COFFEE CHARACTERISTICS EVALUATION FROM CHERRIES TO ROASTED BEANS: A CASE OF NORTHERN THAI ARABICA COFFEE

SAI AUNG MOON

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Author: Sai Aung Moon

Examination Committee:

Associate Professor Sila Kittiwachana, Ph. D.	Chairperson
Assistant Professor Rattapon Saengrayap, D. Eng.	Member
Sirirung Wongsakul, Ph. D.	Member
Associate Professor Hiroaki Kitazawa, Ph. D.	Member
Associate Professor Prinya Wongsa, Dr.sc.agr.	Member
Assistant Professor Siripat Suteerapataranon, Ph. D.	Member

Advisors:

Rattapon Saengrayap .....Advisor

(Assistant Professor Rattapon Saengrayap, D. Eng.)

S. Wongsakul .....Co-Advisor

(Sirirung Wongsakul, Ph. D.)

Hiroaki Kitazawa .....Co-Advisor

(Associate Professor Hiroaki Kitazawa, Ph. D.)

Dean:

Sutthiwal Setha .....

(Assistant Professor Sutthiwal Setha, Ph. D.)

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Sai Aung Moon

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Author	Sai Aung Moon
Degree	Doctor of Philosophy (Food Science and Technology
Advisor	Assistant Professor Rattapon Saengrayap, D. Eng.
Co-Advisor	Sirirung Wongsakul, Ph. D. Associate Professor Hiroaki Kitazawa, Ph. D.

ABSTRACT

Thai coffee is celebrated globally for its distinct flavors and aromas, yet farmers encounter numerous obstacles, including unstable prices, limited market access, high production costs, and issues in farm and postharvest management. Key challenges include climate change, mix varieties growing, contamination from fungi and mycotoxins, insufficient facilities for drying, storage, and packaging, and variable weather impacting drying processes, which leading to inconsistent quality. Postharvest drying is critical for reducing microbial growth and developing desired flavors, while storage conditions significantly affect green coffee bean (GCB) quality. Extended storage, typically six months to a year, often leads to oxidation, resulting in quality loss through browning, aroma degradation, off-flavors, and increased spoilage risk. This research studies the impact of various drying, processing, and storage techniques on Thai coffee quality.

In dying techniques on their physicochemical characterizes, this research examines the effects of different drying methods and post-harvest processing techniques on the quality of Thai GCB and roasted coffee beans (RCB). Thai coffee producers utilize sun drying (SD), controlled-environment drying (CED) at 20–30 °C and 50–55% RH, and fast drying (FD) at 30–45 °C to enhance quality and cupping scores. Results show that drying and processing methods significantly impact the

physicochemical properties of GCB, including true density, moisture content, water activity, color, caffeine, trigonelline, chlorogenic acid, caffeic acid, sucrose, and fructose. CED produced the highest levels of these qualities, followed by SD and FD. The study also highlights that roasting decreases initial GCB qualities while developing characteristic flavors and aromas. Among post-harvest processes, dry processing (DP) yielded the highest caffeine, trigonelline, and chlorogenic acid levels, while honey processing (HP) increased sucrose and fructose, enhancing flavor complexity in the cup.

In accelerated storage and packaging, this study investigated lipid oxidation in GCB under accelerated storage conditions (30, 40, and 50°C with 50% RH) and various packaging types: plastic woven (PW), low-density polyethylene (LDPE), and hermetic (GrainPro®/GP) bags. Samples collected every five days over 20 days were analyzed for oxidation markers, including acid value (AV), free fatty acids (FFA), peroxide value (PV), ρ-anisidine value (PAV), total oxidation value (TOTOX), and thiobarbituric acid reactive substances (TBARS), as well as moisture content, water activity, and color. Results showed primary and secondary oxidation with increasing AV, FFA, PAV, PV, and TBARS, impacting flavor and aroma. Higher temperatures accelerated lipid oxidation and quality degradation, with GP bags best preserving GCB quality by minimizing oxidation rates. The study highlights that selecting appropriate storage conditions and packaging materials, particularly hermetic packaging, is essential to maintaining GCB quality during storage.

In accelerated storage and non-destructive techniques, this study evaluated the shelf-life and lipid oxidation of DP and HP coffees stored in GP bags under accelerated storage at 30, 40, and 50 °C with 50% RH. Using a kinetic model, the shelf-life was estimated at 45.67, 29.9, and 24.92 days for DP, and 60.34, 38.07, and 19.22 days for HP at 30 °C, 40 °C, and 50 °C, respectively. Partial least squares (PLS) modeling demonstrated predictive accuracy for TBARS (R^2 = 0.801) and peroxide values (PV) (R^2 = 0.469) with significant wavenumber ranges identified via ATR-FTIR spectroscopy as indicators of lipid oxidation. ATR-FTIR proved effective for non-destructive, rapid analysis of oxidation, and demonstrated that lower storage

temperatures extended GCB shelf-life. Findings confirm that temperature and processing method significantly influence GCB shelf-life, with ATR-FTIR as a valuable tool for quality monitoring during storage.

In roasting profiles, this study examines the effects of roasting levels and storage conditions on coffee quality by evaluating moisture content, color, peroxide value, shelf-life, and volatile compounds using SPME-GCMS. Coffee samples from Doi Chang, Thailand, processed by DP, WP, and HP were roasted to light (205°C), light-medium (210°C), and medium (218°C) levels, then stored in hermetic bags under accelerated conditions (30, 40, and 50°C, 50% RH) for up to 21 days. Roasting level and storage temperature significantly influenced (p<0.05) coffee quality, with higher temperatures accelerating degradation. Eighty-two volatile compounds were identified, with furans (35.20–53.55% d.w.), pyrazines (13.16–32.31% d.w.), and esters (4.21–16.70% d.w.) being the dominant contributors to aroma. Shelf-life at 30°C was longest for light roast (10.03–11.68 days), followed by light-medium (7.28–8.82 days) and medium (6.33–7.68 days). Washed coffee exhibited better long-term stability than honey and natural-processed coffee. While volatile compound concentrations generally declined during storage, organic acids, phenolics, and pyrazines increased due to thermal oxidation, with the most significant changes occurring at 50°C. These findings provide valuable insights for coffee roasters and buyers in optimizing storage conditions to preserve coffee quality and extend shelf-life.

In dying techniques on their volatile compound and cupping, this study explores the effects of drying techniques; CED, SD, and FD combined with processing methods; DP, WP, and HP on the quality of roasted Thai coffee. CED-DP and CED-HP achieved the highest cupping scores of 83.17 ± 1.26 and 83.33 ± 0.58 points, respectively, with CED enhancing ester and nitrogenous compounds, SD increasing acids, alcohols, and ketones, and FD promoting acetate compounds. PCA revealed an 87.97% correlation between volatile compounds and cupping scores. DP was linked to high acidity, sweetness, and ester content; WP to uniformity and clean cup; and HP to sensory qualities like body and balance. CED proved most effective for enhancing acidity and flavor complexity, while FD showed higher pH and lower acidity, with each method

contributing unique volatile profiles. Key volatile compounds were identified for each process, supporting the potential for tailored drying and processing methods to improve flavor and aroma in specialty coffee. This study offers insights for Thai producers and positions establishment for further research on optimizing coffee quality across different climatic conditions.

Therefore, this research outlines a comprehensive strategy for improving specialty coffee quality through advancements in drying, storage, packaging, roasting, and analysis. Controlled environment drying (CED) dramatically enhanced physicochemical and sensory properties, particularly in dry and honey-processed beans. Accelerated shelf-life testing, along with enhanced lipid oxidation markers and ATR-FTIR spectroscopy, revealed new, non-destructive insights into coffee stability. Optimizing the roasting profile had a further impact on volatile component retention and shelf life. Concurrently, these advances contribute to a comprehensive approach for increasing flavor, uniformity, and storage stability, benefiting farmers, roasters, and quality systems in Thailand and abroad.

Keywords: Accelerated Storage, Drying, Multivariate Analysis, Non-destructive, Specialty Coffee

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ABBREVIATIONS AND SYMBOLS

ATR-FTIR	Attenuated Total Reflectance Fourier Transform Infrared Spectroscopy
AV	Acid Value
a_w	Water Activity
C16:0	Palmitic Acid
C18:0	Stearic Acid
C18:1	Oleic Acid
C18:2	Linoleic Acid
C20:0	Arachidic Acid
CA	Caffeic Acid
CED	Controlled-Environment Drying
CGA	Chlorogenic Acid
CV	Cross-Validation
DP	Dry Process
FD	Fast Drying
FFA	Free Fatty Acid
GCB	Green Coffee Beans
GP	GrainPro®
HCA	Hierarchy Clustering Analysis
HP	Honey Process
LDPE	Low-Density Polyethylene
LOOCB	Leave-One-Out Cross-Validation
LVs	Number of Latent Variables Used
LR	Light roasted
LMR	Light-Medium Roasted
MC	Moisture Content

ABBREVIATIONS AND SYMBOLS

MR	Medium Roasted
PCA	Principle Component Analysis
PLS	Partial Least Squares
PV	Peroxide Value
PW	Plastic Woven
RCB	Roasted Coffee Beans
RH	Relative Humidity
RMSE	Root Mean Square Error
RPD	Residual Predictive Deviation
SCA	Specialty Coffee Association
SFA	Saturated Fatty Acid
SPME-GC-MS	Solid-Phase Microextraction-Gass Chromatography Mass Spectroscopy
T	Temperature
TA	Total Titratable Acidity
TBARS	Thiobarbituric Acid Reactive Substances
TD	True Density
TFA	Total Fatty Acids
TOTOX	Total Oxidation Value
TSS	Total Soluble Solids
USFA	Unsaturated Fatty Acids
WP	Washed Process

CHAPTER 1

INTRODUCTION

1.1 Background and Problem Statement

Globally, coffee is one of the most beloved beverages, celebrated for its rich aroma, complex flavors, and stimulating effects, with demand continuing to grow (1). However, the quality of Arabica coffee (*Coffea arabica*), valued for its refined flavors and traditionally cultivated at high altitudes, faces multiple threats, including climate fluctuations, post-harvest handling challenges, and storage practices. Recently, Arabica production declined by 7.1%, while Robusta saw a 5.1% increase possibly reflecting adaptive shifts in response to environmental stress (2). Thailand's Chiang Rai region, specifically highland areas such as Doi Chang, Pang Khon, Mae Chang Tai, and Doi Tung, offers an ideal climate and elevation for Arabica, which was introduced to Thailand in 1849 and is now grown across 19,900 hectares (3, 4, 5). Here, varieties like Catimor, Caturra, Typica, and Bourbon develop distinctive profiles characterized by fruity-floral aromas, acidity, and clean, full-bodied flavors highly prized in global markets (6, 7, 8).

Despite recent growth, Thai Arabica coffee production faces significant challenges, including unstable prices, limited market access, and high production costs driven by labor and fertilizer expenses, underscoring the need for sustainable farming practices (7, 9). Climate change adds further risk, with rising temperatures and water scarcity threatening coffee quality in regions like Chiang Rai (6, 10). Storage issues also impact quality, as sensory attributes like aroma and flavor can degrade, and poor storage conditions can lead to mold contamination, producing harmful mycotoxins from fungi such as *Aspergillus* and *Penicillium* (11, 12, 13).

To support quality and scalability, advanced processing techniques and research are needed to enhance post-harvest practices including drying, storage, and packaging, as these directly affect flavor, aroma, and safety. The unique sensory profile of Arabica coffee depends on various factors, including coffee variety, altitude, climate, soil,

farming practices, and post-harvest processes, which collectively shape its aroma, flavor, and health-related attributes (14, 15, 16, 17, 18). Coffee processing plays a crucial role in maintaining the physicochemical properties and flavor profile of coffee, contributing to about 60% of the quality of green coffee beans (GCBs). This process includes several stages: separation and washing to remove impurities like soil, leaves, and floating cherries; de-pulping; fermentation; drying; de-hulling; cleaning; sorting; grading; storage; roasting; grinding; and cupping (14). Proper processing is essential to prevent spoilage, undesirable fermentation, or mold formation during dehydration, as well as to remove the outer skin, mucilage, and parchment before roasting. The method of processing, whether parchment-dried (washed), mucilage-dried (honey), or skin-dried (natural), involves a crucial drying stage, each of which influences the final quality of the coffee beverage (16, 19).

Drying is a critical step in coffee processing, reducing moisture content from 55-60% to a stable 9-12% to ensure safe storage and prevent microbial growth, preserving flavor and aroma (20). In Thailand, sun drying is commonly used but depends on favorable climate conditions, influencing coffee taste and quality. While mechanical drying offers consistency in industrial settings, it can cause structural damage or instability if temperatures are too high (21, 22). The drying process also affects key physicochemical properties such as density, moisture content, and water activity, which in turn impact coffee's aroma, flavor, and storability (23, 24, 25). Biochemical compounds like caffeine, sugars, and chlorogenic acid shape the coffee's acidity, bitterness, and aroma (26, 27), with sugars especially sucrose, glucose, and fructose, playing a key role in enhancing sweetness and forming important flavor compounds during roasting (28, 29). Jitjaroen et al. (30) suggest that low-temperature, low-humidity drying (LTLH) methods can help preserve and enhance sugars, improving the final product's quality. Understanding these drying techniques is vital for producing high-quality Thai coffee with consistent flavor, better storage stability, and higher market value.

Proper storage and packaging are crucial for preserving coffee’s sensory attributes and preventing contamination (31). Storage can lead to oxidation, mold growth, and aroma loss, which degrade coffee quality. Although no packaging can fully prevent sensory degradation over time, monitoring factors such as moisture content,

density, and odor is essential to maintain quality (32, 33). Environmental conditions can further impact physical and chemical properties, affecting both safety and marketability. Accelerated storage techniques, which simulate long-term conditions by controlling temperature, humidity, and light, help study aging processes and the effects of oxidation, particularly in GCBs with high levels of unsaturated fatty acids (34, 35). However, the impact of accelerated storage on Thai Arabica GCBs is underexplored, highlighting the need for effective preservation methods to maintain sensory quality (9). Packaging like GrainPro® can slow oxidation, but no solution can completely prevent it (36, 37). Methods like peroxide value (PV) and TBARS are key for assessing oxidation and predicting shelf-life, but they are time-consuming and impractical for large-scale applications (34, 38, 39).

