in 2021 (Malaysian Pepper Board Statistics, as cited in Khew *et al*., 2022).

According to DOSM and MPB, in 2022, Malaysia exported 5,530,000 tonnes of black pepper, generating RM138.29 million in revenue (Ministry of Plantation and Commodities, 2022), supporting the livelihoods of approximately 35,000 farmers in Sarawak. For drying of black pepper, traditional drying methods, such as open-sun drying (OSD), are commonly employed due to their low cost and the samples have lower dry recovery. However, there is several limitations. For examples, OSD is highly dependent on weather conditions, requiring several days (6-7) for adequate drying (Fudholi *et al*., 2015; Hirko *et al*., 2022). This prolonged exposure to sunlight can lead to contamination from soil, insects, and microbes, resulting in unattractive grayish discoloration and potential quality degradation due to short UV radiation (Paul *et al*., 2021). Moreover, OSD is labor-intensive and susceptible to weather interruptions, hindering the drying process during cloudy or rainy periods (Lakshmi *et al.*, 2020). Besides, Consumer preferences for black pepper are heavily influenced by its visible physical qualities, such as color, and its nutritional value. Research on the nutritional composition of black pepper dried using optimized hybrid solar drying systems (HSDS) is limited. Therefore, this study aims to evaluate the efficiency of HSDS compared to OSD, and investigate whether the nutritional and physical qualities of black pepper dried by HSDS meet the quality standards of commercially available black pepper. This will be achieved by assessing key parameters such as CHO, protein, oil content, moisture content, total ash, crude fiber, colour, diameter, and density.

1.3 Research Objectives

General Objective

To investigate the nutritive value and physical quality of black pepper dried using optimized hybrid solar drying system.

Specific Objectives

1. To determine the efficiency of optimized hybrid solar drying system in drying of black pepper while preserving the nutrients.
2. To assess the nutritional value of black pepper dried using optimized hybrid solar drying system.
3. To evaluate the physical quality of black pepper dried using optimized hybrid solar drying system.

1.4 Research Questions

1. How was the effectiveness of optimized hybrid solar drying system in drying of black pepper while preserving the nutrients?
2. What are the nutritional values of black pepper dried using optimized hybrid solar drying system?
3. What are the physical properties of black pepper dried using optimized hybrid solar drying system?

1.5 Research Hypothesis

Null Hypothesis, Ho

There is no significant difference in the nutritive and physical quality of black pepper dried using optimized hybrid solar drying system with commercial black pepper.

Alternative Hypothesis, Ha

There is significant difference in the nutritive and physical quality of black pepper dried using optimized hybrid solar drying system with commercial black pepper.

1.6 Significance of research

The findings of this study will contribute greatly to the country as the optimization of sustainable and consistent food preservation technique is critical in enhancing the spices quality and hence increase the export income. As black pepper is a valuable commodity, the greater demand for high quality spices justifies the need of more effective drying approaches to preserve the quality. By implementing of the optimized solar hybrid drying system recommended by this study will enable the producers to preserve the physical and nutritive quality of black pepper more effectively compare to prolong traditional open sun drying as the short UV will reduce the quality of spices. Next, the industry practitioners can use this study results as a guide to find out the best practices to dry the spices meanwhile preserve the quality. Besides, for researchers, this study can be a foundation for other critical food and spices preservative areas that have yet to be explored.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview of black pepper (*Piper Nigrum*)

Black pepper (*Piper nigrum* L.) is a tropical plant widely recognized for its fruit, which is commonly used as a spice across the globe. Black pepper is known as the 'king of spices' by virtue of its massive trade share in the global market. The term "pepper" is derived from the Sanskrit word *pippali*, meaning berry (Takooree *et al*., 2019). Black pepper belongs to the Piperaceae family, an ancient group of pantropical flowering plants that is notable for its extensive variety of spices, encompassing approximately 2000 species classified into fourteen genera. Among these, the genera *Piper* and *Peperomia* represent 90% of all species.