To ensure the longest possible shelf-life without compromising quality, packaging is essential for green coffee beans (GCB). However, no packaging system can fully preserve coffee's initial sensory qualities over time, making it crucial to develop methods for detecting chemical changes before they negatively impact quality (40). Non-destructive evaluation methods, such as Fourier transform infrared (FTIR) spectroscopy, are valuable tools for assessing the physical, chemical, and sensory properties of coffee. FTIR can quickly detect key compounds such as caffeine, chlorogenic acids, lipids, and volatile aroma compounds, which influence coffee’s flavor profile (41). These methods are used to analyze processing types, roasting levels, and sensory traits, as well as to monitor moisture content, water activity, oxidation, and volatile compounds during processing and storage (41, 42). Although FTIR has potential for assessing coffee shelf-life and oxidation, further research is needed, particularly for Thai producers aiming to optimize storage practices and preserve quality during long-term storage (43). When combined with predictive models like partial least squares (PLS) regression, FTIR can help estimate shelf-life and guide quality control, improving coffee’s marketability and appeal (43, 44).

Moreover, coffee roasting transforms GCB by heating them through stages like drying, browning, and caramelization, which influence the aroma and flavor (45, 46). Different processing methods and roasting levels impact aromatic compounds and sensory qualities, such as taste and mouthfeel, which are vital for specialty coffee quality (45, 46, 47). The Specialty Coffee Association of America (SCAA) defines

cupping standards, with color classifications of 63 Agtro for "Gourmet" and 48 Agtro for "Commercial", and roasting profiles completed within 8 to 12 minutes (47). According to Fibrianto et al. (48) light roasts exhibit fruity and sour notes, medium roasts offer a balanced mouthfeel with complex aroma, while dark roasts develop bitter, burnt, and smoky flavors. As roasting progresses, coffee aromas shift toward smoky, earthy, and sulfurous notes (49). Therefore, selecting an optimal roasting profile between light and medium is essential for enhancing coffee quality. SCAA cupping protocol is commonly used for quality assessment, evaluating attributes like aroma, acidity, and body, with sensory scores correlating to chemical indicators such as titratable acidity (TA), pH, and total soluble solids (TSS), which influence flavor (47, 50). Volatile compounds responsible for coffee's aroma are influenced by drying techniques and processing conditions. For instance, freeze drying can help preserve volatiles like pyrazines, which are vital for aroma and antioxidant properties (15, 51). However, the relationship between volatile compounds, chemical properties, and cupping scores across various processing methods requires further exploration. Analytical methods like solid-phase microextraction-gas chromatography/mass spectrometry (SPME-GC-MS) with principal component analysis (PCA) offer precise profiling of aroma compounds, helping to identify patterns across drying methods and improving quality control (15, 52). These insights are crucial for adapting post-harvest practices to enhance coffee quality and meet consumer preferences amidst environmental challenges.

Emphasizing these areas in Thai coffee studies could enhance the industry's resilience, support consistent quality, and meet the standards of a competitive global coffee market. Thus, the main impartial was related to the evaluate the quality of northern Thai Arabica coffee throughout the process from coffee cherries to roasted beans, and how the parameters affecting coffee processing, storage, packaging and roasting on specialty coffee quality. These techniques would provide scientific evidence of new novel of non-destructive methods for reducing quality loss during processing, drying, storage, roasting and packaging of Thai Arabica coffee.

1.2 Objectives

The objectives of this research were:

1.2.1 To evaluate the influence of different drying methods and processing on the physicochemical characteristics, volatile compounds and cupping quality.

1.2.2 To determine the shelf-life of green coffee beans (GCB) under different accelerated storage conditions and packaging by using conventional and FTIR techniques.

1.2.3 To investigate the impact of roasting profiles and storage condition (on the shelf-life of the roasted coffee beans (RCB).

1.3 Research Hypotheses

This study examined research questions coffee five experiments, which were applied to northern Thai Arabica coffee on post-harvest processing, drying, accelerated storage by different packaging and ATR-FTIR on shelf-life of coffee quality and roasting profiles.

1.3.1 The northern Thai Arabica coffee quality would be improved through optimized post-harvest processing, drying methods and storage conditions.

1.3.2 The optimum parameters for coffee processing, green bean storage and roasting would be identified, leading to better preservation of physicochemical properties and flavor attributes.

1.3.3 Different drying methods (sun drying, controlled-environment drying, and fast drying) and post-harvest processing (dry, washed, and honey processes) would significantly affect the physicochemical and biochemical properties of Thai Arabica coffee, including moisture content, water activity, color, and bioactive compounds.

1.3.4 Storage conditions (temperature, humidity, and packaging type) would significantly influence lipid oxidation and shelf-life of green coffee beans, with hermetic packaging (GrainPro®) providing superior preservation compared to plastic woven and LDPE bags.

1.3.5 Roasting profiles and storage conditions would impact the chemical composition, lipid oxidation, and volatile compound profile of roasted Thai Arabica coffee**,** influencing its sensory attributes and overall cup quality.

1.3.6 Implementing optimized post-harvest processing, drying techniques, and efficient storage solutions would help farmers improve quality control, extend the shelf-life of green coffee beans, and reduce costs associated with packaging while maintaining coffee quality for the market.

1.4 Research Scope

1.4.1 To study investigated the impact of different drying techniques, i.e., sun drying (SD), controlled-environment drying (CED) at 20–30 °C, 50–55% RH, and fast drying (FD) at 30–45 °C, 50–55% RH, along with different post-harvest processing, i.e., natural (DP), washed (WP), and honey processes (HP) on the physicochemical and biochemical properties of Thai Arabica coffee including true density, moisture content (MC), water activity (a_w), color, caffeine, trigonelline, chlorogenic acid, caffeic acid, sucrose, glucose, fructose, pH, titratable acid (TA), total soluble solids (TSS), volatile compounds and cupping quality.

1.4.2 To investigate the influence of packaging and processing on shelf stability of GCB. shelf-life of GCB under different acceleration storage conditions (30, 40, and 50 °C with 50% RH.) and packages, i.e., plastic woven (PW), low-density polyethylene (LDPE), and hermetic/GrainPro® (GP) bags. The samples were collected every five days (0, 5, 10, 15, and 20 days) and analyzed for lipid oxidation parameters, including acid value (AV), free fatty acids (FFA), peroxide value (PV), ρ-anisidine value (PAV), total oxidation value (TOTOX), thiobarbituric acid reactive substances (TBARS), moisture content (MC), water activity (a_w), color, lipid, fatty acids, and cupping profiles.

1.4.3 To investigated natural dry process (DP) and honey process (HP) green coffee beans stored in GrainProR bags for 0, 5, 10, and 20 days under accelerated storage conditions at 30, 40, and 50°C with relative humidity of 50% based on lipid

oxidation reactions as PV and TBARs by their shelf-life determination with ATR-FTIR under accelerated storage conditions.

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CHAPTER 2

LITERATURE REVIEW

2.1 Coffee

Coffee is a popular beverage derived from the seed of the Coffea plant, specifically from two primary species: Arabica (*Coffea Arabica*) and Robusta (*Coffea Canephora*) (1,2). Arabica coffee, known for its superior taste and aromatic qualities, accounts for approximately 60-70% of global coffee production (3). Arabica is the most productive, offers the highest quality, and has grown at high elevations above 1,000 m with cooler climates (4,5). Arabica has higher acidity, sweet with pleasant notes of fruits, nuts, chocolate, and other ingredients. In content, Robusta is typically hardier, with a stronger, more bitter flavor and high caffeine content with global production approximately 30-40 % (3). Robusta is of lower quality, and cheaper than Arabica; however, it contains more caffeine content and is mainly grown at a low elevation of less than 800 m in warmer climate (6). Robusta has lower acidity, and woody or burnt rubber flavor. Quality of coffee is vary significantly based on pre-harvest and post-harvest practices, as well as how the coffee managed during its journey form farm to consumer (4,5).

However, the quality and sensory attributes of coffee, such as aroma, acidity, body and aftertaste, are evaluated during a cupping process, which plays a crucial role in determining its market value (4). Thus, Arabica and Robusta are both economically significant and globally cultivated species (7). It is characterized by its distinct flavor profile, which is influenced by several factors, including botanical variety, environmental conditions, and processing methods (1,2).

2.1.1 Coffee in Global

Global production is expected to increase by 5.8 %, reaching around 178 million bags due to favorable condition, particularly in Brazil, which leads in Arabica output. The increase is likely to create a surplus of approximately 1 million bags (8). Consumption, which dipped by 2% in 2022/2023 due to economic pressures, is

anticipated to recover to about 177 million bags, spurred by stabilization in non-producing countries and adjustments in disposable incomes (3). April 2024 data also reflects a 15.3% rise in green coffee exports year-over-year, with notable contributions from Brazilian and Robusta varieties though Asia saw a slight decline in exports. These combined factors, with higher production exceeding demand, indicate a modest surplus that might help stabilize global coffee prices amid fluctuating economic conditions (3,8). Coffee export around the world is 80 % product as around 43 % in South America, Asia and Oceania (24 %), Central American and Mexico (18%), and Africa (16 %) in 2018-2022 (9). Asia contributes around 25 % of the global coffee exports 2023-2024 driven primarily by Vietnam, the region's leading coffee producer and one of the top producers globally (3). Other Significant producers include Indonesia and India, which help boost the continent's overall market share. Thailand, though smaller in output, plays a notable role within Asia, particularly in specialty coffee segment, producing high-quality Arabica beans from regions of the Northern Thailand. This focus on premium Arabica positions Thailand as a unique player in Asia's coffee scene, catering to both domestic and international markets interested in specialty and sustainably produced coffee (3,8).

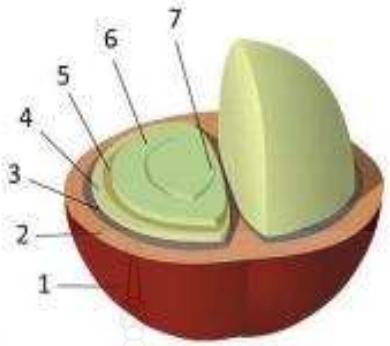
According to World Coffee Reacher trends, coffee industry face pressing problems, primarily stemming from climate change and consolidation of coffee productions. Research indicates that climate change is expected negatively impact both Arabica and Robusta coffee yields, with projections suggesting a decline in planted area and yield by 2050 (10). Additionally, the concentration of coffee production in a few countries particularly Brazil, Vietnam, Colombia, poses risks to flavor diversity and increase vulnerabilities by climate-induced disruptions (8,10). Thus, to maintain the substantial of coffee production and meet rising consumer demand, substantial investment in agricultural research and development is deemed essential.

2.1.2 Coffee Structure

The structure of coffee cherries is quite complex, comprising several distinct layers that contribute to the overall quality of the coffee produced. The cherry itself is classified as a drupe and consists of seven primary layers in Figure 2.1: outer skin (exocarp), pulp (mesocarp), mucilage, the parchment (endocarp), silver skin (spermoderm), coffee bean (endosperm), and center cut.

Exocarp (outer skin) is the outermost layer, which is usually green in unripe cherries, and turns red or yellow when ripe. The color change is often used as an indicator of ripeness and is correlated with the development of flavor profiles in the coffee (11). Mesocarp (pulp), the fleshy layer is sweet and provides nutrients to the developing seed. It typically contains pectin, which aids in moisture retention (11,12,13). Mucilage found underneath the pulp, this layer is sticky and highly hydrated primarily composed of pectin and sugars. It plays a role in the fermentation process during washed/ wet processing (11,12,13). Endocarp (Parchment) is thin, protective layer surround the coffee bean and must be removed to obtain green coffee beans (11,12). Spermoderm (silver skin) is a thin layer that encases each coffee bean, this layer could affect the flavor and quality of the coffee (11,12). Endsperm (coffee bean) is the seed of the coffee cherry and contains essential oils and compounds that contribute to the coffee's aroma and flavor profiles. The endosperm comprises storage cells rich in nutrient (11,12,13). Center cut refers to the inner structure of the coffee beans, where the main the biochemical reactions occur during roasting, leading to the development of flavor compounds through process such as Maillard reaction (12,13).

All of layer are related to final quality of green coffee bean (GCB) during coffee per-harvesting and post-harvesting (5). On the other hand, the GCB quality is significantly influenced by coffee processing and also related several factors like drying technique, storage, packaging, farm manage including soil, climate, origin seed, latitude and altitude, and agricultural practices (5,14,15).



Note 1 (Outer Skin/ Pericarp/ Exocarp) 2 (Pulp/ Mesocarp) 3 (Mucilage) 4 (Parchment/ endocarp) 5 (Silver skin/ Spermoderm) 6 (Bean/ Endosperm) 7 (Center Cut)

Source (12)

Figure 2.1 The Structure of Coffee

2.1.3 Coffee in Thailand

Coffee cultivation hold significant importance in Thai agriculture, with distinct regions dedicated to two major coffee varieties: Arabica in Northern Thailand and Robutsta in The Southern (16,17,18). Arabica coffee, introduced to Thailand in 1849, has since become the primary variety in the highland regions of the North, notably in provinces like Chiang Rai, Chiang Mai, Nan, Lampang, and Tak (19,20). Arabica cultivars found in these regions include Catimor, Caturra, Typica, Bourbon, Catuai, and Mundo Novo, each contributing unique traits to Thai coffee productions (19,20). For instance, Chiang Rai's Doi Chang, Pang Khon, Mae Chang Tai, and Doi Tung areas are renowned for Arabica cultivation, covering and estimated 19,900 hectares in the highlands as of 2019 (21). This geographic and varietal diversity underpins Thailand's growing reputation in coffee production, particularly in premium Arabica beans.

The harvesting season for Thai Arabica coffee typically extends from October to February. The distinct season: summer form mid-March to mid-May, a rainy season until mid-October, and a winter season form mid-October to February (22). Thai Coffee is predominantly cultivated at altitude range from 700 to 1,400 meters, under annual average temperature between 18 and 28 °C, and a rainfall of approximately 1,200-1,500 mm per year (20). Additionally, the average of annual rainfall from the northern

Thailand is 1354 mm, and maximum and minimum temperature of 31.5 °C and 20 °C, which provide Chiang Rai Arabica coffee cultivation (22). Doi Chang, Chiang Rai area is a high mountain rising to an altitude of 1,100-1,700 meters (3,933 to 5,577 feet) above sea level between latitude 19 degree, 48 arcmins, 48 arcsec North and longitude 99 degrees, 34 arcmin East, and is suited for the cultivation of Arabica coffee (23). Coffee plant under the canopy of sun-filtered plum, peach, pear, and macadamia nut trees. However, Climate change poses a growing challenge to Thai coffee agriculture, particularly for both Arabica and Robusta varieties, as shifting precipitation patterns, higher atmospheric moisture, and rising temperatures impact crop quality and yield (22). These changes not only disrupt traditional growing seasons but also stress coffee plants, affecting flavor profiles and production stability. Therefore, implementing adaptive strategies tailored to each farm's unique conditions has become essential to mitigate the adverse effects of climate shifts, particularly as rainfall irregularity and temperature extremes influence coffee maturation and flavor development.