Piper nigrum is an aromatic, perennial woody climber that can reach a height of 50-60cm. According to Shango (2021), pepper reaches fully maturity about 180 to 230 days (6 – 8 months) after flowering, depending on the variety planted and the environmental circumstances at that time. Black pepper requires high rainfall, humidity and consistent temperature to thrive successfully. These conditions are typically found at altitudes of up to 1500 meters above sea level. Black pepper thrives best at temperature between 23 and 32 °C and relative humidity ranging from 75% to 80%. It requires well-distributed high rainfall of 1000 to 3000mm per year. Black pepper is a day-neutral plant, indicating it does not have specific photoperiod requirements for flowering. It flourishes under partial shade, ideally around 50%, as it is unable to endure prolonged periods of excessive heat and dryness. Black pepper plants are adaptable to various soil types, from heavy clays to light sandy clays, as long as they have a pH ranging from 5.5 and 6.5, are well-drained and high in humus. Black pepper plants typically have a productive lifespan of 12 to 15 years, with the first harvest typically occurring in the third year after planting (Shango *et al*., 2020).

Since the black pepper plants unable to tolerate frost, require high temperatures, heavy and frequent rainfall, as well as well-draining soil to thrive best, they are predominantly cultivated in tropical areas. Approximately twenty-six tropical countries are involved in the cultivation of black pepper, with Vietnam, India and Indonesia being the main producers (Wilde *et al*., 2019). For example, the Central Highlands of Vietnam, Kalimantan in Indonesia and Kerala in India are some of the key areas where black pepper is cultivated. Since the conditions are met in these regions, these countries are largest commercial exporters of peppercorns. Black pepper is native to India, but the leading producer is Vietnam. According to the World's Top Black Pepper Producing Countries by Benjamin Elisha Sawe, published on June 7, 2019, in Economics, Vietnam is the largest producer of black pepper spices, which producing 163,000 tonnes, accounts for 34% of the world-wide production of 470,000 metric tonnes. Indonesia is the second-largest producer with 89,000 tonnes, India is third with 53,000 tonnes, followed by Brazil with 42,000 tonnes and China with 31,000 tonnes (Hammouti *et al*., 2019). In 2020, Malaysia ranked among top five after Vietnam, Brazil, Indonesia, and India in black pepper production (International Pepper Community, 2020, as cited in Khew *et al*., 2022).

According to Takooree *et al*., (2019) and Spence (2024), black pepper is primarily used as a culinary ingredient in a wide variety of dishes, particularly in Western cuisine, as a seasoning to enhance food flavour with its gustatory pungency by virtue of alkaloid piperine, as well as in food preservation. As a flavour enhancer, black pepper is free from the negative health effects or public concerns associated with additives like monosodium glutamate or kokumi. Its versatility positions it as an ideal healthy flavour enhancer, enabling consumers to personalize their culinary experiences. This is a quality that is highly valued by chefs and food enthusiasts worldwide (Spence, 2024).

Other than the culinary uses, black pepper can also be used in medicinal purposes. Historically, black pepper has been widely used for medicinal purposes, such as relieving digestive issues and treating the common cold. Piperine, a compound found in black pepper, has been shown to exhibit blood pressure-lowering and vasomodulatory effect. There are a wide range of contemporary research supports that black pepper have remarkable anti-microbial, anti-oxidant, anti-inflammatory, anti-carcinogenic properties and other health-related properties (Takooree *et al*., 2019).

2.2 Formation of Black Pepper

Depending of the processing methods, the fruits of black pepper can yield different products, including white, black, red and green pepper. Mature green pepper berries derived from the pepper plant, scientifically known as *Piper nigrum*, are processed to produce the famous spice known as black pepper (Paul *et al*., 2021). Black pepper is produced by drying unripe fruit until it becomes wrinkled, retaining the pulp (Takooree *et al*., 2019). The black colour of black pepper is due to the enzymatic browning of green colour of pepper berries by fermentation and oxidization of phenolic compounds (Hirko *et al*., 2022 & Paul *et al*., 2021). The primary enzymes responsible for the browning reaction and the blackening of black pepper are polyphenol oxidase (PPO) and peroxidase

(POD) (Variyar *et al*., 1988 and Weil *et al*., 2017 as cited in Hirko *et al*., 2022). Paul *et al*. (2021) and Hirko *et al*. (2022) stated that the quality of black pepper, including its pungency, colour and fresh aroma, highly depends on the drying methods used.

2.3 Drying of black pepper

According to Aduewa *et al*. (2022), drying is an energy-based method that is universally used to prolong the shelf-life of numerous agricultural products in tropical countries due to its cost-effectiveness and efficiency. The minimum temperature required for the effective drying of spices is recommended at 40°C (Majumder *et al*., 2021). Drying minimizes the amount of moisture present in agricultural products. The removal of moisture content is imperative to hinder microbial growth and contamination, thereby preventing the deterioration of products resulted by whether enzymatic or non-enzymatic browning reactions, as well as the oxidation of lipids and pigments (Aduewa *et al*., 2022).

Peppercorns are hygroscopic, meaning they readily absorb moisture from the environment during storage (Shango, 2021). Maintaining an appropriate moisture level is crucial to prevent mold growth, minimize microbial attacks, and inhibit chemical deterioration in black pepper (Sousa *et al*., 2023). According to Jayatunga & Amarasinghe (2019), maintaining a moisture content between 12% and 14% (dry basis) in stored black pepper effectively inhibits mold development. According to previous studies, black pepper contains 8.7 to 14.0% moisture (Milenković & Stanojević, 2021). Hence, to ensure quality preservation and suitability for commercialization, the final moisture content of black pepper should be reduced to 12% (w/b) from an initial moisture content of approximately 65% (w/b) (Sousa *et al.*, 2023).

For the preservation of pepper quality, the commonly used drying system is sun-drying, which relies solely on open sunlight as an energy source due to its low cost and the availability of natural resources. For black pepper, the drying process typically takes about 6 to 7 days to complete (Fudholi *et al*., 2015 & Hirko *et al*., 2022). However. the characteristic shiny black colour of black pepper deteriorates with prolonged direct exposure to sunlight (Akshitha *et al*., 2023). Depending on the drying technique used, the colour of black pepper samples may change from greenish berries to brown-black, dark brown or black after drying (Hirko *et al*., 2022). The main drawback of the OSD method is its heavy reliance on the availability of sunlight, making it impossible to proceed after sunset or during cloudy and rainy weather (Lakshmi *et al*., 2020). Additionally, this prolonged drying process in direct sunlight increases the susceptibility to contamination of black pepper by soil, insects and microbes, which may result in unattractive grayish products (Paul *et al*., 2021). This method may also lead to degradation of quality due to short-wave UV radiation. Natural light promotes colour degradation or fading through oxidation reactions (Hirko *et al*., 2022).

According to Tang *et al*. (2024), the wavelength of UV radiation ranges from 100 to 400nm and can be further subdivided into three types: UVA (320 – 400nm), UVB (280-320nm), and UVC (100-280nm). UVA rays have the longest wavelengths, followed by UVB and UVC. UVC rays possess the shortest wavelengths, but they are entirely absorbed by atmosphere and do not reach the Earth’s surface. In contrast, the Earth’s atmosphere provides only limited shielding against UVB rays. An experiment conducted by Hinds *et al*. (2021), showed that the total phenolic content of black peppercorns increased after 10 minutes of exposure to 300nm UV light but began to decrease after 20 minutes of exposure. Interestingly, phenolic content exhibited in a time-dependent response to 365nm of UV radiation. The phenolic content decreased after 10 minutes of exposure. However, in contrast to the 10 minutes group, extending the UV light treatment duration to 20 minutes not only reversed this decline but also resulted in an increase in phenolic content (Hinds *et al*., 2021).