On the other hand, a cup quality coffee is a complex characteristic which depend on several factors such as the species or variety (genetic), environmental conditions (ecological), agronomical practices (cultivation), processing system (postharvest), and storage conditions (5). The post-harvest processes, i.e., processing, drying, and storage, are critical to ensuring the sensory qualities of Thai coffee. During these stages, careful handling helps to retain the delicate fruity and floral notes and the clean, full-bodied taste unique to Thai coffee. With precise attention to post-harvest care, from maintaining optimal moisture levels during drying to protecting beans during storage, farmers can better safeguard the qualities that make Thai coffee appealing to global markets. Studying these techniques is essential for maintaining high-quality coffee, as they enable producers to navigate environmental challenges and sustain the distinct characteristics of Thai coffee, making it a sought-after product internationally. Thai coffee has spread worldwide, such as the USA, Canada, UK, South Korea, Singapore, Malaysia, Cambodia, Laos, and others. Thai Arabica coffee can develop unique profiles of intense fruity-floral aroma, acidity, clean-cup, full profile, and flavors that rest on the processing (23,24).

According to Ratchawat et al. (17) is described as Thailand's coffee strategy to improve the competitive capability of coffee production and coffee quality in ASEAN

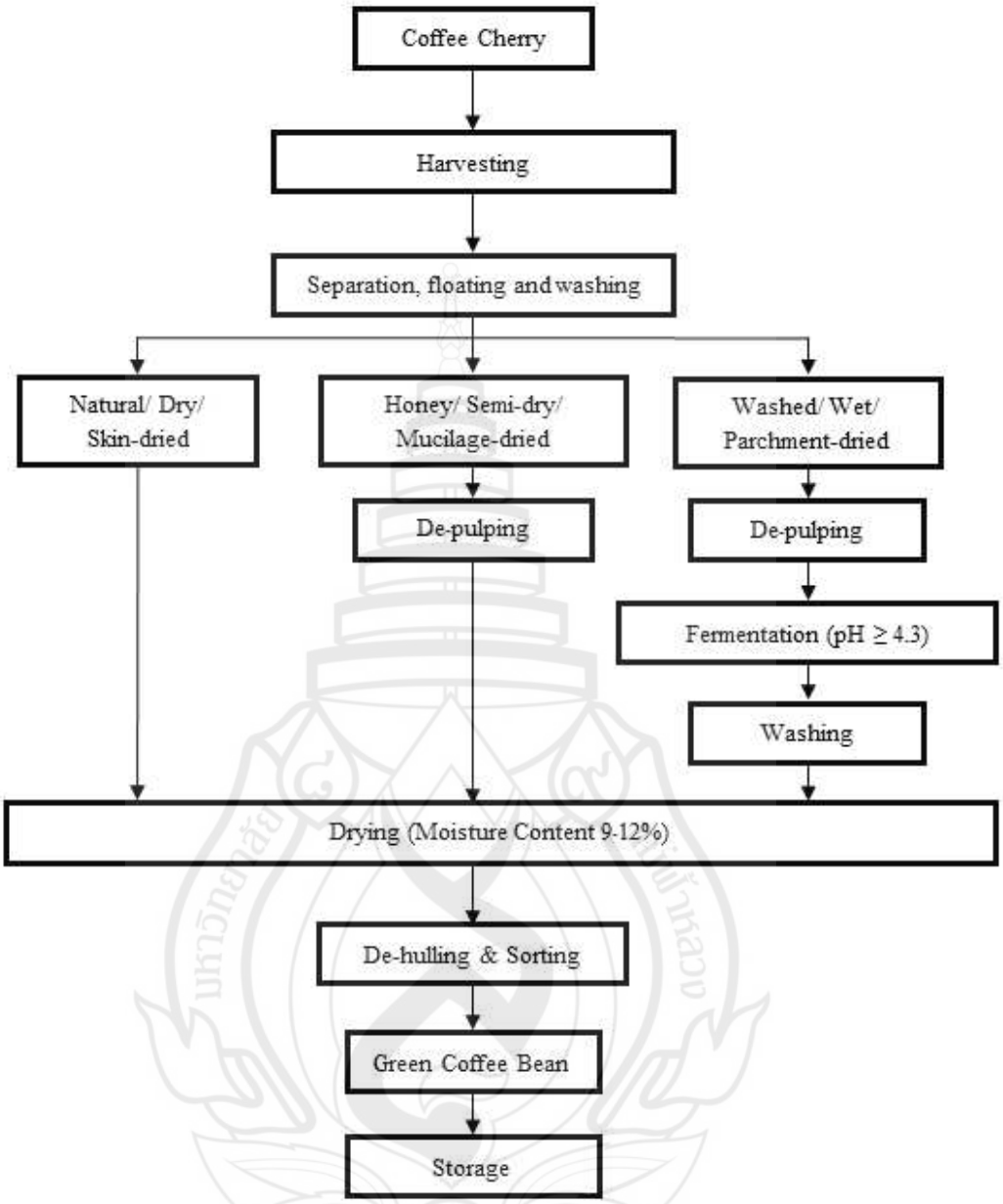
markets the Thais government from 2017 to 2021. This strategy focuses on increasing coffee production yield through the re-cultivation of old coffee plants with high yield, reducing production cost by at least 10%, and improving coffee quality. On the other hand, one of the researchers presented that coffee farmers have faced unstable prices of coffee beans, lack of market access, and high production costs due to hired labor and chemical fertilizers, which necessity to sustainable farming practices with geographical indication to support the local community and improve the living standard of farmers (24). Chuqian (18) also has suggested introducing advanced processing techniques and equipment to develop a qualified, precise, commercialized industry on a large scale, and improve the product to high-quality products, more comprehensive investigations and researchers of the status and issues.

In Thai, coffee farmers and roasters usually keep GCB for six months to one year before roasting the coffee bean. During Thai coffee postharvest, sun drying methods have affected the loss quality in the chlorogenic acids, total phenolic content, antioxidant activities, and color of green Arabica bean than heat drying (25). Maman et al. (26) reported Thai Arabica coffee during postharvest and storage; the coffee bean can be contaminated by fungi that produce mycotoxins such as ochratoxin A (OTA), *Aspergillus* and *Penicillium*, especially on coffee cherries, parchment coffee, and GCBs. Thus, fungi can be observed in processing steps such as fermentation, drying, and storage, and present microbiota can affect coffee's final taste and sensory qualities. Additionally, the technique applied on coffee processing, drying and storage conditions must be important to improve, and maintain the unique Thai coffee quality to specialty coffee grade.

2.2 Coffee Processing

After harvesting, coffee cherries undergo processing, a crucial step that contributes approximately 50-60% to the quality of green coffee beans (27,28). This process includes several stages, such as separating and washing to remove soil, dirt, leaves, twigs, and floating cherries, followed by de-pulping, fermentation, drying, de-hulling, cleaning, sorting, and storage before roasting, grinding, and cupping. Effective

processing is essential for high-quality green coffee beans, as it prevents spoilage from undesirable fermentation or mold during dehydration and removes the outer skin, mucilage, parchment, and silver skin, all of which impact the final coffee quality (29). The goal is to reduce the beans' moisture content to 9-12%, while imparting distinct characteristics associated with each method. The primary processing methods are parchment-dried (washed or wet, WP), mucilage-dried (honey or semi-dry, HP), and skin-dried (natural or dry, DP) (14,15,29,30). The three types of coffee processing showed in Figure 2.2.



Source (14,29)

Figure 2.2 Three Types of Coffee Processing

2.2.1 Skin-dried/ Natural/ Dry Process

Skin-dried (dry/natural) process is the oldest known as natural processing. The dry process consists of sorting to remove soil, dirt, leaves, and twigs, washing to remove cherry floating on water, drying cherry until 9-12% moisture, dehulling until getting the GCB is obtained, and storing for future analysis (14,29). According to Duarte et al. (31), the skin-dried process produces a fruity, heavy in body, sweet, smooth, and complex flavor. The natural process improves flavors such as fruitiness and sweetness and common notes include strawberry, blueberry, tropical fruits, and red wine-like. The skin-dried process is one method for producing high-quality coffee. It is simple, low cost, few handling steps, less used water, and easy to carry out.

2.2.2 Parchment-dried/ Washed/ Wet Process

According to Sai (14), and Wintgens (15), the parchment-dried (washed) process is used to remove outer skin and mucilage from coffee cherries. The parchment-dried processes include adding water in fresh cherries and pulping them with pulper machine, fermentation, parchment washed and drying coffee beans until they are 9-12 % moisture, de-hulled, and storage. The de-hulling machine consists of a steel screw for removing the pericarp, cleaned defective beans by using winnowing, and scans the same size of green coffee bean together and then storage at the warehouse (15). During de-pulping, the machine removes the outer red skin (exocarp) and white fleshy pulp (mesocarp) and submits to fermentation. Microbes break down the pulp when the samples are fermented. This fermentation takes time over 36 to 48 hours of pH 4.3 - 4.5 that objective to cut off the mucilage parts. This fermentation time also could break down the cellulose in the pulp to relief the coffee beans. Coffee samples have been washed to separate the coffee beans from the pulp. The fermentation takes time, but it gives the best quality (32,33). According to Lee et al. (34) fermentation in water is to assist the removal of mucilage which make a balance and clean cup coffee. Fermentation is expected to have a high flavor and color quality. After fermentation, it is parchment coffee that the seed retains its endocarp layer. The parchment-dried process is another method that produces better cup quality because it can control the acidity of coffee cherries, which has a real impact on the taste of a cup of coffee. The parchment-dried process has a cleaner parchment, a cleaner cup, better taste, pleasant aroma, less prone to fungal attack when compared to other processes.

2.2.3 Mucilage-dried Process/ Semi-dry/ Honey Process

Mucilage-dried (honey) process present stage of both skin-dried and parchment-dried methods, where the coffee cherries are mechanically de-pulped and then straight to the drying tables until MC 9-12%, dehulling until getting the GCB is obtained and storage. The bean is dried quickly, yielding yellow, red, and black honey coffee (14,35,36). Mucilage-dried process has less over-fermentation than skin-dried process, and commonly noted for its overall sweetness likely honey, good body, and more acidity and brightness flavor than parchment-dried process.

2.3 Drying techniques

The drying stage is a crucial postharvest process that significantly impacts coffee's sensory attributes and quality by reducing moisture content and water activity to prevent spoilage and stabilize beans for storage. This stage also influences natural fermentation, during which microorganisms such as bacteria and yeast ferment mucilage sugars, breaking down complex compounds into simpler sugars, organic acids, and phenolic compounds that enhance the coffee’s sweetness, acidity, and complexity (37,38,39). Effective drying is essential for preserving coffee quality, as improper conditions can lead to fungal growth that negatively affects flavor and may introduce harmful toxins (40). Additionally, the drying method influences key chemical components such as total phenols, chlorogenic acids, sucrose, caffeine, amino acids, and antioxidant activity (25,41). Thus, careful microbial management during drying not only preserves quality but also enhances desirable flavors, contributing to food safety (27).

Moreover, environmental conditions influenced the dynamical behavior of yeast inoculation, volatile and nonvolatile compound profiles, and the sensory perception of fermented coffee (42). It has been discovered that naturally, fermented coffee produces slightly higher cup quality than coffee processed by the enzyme as alkali wash and machine wash (43). In coffee peel and mucilage, when de-pulped like honey and washed process could reduce sucrose concentration (42). Bressani et al. (44) obtainable a higher number of volatile compounds with main groups of acids, alcohols,

and aldehydes at the beginning of fermentation, which perception of sensory attributes fruity, nutty, and cocoa. Thus, drying techniques is one of essential, especially for specialty coffee, and contributes to distinctive the aroma and flavor profiles. Ongoing research into controlled drying and post-harvest processing offers pathways to optimize and enhance the quality of specialty coffee, catering to increasingly discerning consumer tastes.

2.4 Coffee Storage

After pre-harvest and post-harvest steps, storage becomes essential to preserving green coffee bean (GCB) quality for long-term warehousing prior to roasting (45). The goal of GCB storage is to maintain commercial value and quality by preserving bean integrity (15, 46). This phase significantly impacts coffee's sensory characteristics by either producing or degrading key compounds (47). Proper storage is crucial for ensuring quality, enabling manufacturers to achieve optimal market prices (48). However, environmental factors during storage can intensify changes in the coffee's physical and chemical properties (48,49), with prolonged periods potentially fostering mold growth and toxin production, affecting both quality and consumer safety (26). Storage conditions could impact moisture content, density, odor, aroma, and flavor, all of which influence the final coffee beverage.

2.4.1 Accelerated Storage Conditions

The accelerated storage technique is widely used to control environmental deterioration, reduce the experimental time required for long-term assessments, and simulate product aging. This method typically manipulates storage conditions such as temperature, humidity, and light to accelerate sensory, chemical, biochemical, and physical changes in the product (50, 51,52). Accelerated storage is particularly useful for studying physicochemical changes in agricultural products and includes tests to predict microbial growth under these conditions (53). Subramaniam (53) also outlined its diverse applications, such as predicting shelf-life, assessing stability, performing abuse testing, troubleshooting, and screening formulations during product development. In coffee research, accelerated storage at 40 °C, 50 °C, and 60 °Cover 20

days has been shown to impact key quality indicators in Robusta beans, including lipid oxidation, acid value, peroxide value, and free fatty acids, with beans stored at 40°C showing better longevity compared to higher temperatures (50). However, no accelerated storage studies have yet been conducted for Arabica beans. Thus, accelerated storage remains an important research tool to monitor and control quality changes, enhancing both scientific understanding and commercial outcomes.

2.4.2 Coffee Packaging

Packaging plays a critical role in maintaining the shelf-life of food products by controlling moisture, humidity, and oxygen, which directly impact product stability (54). For green coffee beans (GCB), no current packaging fully preserves sensory quality during extended storage, highlighting the need for methods to detect chemical changes early (55). The primary GCB packaging options include jute sacks, plastic (polyethylene) bags, hermetic bags (e.g., GrainPro®), and vacuum-sealed bags. Jute bags, the traditional choice, allow gas and water vapor exchange with the environment, which accelerates quality loss, making them unsuitable for specialty coffees (55). Studies show that coffee stored in jute has reduced sweetness and acidity (48). High-density polyethylene bags, often used as liners, help retain moisture and key compounds like chlorogenic acid for up to a year, while hermetic bags like GrainPro® better preserve chlorogenic acids, caffeine, and trigonelline, slowing degradation and enhancing coffee aroma (47,49). GrainPro® has also proven viable for commercial storage for up to 12 months (49). Vacuum packaging, preferred by specialty coffee exporters, extends sensory quality for about nine months (56).