2.4 Nutritive value of black pepper dried

According to the 2017 Codex Alimentarius (amended in 2022), black pepper is graded into three categories. Grade I and II are defined by a maximum moisture content of 12.0% (m/m), while Grade III allows a slightly higher moisture content of 13.0% (m/m). Total ash content is limited to 6.0% (m/m) for Grade I and 7.0% (m/m) for Grade II and III. Furthermore, the minimum volatile oil content is established as 2.0% for Grade I, 1.5% for Grade II, and 1.0% for Grade III.

Table 2.1 shows the comparative proximate composition of black pepper dried from different studies. According to Milenković & Stanojević (2021), previous studies indicate that black pepper contains 8.7 to 14.0% of moisture, 1.5% to 2.6% of total nitrogen, 8.7% to 18.0% of crude fiber, and 3.6% to 5.7% of total ash. Ashokkumar *et al*. (2021) reported total ash content ranging from 3.43% to 5.09% and crude fiber content between 10.79% and 18.60%. Besides, starch is the main component of black pepper fruit, accounting for 50% of its dry weight. Studies have shown that the starch content typically ranges between 28% and 49%, with one report documenting it at 30.4%. Pepper protein has not been tested in detail in this study as pepper protein is mainly used as a spice to improve the food aroma while based on Nunes Pinto Paracampo *et al*. (2022), the percentage of protein in black pepper is about 8.63% to 13.09%, and can be within the range of 3.27% to 16.86% based on another study. Black pepper contains fats ranging from 1.9% to 9.0%, occasionally reaching up to 15%. The predominantly fatty acids include palmitic acid (16-30%), oleic acid (18-29%), linoleic acid (25-35%), and linolenic acid (8-19%). Black pepper fruit contains 2-9% piperine content and 2.33-12% oleoresin content (Milenković & Stanojević, 2021). Ahmad *et al*. (2024) determined the proximate analysis of black pepper seeds was found as moisture content 11.1%, ash content 2.5%, protein content 13.13%, fat content 6% and crude fiber content 8.5%.

Table 2.1 Comparative proximate composition of black pepper dried from different studies

Proximate Analysis	**Milenković & Stanojević (2021)**	**Ashokkumar *et al.* (2021)**	**Nunes Pinto Paracampo *et al.* (2022)**	**Ahmad *et al.* (2024)**
Moisture content (%)	8.7 - 14.0	-	-	11.1
Total Ash (%)	3.6 - 5.7	3.43 - 5.09	-	2.5
Protein content (%)	1.5 - 2.6 (in total nitrogen)	Not tested in detail	8.63 -13.09 (3.27 – 16.86 on another study in the literature review of this study)	13.13
Oil Content (%)	-	-	1.9 - 9.0 (Occasionally reaching up to 15.0)	6
Crude Fiber Content (%)	8.7 - 18.0	10.79 - 18.60	-	8.5

Based on another study is about the chemical composition of 100 grams of black pepper seeds. 100 g of black pepper seeds includes 66.5 grams of carbohydrates, 10 gram of protein, and 10.2 grams of fat (Ashokkumar *et al*., 2021).

2.5 Physical quality of black pepper dried

The quality of black pepper is assessed based on its physical and chemical characteristics. According to the Codex Alimentarius (2017, amended in 2022), black pepper should exhibit a brownish to dark brownish or blackish hue and must be free from any added colouring. In terms of shape, black pepper should be whole, globular, and possess a wrinkled pericarp. The diameter of the black pepper typically ranges from 2.5 to 7.0mm. Moussa Coulibaly *et al*. (2023) reported that the diameter of the dried peppercorns varied across different locations, ranging from 4.2mm to 5.1mm. Most dried peppercorns displayed a well-rounded or oval shape with a crumpled pericarp.

Based on the findings of Shreelavaniya & Kamaraj (2017), the true density of black pepper increased linearly from 985.1 to 1010.2 kg/m^3 as moisture content rises. This increase in density can be attributed to the absorption of moisture, which leads to an increase in the volume of the peppercorns. Moreover, Moussa Coulibaly *et al*. (2023) observed that the densities of the dried black pepper varied across different locations, ranging from 1002.4 to 1006.4 kg/m^3.

Shreelavaniya and Kamaraj (2017) further reported that black peppercorns swell upon exposure to moisture due to the absorption of water into their internal capillaries, leading to an expansion in size along their major (L), medium (T), and minor axes (W), as well as increase in their geometric mean diameter. With moisture content rising from 3.3% to 18.1%, L increased from 4.92mm to 5.37mm, T from 4.59mm to 5.08mm, and W from 4.42mm to 4.89mm. In a related study, Lakshmi *et al*. (2020) found that the dimensions of black peppercorns, including the major axis (L), medium axis (T), minor axis (W), and geometrical mean diameter, decreased from 33.65mm to 4.62mm, 34.41mm to 4.72mm, 37.00mm to 4.32mm, and 34.97mm to 4.72mm respectively along with the decreasing of moisture content from fresh samples by 59 hours OSD. Additionally, Zeyb Sayyadan & Moniri (2019) reported that the geometric mean diameter, sphericity and porosity of black pepper grains ranged from 4.37mm to 5.26mm, 96.30% to 98% and 57.5% to 60.4% respectively.

Pulses, which share hygroscopic properties with black pepper, exhibit a linear increase in sphericity with rising moisture content (Gupta *et al*., 2023). It is plausible that a similar trend occurs in black pepper, as aligned with the findings of Shreelavaniya and Kamaraj (2017), who reported that the sphericity of black peppercorns increased linearly from 0.938 to 0.949 as the moisture content increased from 8.65 to 81.3% (w.b.).

Hirko *et al*. (2022) observed that drying methods significantly influence the colour of black pepper, with different drying techniques resulting in varying degrees of darkening. Based on Moussa Coulibaly *et al*. (2023), statistical data for the L*, a* and b* colour parameters were reported for dried black pepper samples. All dried black pepper samples exhibited L* values closer to black (0) than to white (100), ranging from a maximum of 22.01 to a minimum of 11.96. The a* values ranged from 2.04 and 4.54, while the b* values ranged from 2.84 to 4.97. Colour plays a crucial role in food valuation, as it forms the basis of the consumer's initial perception. The intensity of blackness in the peppercorns was significantly influenced by the blanching and drying processes. The effect of drying on colour is reflected in specific chromatic values, particularly in the a* (yellowing) and b* (reddening) parameters, which are impacted by heat-induced changes in pigments and other colour-determining compounds in the pepper. For colour, a darker black pepper, indicated by a lower L*, is expected to command higher prices in the market, as reported by Akshitha *et al*. (2023).

2.6 Hybrid Solar Drying System (HSDS)

Based on EL-Mesery *et al*. (2022), solar dryers, which utilize solar radiation to generate heat for dehydration, offer several advantages over traditional sun drying. By regulating the drying process within a dedicated structure, they protect products from environmental factors like dust, rain, and insects, while also reducing the drying time and improving product quality such as better colour compared to OSD. Solar dryers can be categorized based on their heating methods or operating systems, including direct, indirect, mixed-type, greenhouse, hybrid, and those with energy storage systems.