Sensory changes in GCB during storage, primarily due to lipid oxidation, reduce commercial value (55). Initially, sensory differences between permeable and hermetic bags are minimal, but by six months, sensory attributes vary significantly by process type. Natural (dry-processed) coffee stored in permeable bags shows sensory degradation within three months, developing "old crop" flavors by the sixth month. Pulped (honey-processed) coffee, however, maintains quality longer, with notable changes occurring around the ninth month (46). While hermetic and vacuum bags offer clear benefits, cost-effective packaging alternatives, including jute and polyethylene for various processing methods, need further exploration to support market requirements. The advantage and disadvantage of different coffee packaging shown in Table 2.1.

Table 2.1 The Advantage and Disadvantages of Different Coffee Packaging

Package Bags	Advantage	Disadvantage
Jute Bags/ Sisal/ Hessian/ Plastic Woven	• The most cost-effective green bean packing options. • Easy to handle, as well as pack and stack. • Good for gain bioactivities in long-term storage. • High trigonelline & caffeine in cooled storage.	• Jute bags couldn't protect GCB moisture content. • Negative effect on coffee flavors from strong odors • Could be compromised due to mold. • Too long stored, increased water activity, create baggy flavor to coffee. • Unable to control water activity, when changes humidity and environment can occur. • Sweetness & acidity low.
Polyethylene Bags (LDPE / HDPE)	• Used with plastic (impermeable) inside Jute bags good for prolonged storage.	• MC increase during storage • Sensory damage at 3 months. • Color change during storage.
GrainPro/ Hermetic Bag	• Improvement and advancement on jute bags, seal the beans in a stable atmosphere, and protects against insects and fungal contaminants. • Preserve CQAs, caffeine, and trigonelline better than Jute bags. • Maintain quality, exhibit coloration, and preserves the desirable coffee aroma. • Can keep time period 7-12 months, preserve the sensory quality.	• High cost than jute bags • Making handling more difficult.

Table 2.1 (continued)

Package Bags	Advantage	Disadvantage
Vacuum Packing	• Removes all air from the packing bag & preserves coffee flavor for longer. • Keeping beans protected from water and other outside influences that affect quality. • Nine months storage, great influence sensory coffee. • Considered specialty coffee exporters and importers for preservation GCB.	• The most expensive. • Often boxed smaller.

Source (46,47,55,48)

2.5 Coffee Roasting

Coffee roasting is a crucial step for enhancing the quality of green coffee beans (GCB) by transforming their chemical and physical properties to produce the desirable aroma and flavor compounds. This process heats the beans through various stages: drying, browning, and development, which involve key chemical reactions like the Maillard reaction, Strecker degradation, and caramelization (57). The Maillard reaction, between amino acids and reducing sugars, produces essential coffee flavors such as nutty, caramel, and roasty notes, with major transformations occurring at 150-200°C (58,59). Strecker degradation further contributes by forming aroma compounds like aldehydes and ketones. Caramelization, where sugars break down under heat, adds to the sweetness and brown coloration of the beans (59).

The roasting profile, ranging from light to dark roasts, affects the development of coffee flavors. Light roasts are achieved after the "first crack," while medium and dark roasts progress through further pyrolysis and the "second crack," which breaks down cellulose in the bean, resulting in darker color and oil release on the bean surface (60). Each roast level influences volatile compounds responsible for the unique coffee aroma and taste. The choice of roasting level also interacts with the bean’s initial processing method (dry, wet, or honey), which affects the sensory profile and physical properties of the brewed coffee (61).

Roasting-induced changes in color, from greenish to dark brown, and reductions in moisture content result from the formation of melanoidins, which enhance coffee's final aroma and flavor characteristics. The Specialty Coffee Association (SCAA) provides standards for optimal roasting profiles, recommending a minimum roast duration of 8 minutes and a maximum of 12 minutes to achieve premium cupping scores (62). Different roasting and processing methods continue to play a critical role in defining the sensory qualities and market value of coffee (14).

2.6 Physicochemical Properties

The physicochemical properties of coffee are the fragment for coffee quality, aroma compounds, flavor, and taste profiles, which are developed by the coffee varieties, the environment of the coffee plantation, and farming management as soil, climate, husbandry (farming), geographical (latitude and altitude), harvesting, coffee processing, storage, and coffee roasting (14,15,28,61,63).

2.6.1 Physical Properties

The physical characteristic of the green coffee bean influences the quality of the beverage and its additional compounds. The physical properties of green coffee beans are influenced through different coffee processing methods. Density, color index, and Fourier Transform Infrared spectroscopy (FTIR) are critical factors for assessing the physical attributes of coffee.

2.6.1.1 Density

Density, defined as the ratio of mass to volume (64), is a critical parameter in assessing coffee bean quality, impacting separation, trade, packaging, storage, and transport. According to ISO standards, coffee density can be measured as bulk density or true density. Bulk density, an indicator of bean quality, ranges from high (0.68–0.7 g/mL), medium (0.65–0.67 g/mL), to low (0.56–0.64 g/mL), with higher density beans valued for their cell concentration and lower moisture loss during roasting (65). True density, the ratio of bean weight to the volume occupied, ranges from 1.2 to 1.6 g/cm^3 for green coffee beans (GCB) and varies in roasted coffee beans (RCB) from 1.092 to 1.842 g/cm^3 (64,66). During roasting, density affects both heat absorption and roasting

time. Higher density beans retain mass better, aligning with quality traits like sweetness, acidity, and complexity, while lower-density beans tend to lose mass faster and exhibit lower acidity and sweetness in the cup (67). As moisture content decreases, true density declines, particularly at higher roasting temperatures. Thus, density offers insights into bean quality and influences roasting dynamics, with factors like cultivation, processing, storage, and handling impacting GCB density (65).

2.6.1.2 Color

Color plays a crucial role in assessing food quality, particularly for sensory attributes, and can enhance sweetness perception in foods, even serving as a sugar substitute. In green coffee beans, color is influenced by environmental factors, harvesting, drying, processing, packaging, and storage (48,49). As a freshness indicator, green coffee bean color reflects moisture, homogeneity, and essential characteristics for roasting and brewing (14,15). According to de Oliveira et al. (68), assessing color in green beans is crucial for evaluating quality and market value, guiding roasters to select premium beans for enhanced quality and consistency.

Roasted coffee color is a primary indicator of roasting level, ranging from light to dark, with each level corresponding to distinct aroma and flavor profiles (69). The colorimeter, following CIE standards, is used internationally to measure coffee color. A greenish-blue hue signifies high-quality, fresh beans, while yellow-red tones indicate over-drying or high-temperature exposure, reducing quality (15,70). The color also relates to beverage quality by marking oxidative processes and biochemical transformations that affect flavor and aroma precursors (48).

2.6.1.3 Fourier Transform Infrared Spectroscopy (FTIR)

The non-destructive technique involves inspecting, testing, or evaluating characteristics during processing without damaging the original material. This approach is particularly beneficial in the food science and agriculture sectors (71,72). It allows for the measurement of food characteristics, including structural, chemical, and physical properties, as well as sensory evaluations, yielding both quantitative and qualitative data (66,71). Non-destructive evaluation is ideal for food processing and quality control, offering a rapid method that requires minimal sample preparation (73,74). It is essential for assessing the quality of green coffee beans (GCB) and roasted coffee beans (RCB) using techniques like FTIR spectroscopy, electronic noses and

tongues, computer vision, ultrasound, radiography, computed tomography, and magnetic resonance imaging (73,74,75).

FTIR spectroscopy is a non-destructive technique that effectively detects coffee characteristics through sensory analysis (Barrios-Rodriguez et al., 2021). It measures fundamental vibrations in the mid-infrared region (4,000-400 cm^{-1}), which arise from molecular absorption overtones and combinations of fundamental vibrational bands (73). Attenuated Total Reflectance (ATR) is a widely used sampling method in FTIR spectroscopy, capable of identifying different post-harvest processing types and sensory analysis (73). The ATR-FTIR method has been shown to differentiate sensory results from various coffee processing methods (dry, semi-dry, and wet) and roasting conditions (medium and dark), while also providing insights into the chemical composition of green and roasted beans.

FTIR-ATR has been utilized in various studies to analyze coffee, focusing on water activity, moisture content, oxidation, and chemical compounds such as caffeine, lipids, chlorogenic acid, and carbohydrates (73,74). It has also been employed in support vector machine classification for roasted ground coffee and in examining different fermentation techniques for Arabica and Robusta varieties (76). FTIR has proven valuable in predicting the quality of specialty coffees and assessing various sensory characteristics, defects, and geographical classifications of coffee (77,78,79). Furthermore, it has been effective in analyzing coffee compounds related to aroma profiles and volatile compounds, moisture content, and antioxidant capacity (73,80). However, there is limited research on the effects of storage conditions and coffee packaging on these analyses.

2.6.2 Chemical Properties

The importance of coffee chemical properties could evaluate the quality on moisture content, water activity, lipid, lipid oxidation, fatty acids, sugar content (sucrose, glucose, fructose), caffeine, trigonelline, and chlorogenic acid (CGA).

2.6.2.1 Moisture Content (MC)

Moisture content (MC) of process coffee bean is an important quality attribute, regulated by coffee exporting and importing countries. The grain moisture directly affects the storage and roasting process. MC of green and roasted coffee is one of the most significant parameters for good quality that moves coffee tastes (30).

According to Gautz et al. (81) , MC in GCBs is very important because if the coffee has too high or too low in moisture will not preserve high cupping quality. MC more than 12.5 % are more prone to microbial growth (e.g., Ochratoxin A), fermentation, mycotoxin formation, fungal grown and alteration of sensory characteristics which is a risk to human health and also can deteriorate due to bacteria, mold, or yeast and can change enzymatic activity and cupping quality (75,82). Lower than nine percent of MC might shirk, making them look like poor-quality coffee (75). According to Adnan et al. (30), the safety range of moisture content is 8 -12.5%. If the moisture content is below 8%, it can cause contracted beans and an undesirable appearance (30,82). Increasing or reducing MC could impact the character of coffee at the end of the product, such as its color, density, and unpleasant aroma compounds. During storage time, packaging, and roasting steps depend on the MC of the GCB. Therefore, MC is one of the additional standing parameters to keep the fresh coffee in processing, storage, packaging, and roasting steps that need analysis.

2.6.2.2 Water Activity (a_w)

Water activity (a_w) is a factor in the water relations of microorganisms and food processing and storage for food preservation. Several factors in food related to water, such as enzyme activity, lipid oxidation, nonenzymatic browning, microbial growth, spoilage, and preservation (83). Barbosa-Canovas et al. (84) and Troller (83) presented that a_w is a measure for the amount of available water to grow microorganisms, with a value between 0 and 1. A value of 0 means there is absolutely no available water; this is very rare in food and 1 means all water in the product is available, which is pure water. The a_w is essential for safeguarding the green coffee bean during the drying phase of processing and storage to achieve and maintain the coffee quality (85,86). a_w could be explained by the water-matrix interactions evidenced in the correspondent adsorption isotherm as it depends on the specific chemical, structural and cellular properties of the coffee bean (86). Pittia, Nicoli, & Sacchetti. (86) reported that a_w content in GCB was 0.523, and RCB were 0.253 (light roast), 0.214 (medium roast) and 0.207 (dark roast). Specialty coffee association of America (SCAA) has presented that the specialty grade of GCB that water activity should be lower than 0.7. High a_w means more water available to take part in a chemical reaction and can facilitate the growth of molds and fungi and toxic which accelerated the

chemical reaction to lead degradation as oxidation and staling. Too low a_w means there is not enough water available for maintain GCB. Additional, minimum a_w level for germination is 0.8 and 0.85 for mycelial growth (87). The maximum a_w level is 0.95-0.99 for growth Ochratoxin A OTA (85,87). Thus, a_w is the importance of physical properties for checking during coffee processing and storage periods.

2.6.2.3 pH, Total titratable acidity (TA), and total soluble solids (TSS)

In food, scientists measure the acidity of a food based on its pH value (88). Both of pH and titratable acid are interrelated conception in food analysis with acidity (89). Titratable acidity is a measurement of the total acid concentration in food contained. The pH scale ranges from 0 to 14, pH below 7 falls in the acidic range while above pH 7 are considered to be in the basic range (88,89). Acidity is one of the attributes commonly associated with high-quality coffee. pH and TA are important parameters influencing the quality of coffee beverages (90). Both pH and TA are related to the logistic regression models in term of "sourness intensity" through rest on roasting conditions (91). pH varied for widely varying brew strengths and extraction yields and strong position correlation to TA.

pH of GCB values ranges from 5.64 to 5.74 (92) and 5.92 to 6.03 (90). pH of RCB value range between 4.74 to 5.14 related to light, medium and dark roast (91,92). de Novaes & Malta (92) obtainable that low pH values could occur in the de-gumming tank fermentation. During fermentation, acid produced, such as acetic acid, may penetrate the husks' part inducing the changes observed for pH (91). Low pH value in the natural process could be occasioned by the long drying period of about 15 days which may cause undesirable fermentation to the coffee bean, especially unfavorable (92). Low pH coffee is more likely to give the impression of sourness to the untrained taster (91).

Total Soluble Solids (TSS), measured in degrees Brix (°Brix), indicate the concentration of dissolved compounds in coffee, such as sugars, acids, amino acids, and trace amounts of vitamins and phenolic compounds. TSS is a critical measure of coffee quality, influencing sensory attributes like sweetness, body, aroma, and bitterness, which shape the overall flavor profile (93). Typically, higher in roasted coffee due to increased cell breakage that enhances compound dissolution, elevated TSS levels are associated with richer brews and intensified flavors (94). Herawati et al.

(95) reported TSS levels of green beans at 1.47 ± 0.21 g/100mL, with light roast at 2.1 ± 0.07 g/100mL, medium roast at 2.15 ± 0.05 g/100mL, and dark roast at 2.06 ± 0.08 g/100mL. Thus, the study of pH, TA and TSS and its changes during processing, roasting, and brewing provides insights into the chemical transformations affecting coffee's taste and aroma, thus making it a critical measure in quality control and coffee research.

2.6.2.4 Lipids/ Fat

Lipid leads coffee to oxidize and product flavors (63,96). Lipid is crucial on the component of GCB that content ranges from 10% to 15% on a dry basis of Arabica (97,98,99). Lipid content is marked by a chain of chemical bonds CH (98). Lipids are a small amount contained in the wax, and the most significant amount in the endosperm of the coffee bean. The mainly of lipid is triacylglycerol with fatty acids in properties. On the other hands, coffee particle size, surface area, choice of solvent and duration of extraction, processing, drying, storage, and geography origin are the important factor related to coffee lipid (32,63,70,100).

Additionally, it is important to beverage quality because lipid serves coffee aroma and flavors during the roasting process (96). Lipid is odorless and importance by texture (crispness, plasticity, viscosity of liquid), mouthfeel (creamy, oily, richness, smooth, chocolate, butter or baked), appearance (color and opacity), and flavor (aroma and taste like typically fruit and vegetable). Lipids are major coffee components, and changes in their composition during storage contributes to sensorial quality loss. According to Cheng et al. (63), Coffee lipids give the texture and mouthfeel of the beverage as they carry flavors. Roasting does not alteration most coffee lipids; however, they are challenging to retain in the final drink. Lipid content can be affected by environmental factors such as shade, high altitude, temperature, and genotypes of coffee (100). Different environmental and area of the plantation is the leading factory that influences the coffee lipid content, which might impact cup quality.

2.6.2.5 Lipid Oxidative Indexes

Lipid oxidation in food could rise to the formation of unhealthy compounds, negatively affects sensory properties, and reduce food shelf-life and waste foods (101). If low moisture content and a high proportion of unsaturated fatty acid in the green coffee beans, the lipid oxidation and rancidity could be formed and then produce rancid

odors, influencing the nutritional quality and product secondary oxidative that harmful to human health (50). Aung Moon et al. (102) have been reported that lipid oxidation including acid value, free fatty acids, peroxide value, ρ-anisidine value, total oxidation and TBARs are affected on Arabica GCBs of color, flavor and odor. High storage temperature influences the loss of GCB quality and different packaging impact on oxidation for GCB under accelerated storage (102).

Coffee has a high total lipid content of 50% in unsaturated fatty acids highly willing to oxidation. The oxidation would be responsible for the loss of cellular structure, seed viability and sensory changes with increased free fatty acids, TBARS value, and carbonyl groups reduce caffeoylquinic acid concentration and loss color of the coffee bean during storing (45). During storage coffee bean sensory is changes due to start the active lipases, free unsaturated fatty acid and hydroperoxides associated with lipid oxidation (99). Coffee beans, the coffee loss its freshness of tastes and flavor due to some lipid oxidation that degrades some compounds inherent to the typical aroma (103). On the other hand, Kocadagli et al. (104) presented that lipid oxidation is also formed during roasting that tended to increase linearly result of pool non-formed carbonyls with sucrose decomposition. Lipid oxidation and source decomposition are play certain role in acrylamide formation or colorless in coffee.

Lipid oxidation has occurred a loss of quality which increase acid value (AV), ρ-anisidine value (P-AV), peroxide value (PV), TOTOX, thiobarbituric acid (TBARS), free fatty acid (FFA) and decreased iodine value (IV) during accelerated storage Robusta green coffee bean for 20 days (50). Lipid oxidation is oxidation at double bond of fact that led to rancidity, nutrient losses, formation of toxic compounds and colored products due to autooxidation. The lipid oxidates to light-induced oxidation at singlet oxygen reaction that prevent by carotenoids called photooxidation and then lipoxygenase to enzyme oxidation.

Al-Hamamre et at. (105) have described that the extracted oil's AV depends on the extraction solvent. AV is defined as the weight of potassium hydroxide required to neutralize the free acid groups in oil, reflecting the total acidity and number of fatty acids. AV is an important index to assess quality since it measures the content of FFAs formed after hydrolysis degradation of lipids molecules and can be used to specify the degree of rancidity in oil hydrolysis (50). Peroxide value (PV) increase during storage

becomes lipid oxidation because of the initial presence of free radicals in coffee; the roasting process promotes free radical formation associated with pyrolysis reactions (104). Ortola et al. (103), PV oxidation increased depending on storage roasted coffee bean, reaches a plateau between 3 and 5 months until 12 months. Different package includes under vacuum, with low oxygen pressure still presented PV oxidation content (103) PV can be used as an oxidative index for the early stages of lipid oxidation, and higher slower increase in the PV usually accompanies higher oxidative stability. An abundance of primary products, peroxides, and hydroperoxides are formed in oils via autoxidative during the oxidation process (50). PV is main initial products of autooxidation. Autoxidation is related to oxidation induced by air at room temperature and oxygen reacts with unsaturated fatty acids that presented loss flavor quality to product rancid flavor like hay, grassy, green, fishy or sour and change of color and texture. The coffee could be loss of nutritional and could affect to health risk by toxic compounds, growth retardation, and heart disease, etc. Panpraneecharoen & Chumanee (106) have described that PV and FFA are important parameters used to determine the chemical quality of extraction coffee oil because both parameters would increase the oxidation reaction and reduce oil stability and degradation. AI- FFA extracted oil is converted into fatty acid methyl ester (FAME) by base catalyzed esterification, an essential quality parameter for maintaining good product quality. High FFA content increases its susceptibility to oxidation (105). FFA content can be used measure the hydrolysis rancidity that occurs either by enzymatic or spontaneous hydrolysis of triglycerides, and FFA is usually used as an indicator of fat hydrolysis (50).

TBARS test involves the reaction between thiobarbituric acid (TBA) and malonaldehyde (MDA), which is produced by the decomposition of hydroperoxides derived from fatty acids with three or more double bonds during the termination stage of lipid oxidation (45). TBARS is defined by the content of malondialdehyde (MDA) present in one kg of samples and TBARS analysis is the most widely used method to determine the secondary oxidation products that can react with protein, and form polymers (45,50). TBARS is a product to malonaldehyde that red complex to highly correlated sensory scores off-flavor. P-AV analysis is a good method to evaluate the secondary lipid oxidation of the oil. Generally, aldehyde carbonyl bonds are formed during secondary lipid oxidation. TOTAX of coffee oil is determined using the PV and

P-AV values. It comprises primary and second oxidation analyses information and indicates the assessed oils' overall oxidation state (50). Thus, determining lipid oxidation could be described as acid value, iodine value, free fatty acids, and peroxide value products colorless, and odorless, and secondly oxidation as ρ-anisidine value, and thiobarbituric acid (TBARS) could produce odors.

2.6.2.6 Fatty Acids

Fatty acids found in crude oil in form of glycerides, free fatty acid and larger classs in lipids of triglycerides, sterols, tocopherols, diterpenes, ester within fatty acids. Fatty acid is presented in oil extraction. Fatty acids are key components of coffee flavor and aroma that influence coffee quality (107). Fatty acid compositions of GCBs are affected by soil composition, climatic condition, variety type, and elevation (altitude), location of coffee plants and processing (14,108). Fatty acids of coffee lipids are composed mainly of triacylglycerols. The main fatty acids present in coffee oil are saturated fatty acids (Palmitic acid C16:0, Steric acid C18:0, Arachidic acid C20:0) and unsaturated fatty acids (Linoleic acid C18:2, Oleic acid C18:1). Fatty acid of Arabica GCBs from the different countries is shown in Table 2.2.

Palmitic acid (C16:0) and Linoleic acid (C18:2) are the main presented high content on GCBs and roasting bean (14,109). The saturated fatty acid of Palmitic acid (C16:0) on GCBs is affected by elevation that presented a high level in lowland than top land regions (108). The unsaturated fatty acid of Linoleic acid C18:2, Oleic acid C18:1 is influenced by climatic conditions, environment and genotype that affect the final quality of coffee (107). High content on unsaturated fatty acids (Linoleic acid C18:2, Oleic acid C18:1) was less intense acidity, fragrance, body, and flavor. Saturated fatty acids including Palmitic acid (C16:0), Steric acid (C18:0), Arachidic acid (C20:0) are likely discriminators of the quality of specialty coffee showing better sensory quality (107).

Table 2.2 Fatty Acid of Arabica Green Coffee Bean from Different Country

Country	Palmitic acid (C16:0) %	Stearic acid (C18:0) %	Oleic acid (C18:1) %	Linoleic acid (C18:2) %	Arachidic acid (C20:0) %	Reference
China	36.67	7.62	8.85	41.86	2.62	(97)
Indonesia	36.04	7.16	7.90	43.64	2.65	(97)
Kenya	36.67	7.21	8.26	43.04	2.34	(97)
Ethiopia	36.7	6.71	7.76	43.89	2.2	(97)
Guatemala	36.4	6.53	7.58	44.77	2.3	(97)
Honduras	36.67	6.48	7.41	44.69	2.33	(97)
Brazil	34.47	8.93	8.94	39.7	3.03	(107)
Thailand	33.75	7.26	7.72	44.64	3.04	(106)

2.6.2.7 Caffeine, Trignonelline, and Chlorogenic acid content

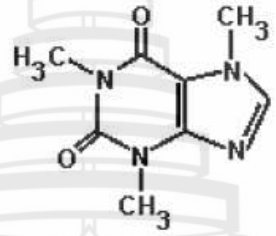
Caffeine, trigonelline and chlorogenic acid are biochemical compounds in coffee that influence coffee flavor, contributing to the acidity and conferring astringency and bitterness (110,111). The biochemical composition of Arabica coffee in caffeine, trigonelline, and chlorogenic acid content is strongly affected by variety, growing environment (112), altitude (113), and processing (114). The caffeine, trigonelline and chlorogenic acid content from different locations of green Arabica coffee are shown in Table 2.3.

Table 2.3 Green Arabica Coffee of Caffeine, Trigonelline and Chlorogenic Acid Content

Location	Caffeine	Trigonelline	Chlorogenic acid	Reference
Ethiopia	0.96-1.62 % dmb	0.88-1.77 % dmb	0.29-0.52 % dmb	(115)
Meru, Kisii, & Kericho	1.01-1.54 % dmb	0.95-1.34% dmb	4-8.4% dmb	(112)
Brazil	1.45 g/100g	1.39 g/ 100g	6.79 g/100g	(116)
Adet	1.362%	0.982%	4.365%	(114)
Woramit	1.33%	1.095%	4.52%	(114)
Doi Chang	1.2-1.26 % dry weight	-	4008-4453.5 mg/100g dry weight	(25,41)
Chiang Mai	1.73 mg/g	0.99 mg/g	-	(117)

1. Caffeine

According to Toschi et al. (118), caffeine is the major constituent in coffee that maintains the final quality coffee beverage. Caffeine provides bitterness attributes to coffee quality and is important to determining coffee flavor due to an alkaloid and a nitrogenous secondary metabolite (113). Caffeine is ranged of 0.92-1.62% (113,115). Arabica coffee's caffeine has less content than Robusta. Low-level altitude (1,100-1,200m) of Arabica coffee farm at Teppi is presented caffeine content in 16.42 mg/g high than high level 1,750-1,775m at Jimma (14.48 mg/g) and 1,940-1,960 m at Gera (13.08 mg/g) (114). The chemical formula for caffeine is $C_8H_{10}N_4O_2$ and the chemical structure is shown in Figure 2.3.

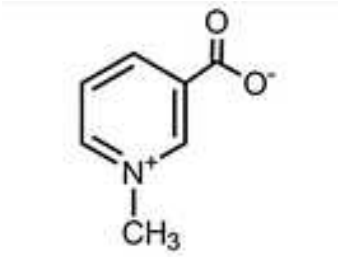


Source (112)

Figure 2.3 Structure of Caffeine

2. Trigonelline

Trigonelline is a natural component in green coffee beans. Trigonelline level in green coffee beans is very significant for the final quality of production and helpful to know the quality of the coffee. Trigonelline is a bitter alkaloid that produces aroma compounds with flavor formation during roasting (119). According to Martin et al. (120), Trigonelline content in the green coffee bean range is 1.24-1.92% on w/w dry base. Trigonelline is mainly related to degradation during roasting that gives several volatile compounds. Trigonelline is derived from the methylation of the nitrogen atom of nicotinic acid, hypolipidemic, sedative, anti-migraine, anti-bacterial, and anti-viral, anti-tumor effects, and potency to improve memory retention and inhibit platelet aggregation (111). Trigonelline content almost 50% of volatile compounds degraded during roasting forming of compounds, namely nicotinic acid, pyridine, 3-methyl-pyridine, and methyl ester of nicotinic acid (94). Trigonelline chemical formula $C_7H_7NO_2$ and the structure of trigonelline showed in Figure 2.4.



Source (112)

Figure 2.4 Structure of Trigonelline

3. Chlorogenic acid (CGA)

Chlorogenic acid is the most prevalent phenol compound found in coffee and the main component that is important for flavor formation (121). The CGA of Arabica coffee has reported a range of 3.5-7.5% of dry matter basis (122), and 2.2 mg/g (121). The content of CGA in coffee extract depends on the species/ variety, and the processing (121, 123). Arai et al. (111) presented that CGA exhibits various biological properties including antibacterial, antioxidant, and anti-carcinogenic activities, particularly hypoglycemic and hypolipidemic effects. GGA, due to the IUPAC system, is a family of esters formed between caffeic acid and (-)-quinic acid. CGA is generally referred to a 3-caffeoylquinic acid (3-CQA), 4-caffeoylquinic acid (4-CQA), 5-caffeoylquinic acid (5-CAQ), 3,4- Di caffeoylquinic acid (3,4-diCQA), 3,5-dicaffeoylquinic acid (3,5-diCQA), 4,5-dicaffeoylquinic acid (4,5-diCQA), 3-ferulolquinic acid (3-FAQ), 4-ferulolquinic acid (4-FAQ), and 5-ferulolquinic acid (5-FAQ) (115,122,123). Chlorogenic acid (CGA) has been associated with the possible health benefits of drinking coffee.

2.6.2.8 Sugar Content

Sugar content is one of the very important compounds in the coffee cherry, mucilage, and pulp until getting green coffee, during processing the microorganism's consumption and breaking them into the cellular structure (39). Sugar content is known as sucrose (non-reducing sugar), and glucose, and fructose (reducing sugar) content which are vital components for aroma and flavor formation during roasting of Maillard and Strecker and degradation reactions (41,124). Maillard reaction is the main of aroma formation in coffee, amino acids and reducing sugars react to form nitrogenous

heterocycles and brown melanoidins to impact the sweetness, and simple carbohydrates (125). This non-enzymatic browning produces hundreds of volatile compounds and sensory attributes. Therefore, controlling sugar and amino acid is processed for to aroma generation and the final flavor of the coffee. High content in sucrose in GCB presented more intense in coffee cupping (125), and flavor precursors (124).

Knopp, Bytof, and Selmar (126) have reported that Arabica GCB from Brazil content at sucrose 7.07 % d.m., fructose 0.39% and glucose 0.23%. Dry processing has a high content in fructose and glucose than wet and semi-washed processing due to de-pulping, washing and fermentation. After fermentation of endosperms step, the sucrose, fructose, glucose and also caffeine concentrations are decreased due to extended fermentation time to drop sugar content concentration and increase the acetic acid, ethanol, glycerol, glucuronic acid, lactic acid, mannitol, and succinic acid concentrations (28,34). Environmental conditions favored the enzymatic of fungal population to hydrolyze which could produce reducing sugars such as glucose, fructose and sucrose on the GCB surface (127).