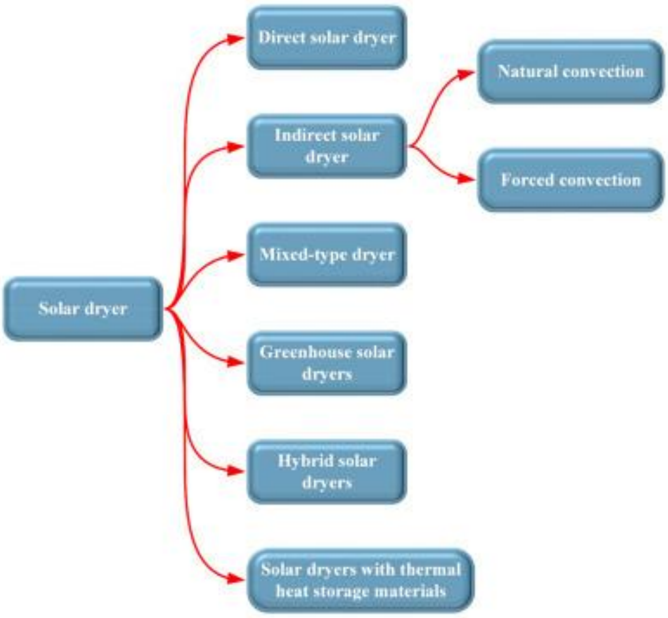

Figure 2.1 Classification of solar dryers

Hybrid solar dryer was designed and constructed using direct solar energy and a heat exchanger. Hybrid solar dryers consist of a solar collector, reflector, a combined heat exchanger and storage unit, with the drying chamber positioned beneath the collector. The dryer operates in solar mode during sunny days and transitions to hybrid mode during cloudy conditions, utilizing stored heat energy collected during sunny periods or electric heaters. This design enables continuous dehydration, even at night and the food is protected from possible microbial degradation. Solar-assisted dehydrating systems are extensively applied for dehydrating agricultural and food products in many developing countries due to the availability of solar radiation and rising cost of fossil fuels (EL-Mesery *et al*., 2022). Researches have shown that hybrid drying enhance up to 40% energy-efficiency compared to electric resistance dryers, shorter drying times compared to open-air or artificial methods. Hybrid dryers have been successfully applied to a range of crops, including mushrooms, pineapples, and cashew nuts, particularly those requiring rapid drying and high product quality (Udomkun *et al*., 2020).

Based on Tiwari (2016), the hybrid solar dryer is to supply ample amount of heat, exceeding the ambient temperature under given humidity. It raises the vapour pressure of the moisture within the product and lowers the relative humidity of the drying air, enhancing the air's capacity to carry moisture. The dryer draws air in via either natural convection or, on sometimes, a fan. As it passes through the collector, it heats up and then partially cools down as it absorbs moisture from the material. The material is heated both by air and sometimes by sun directly. To maintain relative humidity, warm air can contain more moisture than cold air, therefore the quantity of moisture removed depends on both the air's initial absolute humidity and the temperature to which it is heated inside the collector. Air's ability to absorb moisture is influenced by both its initial humidity and the temperature at which it is heated.

With an average solar radiation of 700 W/m^2, a V-groove type solar collector with collector area of approximately $15m^2$, an average output of 50°C temperature and 15.1 m^3/min air flow rate can be achieved. Hot air was discharged into the drying chamber from an outlet duct strategically located for optimal performance. Meanwhile, a 10kW auxiliary heat source was used to ensure continuous operation and more effective temperature control. This can lower the nutritional quality and properties if the drying process is delayed (Tiwari, 2016).

Based on Ali *et al*. (2017), the airflow in v-Groove Hybrid Solar Drier (v-GHSD) was regulated, starting when solar radiation struck the aluminium plate at the v-grooved absorption collector. This radiation was converted to the back of the collector using an axial fan within the chamber. As the air flowed into the chamber, it passed through a v-groove, heating up over the collector, which operated within a temperature range of 50-69°C. The axial fans were programmed to activate when the collector's temperature reached 55°C and to stop when it reached 59°C. The hot air then moved from the back of the chamber through the tray racks and the fan pushed the hot air from collector to the front of chamber while a concentric fan on the wall recycled hot air to the trays. The resulting hot moist air was expelled through a small window at the bottom of the drying chamber. The drying process continued until the chamber's relative humidity decreased and the dried products reaching an equilibrium moisture content (MC). The weight loss of dried products can be calculated based on the formula according to AOAC (2000):

$$\text{Water loss (kg)} = \frac{Xi - \mathrm{XF}}{100 - XF} \times m_0$$

Where:

X_i = Initial moisture content (wb)

X_F = Final moisture content (wb)

m_0 = Total weight (kg)

The drying time for v-GHSD is taken about 38.00h ± 0.57h while for the conventional drying time is 114.00 ± 0.22h to achieve the same weight. Besides, the moisture evaporative capacity for v-GHSD is 64.79 ± 0.12kg while for conventional drying method is 21.93 ± 1.32kg. The average chamber humidity and temperature for v-GHSD is 45.00 ± 3.12 % and 48.00 ± 0.57°C while for conventional drying method is 78.40 ± 2.12% and 30.20 ± 0.19°C (Ali *et al.*, 2017).

This hybrid solar drying system (HSDS) have given several advantages. First and foremost, the hybrid solar dryer (HSD) is considered as a professional machine which are economic friendly for the commercial farmers to obtain the dried agricultural products which are high quality and highly desired (Aduewa *et al*., 2022). A solar dryer can preserve the nutritional values and properties of dried products by drying it at an optimum temperature which is 45℃ to 60℃ for safe drying. This leads to higher product's marketability and hence lead to better financial returns for the farmer (Abdul Razak *et al*., 2021). Based on Tiwari (2016), it can also increase the efficiency of drying by it has higher temperature, air movement and lower humidity which can elevate the drying rate. Due to the faster drying rate, the risk of spoilage of agricultural products by microorganisms will greatly reduce. Besides, since the food is enclosed in the dryer, therefore can protect the food from contamination by dust, soils, insects, birds and animals (EL-Mesery *et al*., 2022). The higher temperature can also deter insects too. Furthermore, this hybrid solar drying system (HSDS) is considered as environment-friendly since it typically used the solar energy, a renewable, sustainable energy as sole energy and will not lead to any pollution.

CHAPTER 3

METHODOLOGY

3.1 Research Design

The type of study that applied was experimental design to know the nutritive and physical quality of black peppers dried by optimized hybrid solar drying system when compare with the commercial black pepper. The optimized hybrid solar drying system used is v-GHSD. The nutritive value and physical quality are assessed by doing proximate analysis, digital vernier calliper, and colorimeter.

3.2 Method of Study

3.2.1 Sample Material

This study utilized black peppercorn dried using HSDS provided by co-supervisor, alongside with commercially sourced black pepper (refer to Appendix 1) that was purchased in the market. This research aimed to assess the nutritive and physical properties of the HSDS-dried pepper and determine its suitability for market requirements.

3.3 Efficiency of HSDS

A moisture removal curve of dry basis of black pepper (g/g) versus drying time (h) was drawn to compare the efficiency of HSDS-dried and OSD- dried black pepper by determining the time to achieve the EMC curve.

3.4 Proximate Analysis

3.4.1 Moisture Content

The air-oven drying method is the most common and widely applied methods for determining moisture content (AOAC, 2023). For this method, the oven was thermally regulated to 105℃ ± 0.5℃, with minimal temperature variations of less than 3℃ (< 3℃) within the oven. A porcelain cup that had been in the oven for 3 hours at 105℃ was weighed and the results were recorded. Afterward, 5.000g ± 0.001 g of the black pepper samples were weighed, placed in the porcelain cup, and oven dried overnight at 105℃. The samples were then cooled to room temperature in a desiccator, weighed again, and this process was repeated until a constant weight was achieved. The results were then recorded.

Calculation

$$\text{Moisture (\% by weight)} = \frac{(W1+W2)-W3}{W2} \times 100\%$$

Where:

W_1 = Weight of aluminium dish (g)

W_2 = Weight of sample (g)

W_3 = Weight of aluminium dish + sample (after drying) (g)

3.4.2 Total Ash

To determine the total ash of a food sample, dry ashing is the standard material (AOAC, 2023). For ashing, 0.500g ± 0.001g of homogenized black pepper samples were weighed and charred on an electric coil heating rack until smoking ceased. The samples