According to Somporn et al. (124), fructose of Arabica coffee is found largest portion of 0.132 g/kg in sun shading condition than 50%, and 0.124 g/kg, and 0.11 g/ kg for 60% and 70% shade, respectively. However, glucose and sucrose are not detected in full sun and 70% shade. Glucose content range between 0.43-0.051 g/kg and sucrose range in 0.013-0.083 g/kg. Reducing sugars are directly related to respiratory activity that effect of elevated electrical conductivity and potassium lixiviation of bean during storage (33). During storage one year, storage leads to fungal population and change the sugar content and other properties like a_w, MC, and OTA production (127). Glucose and fructose of sugar content decreased slightly in storage and glutamine content declined (128). Thus, sucrose, glucose, and fructose are important content in varieties, environment (124,127), coffee processing (28,126), storage time (49,128), and roasting condition (41,127) for final coffee quality.

2.7 Aroma Profiles/ Volatile Compounds

Aroma compounds are volatile molecules that create the sense of smell during the eating process, reaching the olfactory receptors (129). According to Caporaso et al. (61), coffee aroma is a crucial attribute responsible for the flavor characteristics of specialty coffee, often outweighing other taste factors such as sweetness, bitterness, and acidity. The aromatic profile develops through a complex series of thermal reactions during roasting, which transforms the chemical and physical properties of green coffee beans and leads to the degradation of volatile compounds (57). Key reactions involved in this process include the Maillard reaction, which produces a range of flavors such as buttery, nutty, and caramel-like notes (58), and caramelization, which releases aromatic and acidic compounds (59). During roasting, various compounds are formed, including acids, organic acids, alcohols, aldehydes, esters, furans, ketones, phenols, pyrazines, pyridines, heterocyclics N, terpenes, pyrroles, sulfurous compounds, sulfide and other compounds (14,61,130). The identification of volatile compounds with sensory and odor description in roasted coffee beans shown in Table 2.4.

The content of these volatile compounds can be influenced by factors such as coffee seed variety, roasting profiles, and storage packaging (131,132). Caporaso et al. (61) highlighted that volatile compound concentrations are affected by the degree of roasting and the green coffee composition, which is determined by species, geographical origin, and processing methods. Lighter roasted coffees can be distinctly identified from darker roasts, with the roasting degree significantly impacting the coffee's geographical origin (61,131,132). Yang et al. (130) identified specific volatile compounds associated with roasting defects, such as indole for light defects and phenol for dark defects.

For analyzing volatile compounds in coffee, solid-phase microextraction coupled with gas chromatography/mass spectrometry (SPME-GC-MS) is considered one of the most effective methods (133,134). This technique allows for accurate measurement of volatiles directly from the headspace, preserving the integrity of aroma compounds. When combined with GC-MS, SPME effectively captures subtle variations in aroma compounds that occur across different post-harvest processing

techniques (61,135). Utilizing principal component analysis (PCA) alongside SPME-GC-MS enhances the examination of complex data sets, identifying patterns and correlations between specific volatiles and processing conditions (134,136). This analytical combination is invaluable for sensory analysis and optimizing coffee production practices to align with consumer preferences, making it an essential tool in quality control and research on coffee's sensory attributes.

Table 2.4 Identification of Volatile Compounds with Sensory and Odor Description in Roasted Coffee Bean

RT	Volatile Compound	Sensory and Odor Description	Identification methods	Chemical Group
1.29	Acetaldehyde	Pungent, fruity	MS	Aldehyde
1.79	2-Methylfuran	Pungent, fruity	MS, L	Furan
2.09	3-Methylbutanal	Fruity, malty	MS	Aldehyde
2.25	3-Methylbutanal	Malty	GC-MS	Aldehyde
2.28	2-Methylbutanal	Malty	GC-MS	Aldehyde
2.65	2,3-butanedione	Buttery	MS, L	Ketone
2.7	2,5-Dimethylfuran	Ethereal	GC-MS	Furan
3.08	2,3-Butanedione	Buttery, cheesy	GC-MS	Ketone
3.77	2,3-Pentanedione	Buttery, oily, caramel-like	MS, ST, L	Ketone
4.12	Hexanal	Green, grassy, fruity	MS, ST	Aldehyde
4.88	2,3-Pentadione	Oily buttery	GC-MS	Ketone
5.00	Dimethyl disulphide	Onion	GC-MS	Sulphide
5.22	2-Vinylfuran	Ethereal, rum, cocoa note	GC-MS	Furan
5.24	1-Methyl-1H-pyrrole	Smoky, woody, herbal	MS, ST	Heterocyclic N
5.35	Hexanal	Grassy, green oily	GC-MS	Aldehyde
5.54	3-Methylthiophene	Ash	GC-MS	Sulphide
6.13	Pyridine	Sour, putrid, fishy, amine, bitter, roasted	MS, L	Heterocyclic N
6.95	Pyrazine	Cooked spinach, rancid peanuts, storng	MS, L	Pyrazine
7.33	2,3-Hexandione	Buttery, cheesy, sweet, creamy	GC-MS	Ketone
8.4	2-Methyl-pyrazine	Nutty	MS, ST	Pyrazine
8.83	Pyridine	Bitter, astringent, roasted, burnt	GC-MS	Heterocyclic N
8.98	3-Hydroxy-2-butanone	Sweet, buttery, creamy	MS, ST,L	Ketone
9.42	Acetol	Nutty, roasted, grassy	MS	Ketone
10.03	2,5-Dimethylpyrazine	Chocolate, cocoa, roasted nuts, fried	MS, ST, L	Pyrazine
10.22	2,6-Dimethylpyrazine	Nutty, peanut, butter	MS, ST, L	Pyrazine
10.39	Ethylpyrazine	Nutty, roasted	MS, ST	Pyrazine
10.8	2,3-Dimethylpyrazine	Sweet, coffee	MS, ST, L	Pyrazine
11.83	Furfuryl methyl ether	Nutty, coffee grounds-like, rich, phenolic	GC-MS	Ether

Table 2.4 (continued)

RT	Volatile Compound	Sensory and Odor Description	Identification methods	Chemical Group
11.66	1-Hydroxy-2-butanone	Tobacco, oak, moss, leather	MS	Ketone
11.72	3-Ethylpyridine	Flowery, fruity, hazelnut-like	MS	Heterocyclic N
11.99	2-Ethyl-6-methylpyrazine	Cooked spinach, rancid peanuts, storng	MS, ST, L	Pyrazine
12.12	2-Ethyl-5-methylpyrazine	Coffee-like	MS, ST, L	Pyrazine
12.53	2-Methylpyrazine	Nutty, roasted, chocolate	GC-MS	Pyrazine
12.58	2-Ethyl-3-methylpyrazine	Nutty, peanut, butter	MS, ST, L	Pyrazine
12.70	Dihydro-2-methyl-3-furanone	Sweet, roasted	GC-MS	Ketone
13.57	2,3-Diethylpyrazine	Raw, nutty, green pepper	MS, L	Pyrazine
14.17	Acetic acid	Pungent, vinegar	MS, ST, L	Acid
14.58	Furfural	Sweet, woody, almond	MS, ST, L	Aldehyde
14.84	Acetoxyacetone	Fruity, buttery dairy	MS	Ketone
14.96	2,5-Dimethylpyrazine	Nutty, roasted, grassy, corn	GC-MS	Pyrazine
15.21	Furfurylmethyl sulphide	Onion, garlic, sulfuraceous	MS	Sulphide
15.27	2,6-Dimethylpyrazine	Nutty, sweet, fried	GC-MS	Pyrazine
15.38	2-Ethyl-3,5-dimethylpyrazine	Earthy, roasted	MS, L	Pyrazine
15.55	Furaneol	Caramel, sweet	TI	Ketone
15.59	2-Ethylpyrazine	Nutty, roasted	GC-MS	Pyrazine
15.70	2-Acetylfuran	Sweet, balsam, almood, cocoa	MS, L	Furan
16.03	2,3-dimethyl Pyrazine	Nutty, roasted, green	GC-MS	Pyrazine
16.76	Ethyl propanoate	Sweet, fruity, rum, juicy	TI	Ester
16.96	2-Furanmethanol acetate	Etheral-floral, herbal-spicy	MS	Acetate
16.99	Propanoic acid	Pungent, acidic, cheesy, vinegar	MS	Acid
17.42	Dimethyl trisulphide	Onion	GC-MS	Sulphide
17.86	5-Methylfurfural	Spice, caramel, maple	MS, ST	Aldehyde
17.86	2-Ethy-6-methylpyrazine	Roasted, hazelnut-like	GC-MS	Pyrazine
18.19	2,3-Butanediol	Fruity, creamel, buttery	MS	Alcohol
18.59	Trimethyl pyrazine	Nutty, roasted	GC-MS	Pyrazine
19.13	2-Formyl-1-methylpyrrole	Roasted, nutty	MS	Pyrrole
19.25	γ-Butyrolactone	Creamy, oily, fatty, caramel	MS	Ketone
20.70	2-Furanmethanol	Caramellic, burnt, smoky	MS, ST, L	Alcohol
20.96	3-Methyl-butanoic acid	Cheesey, dairy, creamy, fermented	MS, L	Acid
21.81	2-Furfural	Bread, almond, sweet	GC-MS	Aldehyde
22.23	N-Acetyl-4(H)-pyridine	(Not available)	TI	Heterocyclic N
22.91	3-Hydroxy-4.5-dimethyl-2(5H)-furanone	Buttery, seasoning-like	TI	Ketone
22.94	Acetic acid	Sour	GC-MS	Organic acid
23.37	2-Acetylfuran	Balsamic-sweet	GC-MS	Organic acid

Table 2.4 (continued)

RT	Volatile Compound	Sensory and Odor Description	Identification methods	Chemical Group
23.41	3-Methoxy-5-methyl-2-cyclopenten-1-one	(Not available)	TI	Ketone
23.98	3-Methyl-2-butenoic acid	Green, phenolic, dairy	MS	Acid
24.11	Pyrrole	Nutty, hay-like, herbaceous	GC-MS	Heterocyclic N
24.43	3-Methyl-1,2-cyclopentanedione	Spice, carmellic, maple, sweet, burnt	MS	Ketone
24.89	Guaiacol	Phenolic, burnt, smoky	MS, ST, L	Phenolic
26.25	2-(1H-pyrrol-2-yl)-ethanone	Smoky, spicy	MS	Ketone
26.77	1H-pyrrole-2-carboxaldehyde	Musty, beefy, coffee	MS	Heterocyclic N
26.86	4-Ethylguaiacol	Spicy, phenolic, sweet	MS, ST, L	Phenolic
28.28	4-Vinylguaiacol	Clove	MS, ST, L	Phenolic
30.33	Furfuryl alcohol	Burnt	GC-MS	Alcohol
26.60	Phenol	Phenolic, plastic, rubber, smoky	MS	Phenolic
31.3	Butanoic acid	Sour	GC-MS	Organic acid
31.3	Hexanoic acid	Fatty-rancid, acrid acid	GC-MS	Organic acid
35.11	2-Furfuryl methyl disulphide	Coffee-like	GC-MS	Sulphide
36.22	1-Furfurylpyrrole	Hay-like, mushroom-like, green	GC-MS	Heterocyclic N
40.76	Maltol	Caramel	GC-MS	Alcohol
41.16	1-(1-H-pyrrol-2-yl) ethanone	Nutty, musty	GC-MS	Ketone
41.81	Di furfuryl ether	Coffee-like, toasted odor	GC-MS	Ether
42.65	Phenol	Smoky	GC-MS	Phenolic
43.21	4-Ethyl-2-methoxyphenol	Smoky, spicy	GC-MS	Phenolic
45.25	Octanoic acid	Sweet cheesy	GC-MS	Organic acid
55.02	Indole	Burnt, mothball	GC-MS	Heterocyclic N

Note RT = retention time; MS = mass spectra; ST = using standard; TI = tentative identification, L = literature; GC-MS = gas chromatography-mass spectrometry

Source (61,130)

2.8 Cupping and Sensory Evaluation

Cupping tests and sensory evaluations are essential methods for assessing the market suitability of food and beverage products, focusing on attributes such as color, aroma, taste, and mouthfeel (137). In particular, quality cupping is the standard practice for evaluating the taste and flavor of roasted coffee beans, playing a critical role in determining both the quality of the roast and the final product (138). The Specialty

Coffee Association of America (SCAA) cupping protocol is the most widely adopted method in the specialty coffee industry. This protocol evaluates coffee quality based on various sensory attributes, including fragrance, flavor, aftertaste, acidity, body, balance, sweetness, uniformity, and cleanliness (62). Description of the cupping terms shown in Table 2.5 The standardized scoring system enhances consistency across studies, facilitating comparisons of coffee quality based on diverse origins, processing methods, drying techniques, storage, and roasting profiles.

According to the SCAA protocol, cupping is conducted by a minimum of three Q-graders, with coffee samples prepared by roasting and cupping them within 24 hours. The roasting level ranges from light to medium, and the ground coffee is checked for color at 63±2 on the Agtron scale. Each sample is prepared with five cups, each containing 8.25 grams of coffee steeped in 150 mL of hot water at 93°C. The coffee is ground to a 20-mesh size immediately before cupping, ensuring that grinding occurs no more than 15 minutes prior to infusion. Clean, odor-free water with a total dissolved solids level of 125-175 ppm is used for the cupping process. During evaluation, the fragrance of the dry ground coffee is assessed first, followed by aroma once hot water is added. The sensory attributes of flavor, acidity, body, balance, aftertaste, sweetness, uniformity, cleanliness, and overall quality are scored using the SCAA cupping form within 45 minutes. Scores range from 6.00 to 9.75, categorized as follows: good (6.00-6.75), very good (7.00-7.75), excellent (8.00-8.75), and outstanding (9.00-10.00). A final score below 80 points indicates a coffee is not classified as specialty grade, whereas a score above 80 is considered specialty quality, further classified into very good (80-84.99), excellent (85-89.99), and outstanding (90-100).

Table 2.5 Description of Cupping Terms

Terms	Description
Fragrance	The fragrance is presented as the smell of dry ground coffee.
Aroma	The aroma aspects of the ground coffee smell when filled with hot water.
Flavor	Flavor is the coffee principal character as taste and aroma, mid-tons of coffee.
Aftertaste	The aftertaste is defined as the length of positive flavor (taste and aroma) quality starting from the back of the palate and remaining after the coffee is expectorated or swallowed.
Acidity	Acidity is described as brightness when favorable or sourness when unfavorable. The best acidity gives like liveliness, sweetness, and fresh-fruit character.
Body	Body quality is based upon the tactile feeling of the liquid in the mouth, mainly as observed between the tongue and roof of the mouth. Heavy body samples may also high score in terms of quality and a lighter body sample presents a pleasant feeling.
Balance	Balance is how all the various aspects of sample's flavor, aftertaste, acidity, and body work together and complement or contrast to each other.
Sweetness	Sweetness refers to a pleasing fullness of flavor as well as any apparent sweetness, and its perception is the result of the presence of certain carbohydrates.
Clean Cup	Clean cup refers to a lack of interfering negative impressions from first ingestion to final aftertaste, cup transparency.
Uniformity	Uniformity refers to the stability of flavor of the different cups of the samples tasted. If the cup's taste is different, the rating of this aspect would not be as high.

Source (62)

2.9 Coffee Shelf-Life

Coffee shelf-life refers to the period during which it retains acceptable sensory, physicochemical, and nutritional quality under specific storage conditions. The stability of coffee is dependent on its form raw coffee (green, roasted, or ground), roast degree, and packaging system. Roasted beans shelf-life typically keeps on fresh for 2 to 8 weeks at room temperature, however green coffee beans could last 6 to 12 months with high barrier packaging like vacuum sealed or nitrogen flushed bags (47,48,93). Ground roasted coffee is more susceptible to oxidation and has a larger surface area, which results in a more rapid deterioration within two weeks of opening (139). Packaging innovations such as oxygen-barrier layers and one-way degassing valves help mitigate oxidation by releasing CO_2 while blocking oxygen entry (131,140). In roasted coffee, particularly darker roasts, flavor degradation is often linked to surface oil oxidation and ester hydrolysis caused by high-temperature processing (60,61), resulting in increased bitterness and sourness with diminished fruity and sweet notes (141).

The shelf-life of green coffee beans (GCB) is substantially affected by post-harvest biochemical conditions, packaging type, and environmental factors. Mechanical damage, oxygen exposure, and drying rates influence storage stability, whereas elevated water activity (a_w) fosters microbial growth and accelerates oxidative deterioration (142). Effective regulation of water activity is crucial to prevent enzymatic browning, oxidation, and spoilage. Packaging plays a critical role, as LDPE bags offer limited protection compared to high-barrier options like GrainPro®, leading to faster quality loss (47,48). To better predict coffee stability during storage, kinetic shelf-life models based on first-order reaction rates and the Arrhenius equation have been developed. These models utilize CO_2 evolution and degradation kinetics to estimate remaining shelf-life under different conditions (143,144). Supercritical CO_2 treatments have also been explored to prolong shelf-life up to a year by improving microbial and oxidative stability. Additionally, understanding water sorption isotherms provides insight into moisture equilibrium and helps define safe storage parameters (145). However, conducting these studies under real-time conditions can be time-

consuming, making accelerated testing methods essential for practical shelf-life prediction.

Subramaniam (53) describes accelerated shelf-life testing as a quick way to forecast shelf-life, screen formulations, and diagnose stability concerns. Cong et al. (50) found that storing Robusta green beans at 40-60 °C for 20 days led to an increase in lipid oxidation markers such acid value, peroxide value, and TBARs. However, quality declined faster at higher temperatures. Lipid oxidation not only alters flavor, but it can also produce toxic substances and contribute to food waste and reduce the shelf-life (101). Manzocco et al. (146) observed that quality loss during storage is caused by a mix of physical and chemical changes such as volatile loss, ester hydrolysis, non-enzymatic browning, and oxidative processes. Using kinetic models and the Arrhenius equation, one might measure reaction rates and estimate shelf-life in both real-time and accelerated storage scenarios. Cong et al. (50) employed zero- and first-order models to forecast changes in peroxide value and found that shelf-life decreased from 57 days at 40 °C to 23 days at 60 °C in Robusta coffee beans.

The integration of kinetic models with the Arrhenius equation is central to accelerated shelf-life testing. These tools simulate long-term storage effects in a shorter time by exposing coffee to elevated temperatures and monitoring degradation markers. By plotting reaction rate constants against temperature (via Arrhenius plots), researchers can predict shelf-life under normal storage conditions. This approach not only accelerates stability assessment but also helps optimize packaging, processing, and storage strategies for preserving coffee quality over time. Thus, understanding shelf-life is key to maintaining coffee quality, ensuring product consistency, and meeting consumer expectations. Combining advanced packaging, kinetic modeling, and accelerated testing offers an effective strategy to preserve quality, reduce waste, and extend freshness.

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CHAPTER 3

METHODOLOGY

3.1 Raw Materials

Fresh coffee Cherries (*C. Arabica, mixed varieties*) were harvested from two highland farms located in Northern Thailand: Phak Phum Coffee Farm, Doi Chang, Chiang Rai (1,250-1,300 m above sea level), and Phu Pha Coffee Estate Farm, Doi Thep Sadet, Chiang Mai (1,300-1,400 m above sea level). The cherries were collected during the main harvesting seasons from 2021 to 2023. Both locations are recognized for their favorable agroclimatic conditions and consistent production of specialty grade Arabica coffee.

To ensure uniformity, only fully ripe cherries were manually selected based on external color and firmness. Immediately after harvest, the cherries were sorted to remove defective, underripe, overripe, and floating fruits. The selected cherries were then subjected to three commonly processing methods in the region: dry (natural), wet (washed), and honey processing. All processing procedures were conducted under controlled conditions to minimize variability and ensure consistency across the different experimental phases of the study.

3.1.1 Chemicals and equipment's

Table 3.1 and 3.2 are a list of all the chemicals and equipment that are used for analysis in this studying.

Table 3.1 Chemicals lists

Parameters	Chemicals
Lipid content	Petroleum ether (70 mL)
Prepared Oil samples	Petroleum ether
Acid Value	Ethanol, Potassium hydroxide, Phenolphthalein
p-Anisidine Value	2,2,4-trimethylpentane, p-Anisidine
Peroxide Value	Potassium iodide, Sodium thiosulfate, Hydrochloric acid, Potassium dichromate, Starch, Acetic acid, Chloroform
TBARS	Trichloroacetic acid, Polyvinylpolypyrrolidone Thio barbituric acid
Fatty acid	Methanolic sodium hydroxide, Anhydrous sodium sulfate, Helium (He), Hydrogen (H), n-hexane
Sugar	Sucrose standard, Glucose standard, Fructose standard, Acetonitrile
Caffeine, Trigonelline, CGA, Caffeic acid	Caffeine standard, Trigonelline standard, CGA standard, caffeic acid standard, Methanol HPLC grade
Aromatic profile	15% diphenyl 3-Heptanone 95% dimethylpolysiloxane Helium, Methanol

Table 3.2 Equipment lists

Equipment	Model	Manufacturer
Digital balance 4 digits	ML 204/01	Mettler Toledo, Switzerland
Hot air oven	UNB 500	Becthai Bangkok Equipment and Chemical, Thailand
Vortex	G506E	Scientific industries, inc, USA
Centrifuge	Thermo Fisher Scientific,	Osterode, Germany
Refrigerator	Mitsubishi Tiara	Mitsubishi, Bangkok, Thailand
Soxhlet extraction	Foss/ Soxtec TM-2055	Foss Analytical, Slangerupgade, Denmark
Colorimeter	Hunter LAB/ Color Quest XE	Hunter Associates, Laboratory, VA, USA
Blender	HR 2011	Philips's electronics, Suhou, China
Water bath	Memment/ WB 14	Memment, Shwabach, Germany
Storage Chamber	Constant Climate Chamber HPP	Bangkok High LAB, Thailand
UV-VIS Spectrophotometer	Thermo Scientific AquaMate 7100	Thermo Scientific, Bangkok, Thailand
Evaporator	Rotary Evaporator Lab	UK
Ultra-Sonic Bath	Gowe 6.5L 40Hz 150w Nr.JP-031S, 180/200W, 220-240V, 50Hz Ultrasonic Cleaner	RSPRO, Thailand
FTIR	ATR-FTIR spectroscopy analysis	Agilent, Santa Clara, California, USA
pH meter	Benchtop, meter, pH, ph700	NIST, USA
Water activity analyzer	Meter Group, Inc. 13893-05	Aqualab Meter Group, Inc.
Camera	DSLR camera	Canon EOS 800

Table 3.2 (continued)

Equipment	Model	Manufacturer
Gas chromatography	Agilent, GC; 6890N/ MS; 5973	Agilent Technologies, Inc.
HPLC	Water Acquity UPLC H-Class System & Waters Acquity System	Milford, Massachusetts, USA & Shimadzu, LabSolutions, Tokyo, Japan
Roasting Machine	HB-L2 Roaster, & IKAWA Pro 3	The Coffee Company, Ltd., Hong Kong, China, & IKAWA Ltd., London, United Kingdom

3.2 Overall Methodology

Figure 3.1 presents the overall methodological framework of this study, which was divided into three experimental stages: 1 investigation of the influence of post-harvest processing methods and drying techniques on coffee quality, 2 evaluation of the acceleration storage and packaging materials on shelf-life and quality of green coffee, and 3 assessment of the effect of roasting profiles and accelerated storage of roasted coffee quality. Detailed descriptions of the experimental design and analytical parameters for each stage are provided in Chapters 4 through 8.

3.2.1 Influence of Post-Harvest Processing and Drying Techniques

The study on the influence of post-harvesting processing and drying techniques was conducted using coffee cherries collected from Phak Phum Coffee Farm, Doi Chang, location Chiang Rai at an altitude of 1,250-1,300 meters above sea level. The coffee samples consisted of mixed *caffea arabica* cultivars, including *catimor*, *caturra*, *catuai* and *bourbon* harvested during the 2022-2023 season. This experiment result and detailed discussion are presented in chapter 4 and 7.

This study evaluated the effects of three common post-harvest processing methods: dry (DP), washed (WP), and honey (HP) in combination with three drying techniques: controlled environments drying (CED), sund drying (SD) and fast drying (FD). The CED treatment was carried out under controlled conditions of 20 to 30 °C, and 50-55 % of RH, whiles the FD condition was maintained at 30-40 °C, and 50-55 % RH. The SD condition was based on ambient environmental conditions in Chiang Rai

Province (see Table 4.1 and Figure 4.3). A schematic overview of each processing procedure is provided in Figure 7.1.

In Chapter 3, both green and roasted coffee beans were analyzed for several physicochemical properties. These included color parameters (CIE L*a*b* color scale, as described by Wongsa et al. (1), true density according to Chandrasekar & Viswanathan (2), moisture content, AOAC, 2000; Method 979.12 (3), and water activity by Akbar et al. (4). Key chemical constituents such as caffeine, trigonelline, chlorogenic acid, and caffeic acid were quantified using reverse-phase HPLC as a Cordoba et al. (5), while sugars (sucrose, glucose, and fructose) were determined using HPLC according to Constantino et al. (6).

In Chapter 7, additional chemical analyses were conducted, including measurement of pH and total soluble solids (TSS) following the method of Koskei et al. (7), and titratable acidity based on the protocol by Anokye-Bempah et al. (8). Volatile aroma compounds were identified and quantified using solid-phase microextraction gas chromatography–mass spectrometry (SPME-GC-MS), following established methods by Franca et al. (9) and Caporaso et al. (10). These included compounds from various chemical classes such as pyrazines, ketones, aldehydes, nitrogen heterocycles, esters, acids, alcohols, and furans. Sensory evaluation was performed in accordance with the Specialty Coffee Association of America (SCAA, 2015) cupping protocol, assessing attributes such as fragrance/aroma, flavor, aftertaste, acidity, body, balance, uniformity, clean cup, sweetness, overall impression, and presence of defects (11).

3.2.2 Accelerated Storage and Package of Green Coffee Bean Quality

The second stage of this research focused on evaluating the effects of accelerated storage conditions and packaging materials on the quality and shelf-life of green coffee beans (GCB). Coffee cherries were sourced from Phu Pha Coffee Estate, Doi Thep Sadet, Chiang Mai, located at an altitude of 1,300–1,400 meters above sea level. Mixed *Coffea arabica* cultivars were harvested during the 2021–2022 season. Experimental design and findings related to this study are detailed in Chapters 5 and 6. Green coffee beans processed by dry (DP), wet (WP), and honey (HP) methods were used for the accelerated storage study. A total of 250 g of each processed coffee type was packed in three different packaging materials: plastic woven (PW), low-density

polyethylene (LDPE), and GrainPro® (GP) bags. The samples were stored under accelerated conditions in a Constant Climate Chamber (HPP750, Memmert GmbH, Schwabach, Germany) at three temperature levels: 30 °C, 40 °C, and 50 °C, with a constant relative humidity (RH) of 50%. Sampling was conducted at five-day intervals (0, 5, 10, 15, and 20 days). Following each interval, samples were vacuum-sealed in polyethylene packaging and stored at −80 °C in an ultra-low temperature freezer (MDF-193, SANYO, Tokyo, Japan) until analysis. Day 0 samples (controls) were unprocessed by packaging and were used to determine the initial quality parameters of the GCB.

In Chapter 5, physicochemical properties of WP green coffee stored in PW, LDPE, and GP (illustrated in Figure 5.1) were analyzed. Parameters included moisture content (3), water activity (4), color (5), and lipid content via Soxhlet extraction, AOAC, 2000; Method 920.39 (12). Lipid oxidation was the primary focus, analyzed acid value and free fatty acid content, AOAC, 2000; Method 940.28 (13), and peroxide value, AOAC, 2000; Method 965.33 (14). Secondary oxidation markers included p-anisidine value according to Cong et al. (15) and thiobarbituric acid reactive substances (TBARs) as a Redon et al. (16). Total oxidation value (TOTOX) was calculated based on the method according to Cong et al. (15). Fatty acid composition including palmitic, linoleic, oleic, stearic, and arachidic acids was determined by GC-MS, following protocols outlined by Nielsen (17) and David et al. (18). Saturated fatty acids (SFA), unsaturated fatty acids (USFA), and total fatty acids (TFA) were also quantified.

In Chapter 6, green coffee beans from DP and HP were further evaluated using similar analytical methods, with a focus on moisture content, water activity, peroxide value, and TBARs. In addition, kinetic modeling was applied for shelf-life prediction using the Arrhenius equation, as described by Cong et al. (15) and Manzocco et al. (19). Furthermore, attenuated total reflectance–Fourier transform infrared spectroscopy (ATR-FTIR) was employed as a non-destructive analytical technique to monitor lipid oxidation during accelerated storage according to Barrios-Rodriguez et al. (20). Chemometric tools, including partial least squares (PLS) regression and principal component analysis (PCA), were applied to correlate spectral data with conventional lipid oxidation indicators, thereby supporting shelf-life estimation and predictive modeling.

3.2.3 Roasting Profile and Accelerate Storage of Roasted Coffee Bean

The experimental details concerning roasting profiles and the accelerated storage of roasted coffee beans are presented in Chapter 8. Coffee cherries were collected from Doi Chang, Chiang Rai, Thailand, at an altitude of approximately 1,280 meters above sea level, comprising a mix of *Coffea arabica* cultivars harvested during the 2021–2022 season. This study examined the impact of different roasting levels; light, light-medium, and medium on the stability and quality of roasted coffee beans under accelerated storage conditions. A total of 1,500 g of green coffee beans was roasted using a 2 kg capacity drum roaster (HB-L2, The Coffee Company Ltd., Hong Kong), with roast profiles monitored via Artisan software (Version 2.4.4). The degree of roasting was classified according to the Specialty Coffee Association (SCA) Agtron scale using the RoastRite™ Coffee Roast Analyzer (RA-720BF, Brodex Systems Inc., USA), with color values defined as follows: light roast (80–70 Agtron), light-medium roast (69–60 Agtron), and medium roast (59–50 Agtron), measured for both whole and ground beans. After roasting, 250 g samples of roasted coffee beans were packed in GrainPro® bags and stored in a Constant Climate Chamber (HPP750, Memmert GmbH, Schwabach, Germany) under controlled temperatures of 30 °C, 40 °C, and 50 °C with 50% relative humidity. Samples were withdrawn on days 0, 7, 14, and 21, repackaged in vacuum-sealed polyethylene bags, and stored at −80 °C in an ultra-low temperature freezer (MDF-193, SANYO, Tokyo, Japan) until analysis. The physicochemical properties of the roasted beans were evaluated throughout the storage period, including moisture content (3), color using the CIE L^* a* b^* system (4), and peroxide value to assess lipid oxidation (14). Shelf-life prediction was performed using kinetic modeling based on the Arrhenius equation, following the approaches described by Cong et al. (15) and Manzocco et al. (19). Additionally, volatile compounds were analyzed using solid-phase microextraction gas chromatography-mass spectrometry (SPME-GC-MS) according to the methods of Franca et al. ((2009) and Caporaso et al. (10). Identified volatiles were categorized into key chemical groups, including alcohols, esters, organic acids, pyrazines, pyridines, phenolic compounds, sulfides, pyrroles, aldehydes, terpenes, ketones, furanones, and furans, offering insights into the influence of roasting and accelerated storage on the aroma and sensory profile of roasted coffee.

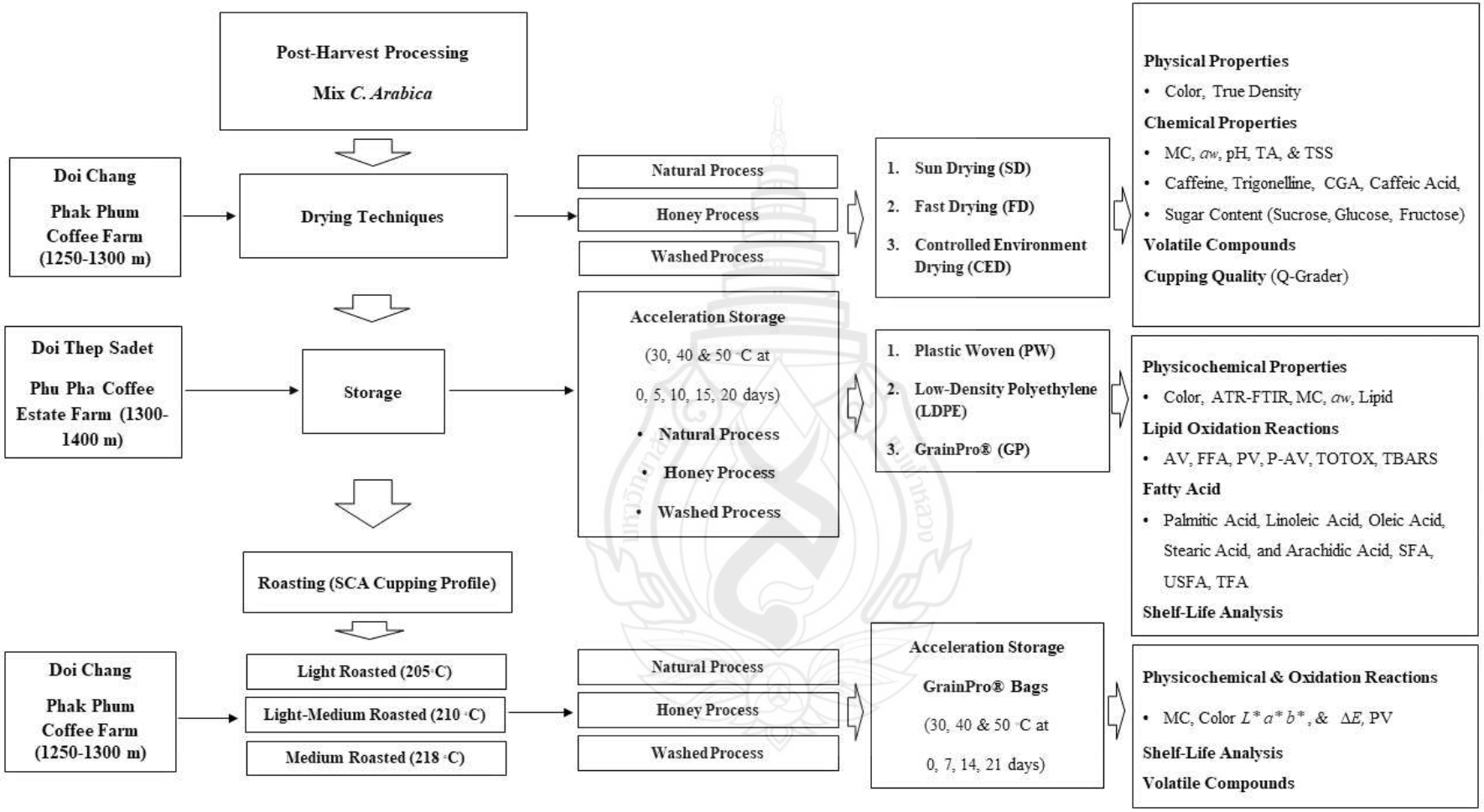

Figure 3.1 Overall Methodology Framework of this Research

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CHAPTER 4

INFLUENCE OF POST-HARVEST PROCESSING AND DRYING TECHNIQUES ON PHYSICOCHEMICAL PROPERTIES OF THAI ARABICA COFFEE[1]

Abstract

Coffee post-processing drying eliminates moisture content, reduces fungal and microbe growth, and develops unique aroma and flavor compounds. Thai coffee producers use controlled-environment drying (CED) techniques to improve the quality and cupping scores of the coffee. This research investigated how different drying methods, including sun drying (SD), controlled-environment drying at 20–30 °C, 50–55% RH, and fast drying (FD) at 30–45 °C influenced the physicochemical characteristics of coffee undergoing dry (DP), washed (WP), and honey (HP) processing. Results showed that true density, moisture content, water activity, color, caffeine, trigonelline, chlorogenic acid, caffeic acid, sucrose, and fructose in green coffee beans were significantly affected ($p < 0.05$) by both drying technique and post-harvest processing. Drying techniques and processing directly impacted the characteristics of green (GCB) and roasted coffee beans (RCB). Findings suggested a correlation between CED, SD, and FD based on the physicochemical and biochemical properties and sugar contents of both green and roasted coffee beans.

Keywords: Controlled-Environment Drying, Drying Characteristic, LTLH, Quality

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4.1 Introduction

Thailand first introduced coffee farming in 1849. The most common coffee varieties are Arabica, which is mainly found in Northern Thailand, and Robusta, which is primarily grown in the southern region (1–3). Arabica varieties, including Catimor, Caturra, Typica, Bourbon, Catuai, and Mundo Novo, are mainly cultivated in Chiang Rai, Chiang Mai, Nan, Lampang, and Tak Provinces (1–3). Many coffee plantations now commonly grow mixed Caffea arabica seeds as it costs more to separate beans during post-harvesting. Climate change also negatively impacts rising temperatures and water scarcity (4). Thus, several Thai coffee farmers focus on the drying stage to reduce the moisture from 55–60 % to 9–12 % as a safe range for storage before roasting while also enhancing the organoleptic qualities of green coffee beans.

The drying stage is a critical post-harvest procedure that contributes significantly to the development of the distinctive color, flavor, and taste of a coffee beverage (5). Sun drying is a common technique utilized by coffee producers in Thailand. The taste of the coffee is significantly affected by the sun-drying process, which depends on climatic conditions (5). Several researchers investigated mechanical drying techniques in industrial settings to reduce drying time (6,7). Shofinita et al. (6) reported that a high temperature during the drying process could lead to reduced storage time and structural damage; therefore, methods of coffee drying, and the operating conditions should be carefully considered. Both sun and machine drying are essential to achieving homogeneity, ensuring the desired color, and controlling pests to enhance the longevity of storage (7). However, many parameters influence coffee quality. The drying phase is an essential element in enhancing the quality of coffee flavor and minimizing damage from an undesirable taste and off-flavor.

Drying and post-processing treatments both impact the physicochemical properties of green coffee beans, such as density (8,9), moisture content (10,11), and water activity (12). These factors contribute to multiple benefits, including weight and volume reduction, storage and transportation costs, handling systems, grading, hulling, aroma, flavor, and texture, as well as sensory attributes (6,7). Biochemical compounds in coffee, including caffeine, trigonelline, chlorogenic acid, and caffeic acid, impact its

flavor by imparting astringency, bitterness, and aromatic formations that contribute to acidity (13–15). Coffee composition undergoes a slight change or remains stable throughout post-harvest processing because enzymatic and chemical processes are influenced by the drying conditions and duration (6,7,15). The biochemical structure of Arabica is strongly affected by variety, growing environment, altitude, and processing (16,17).

Sugar content is an essential element present in the coffee cherry, mucilage pulp, and green coffee beans. The sugar level increases or decreases in response to the consumption and degradation of microorganisms in the cellular structure of the green coffee bean surface during dehydration and post-processing (18,19). The sugar content in coffee consists of sucrose, glucose, and fructose. These sugars play a crucial role in the development of fragrance and flavor during the roasting process through Maillard, Strecker, and degradation reactions (20,21). High sugar content in green coffee beans (GCB) results in a more pronounced ultimate sweetness, as well as stronger precursors (21,22). Therefore, the drying and post-harvest processing techniques perform critical roles in the coffee manufacturing process, with a direct impact on the volatile and physicochemical compounds, collectively establishing the product's quality and desired characteristics and ensuring a high-quality cup of coffee. Jitjaroen et al. (23) investigated the low temperature and low relative humidity (LTLH) conditions for coffee drying by controlling the temperature and relative humidity inside the drying chamber at conditions lower than the ambient. Results showed that sugar concentrations gradually increased during drying. However, knowledge of how controlled environmental drying impacts coffee quality remains limited. Therefore, this study investigated the impact of different drying treatments, such as sun drying (SD), controlled-environment drying (CED), and fast drying (FD), along with different post-harvest processing as dry (DP), washed (WP), and honey processes (HP) on the physicochemical and biochemical properties of Thai Arabica coffee.

4.2 Materials and Methods

4.2.1 Sample Preparation

Coffee (*Caffea arabica* L.) cherries were collected as mixed varieties of Catimor, Caturra, Catuai, and Bourbon from Doi Chang, Thailand, during the 2022–2023 harvesting season, at an altitude of 1250–1300 m. After harvesting the ripe cherry, the samples were floated to remove soil, dirt, leaves, and twigs and washed to obtain clean cherries. Next, the cherries were divided into dry process (DP), washed process (WP), and honey process (HP). DP involved drying the whole cherries, while the WP and HP processes involved de-pulping to remove the outer skin. HP was directly drying with parchment and mucilage. For WP, after pulping, coffee parchment was submerged under water overnight or until the water pH reached 4.3–4.5, and then, mucilage was cleaned by washing and dried.

Two kilograms of samples, e.g., cherry (DP), parchment with mucilage (HP), and wet clean parchment (WP), were put in the basket prior to drying. The initial moisture content (% w.b.) of coffee beans was 73.45 ± 2.40 %, 53.69 ± 3.36 %, and 51.80 ± 5.23 % for DP, HP, and WP, respectively. Different drying techniques, e.g., sun drying (SD), controlledenvironment drying (CED), and fast drying (FD), were applied. Samples were dried until the moisture content reached 9–12 % (w.b.). The details of drying conditions are shown in Table 4.1. For CED and FD, the coffee baskets were placed on the shelf in the drying chamber. A diagram of the drying chamber is shown in Figure 4.1. The drying chamber was the metalized tent with the size of 300 cm × 150 cm × 200 cm equipped with a dehumidifier (LG, MD19GQGA1, Bangkok, Thailand) and heater (Hisense, AP1022HW1G, Suwanee, GA, USA) to control temperature and humidity inside the chamber. Temperature and RH inside the drying chamber were recorded using the data logger (Tinytag Talk 2: TK-4023-PK, Gemini Data Loggers, Chichester, West Sussex, UK). The CED system was controlled by a temperature not exceeding 30 °C, with 55 % RH during the first three days of drying and then with 50 % RH until the end of drying. In the case of FD, the temperature was set in the range of 30–40 °C with 55% RH during the first three days of drying and then set to 50 % RH until the end of drying.

Table 4.1 The Three Drying Methods

Drying Technique	Processing	T (°C)	RH (%)	Drying Time (day)	Final MC (% w.b.)
CED	DP	20–30	50–55	28 ± 0.05 [a]	11.00 ± 0.06 [a]
	WP	20–30	50–55	10 ± 0.01 [d]	11.20 ± 0.10 [a]
	HP	20–30	50–55	14 ± 0.01 [c]	9.69 ± 0.09 [bc]
SD	DP	-	-	21 ± 0.03 [b]	10.96 ± 0.30 [ab]
	WP	-	-	9 ± 0.07 [d]	9.44 ± 0.07 [b]
	HP	-	-	13 ± 0.13 [c]	9.52 ± 1.26 [c]
FD	DP	30–40	50–55	15 ± 0.07 [c]	10.99 ± 0.14 [ab]
	WP	30–40	50–55	8 ± 0.25 [e]	9.40 ± 1.00 [c]
	HP	30–40	50–55	9 ± 0.06 [e]	9.95 ± 0.54 [bc]

Note Data are presented as mean ± SD. Different letters indicate significant differences at $p < 0.05$: CED = controlled-environment drying; SD = sun drying; FD = fast drying; T = temperature; RH = relative humidity; MC = moisture content; DP = natural process; WP = washed process; HP = honey process.

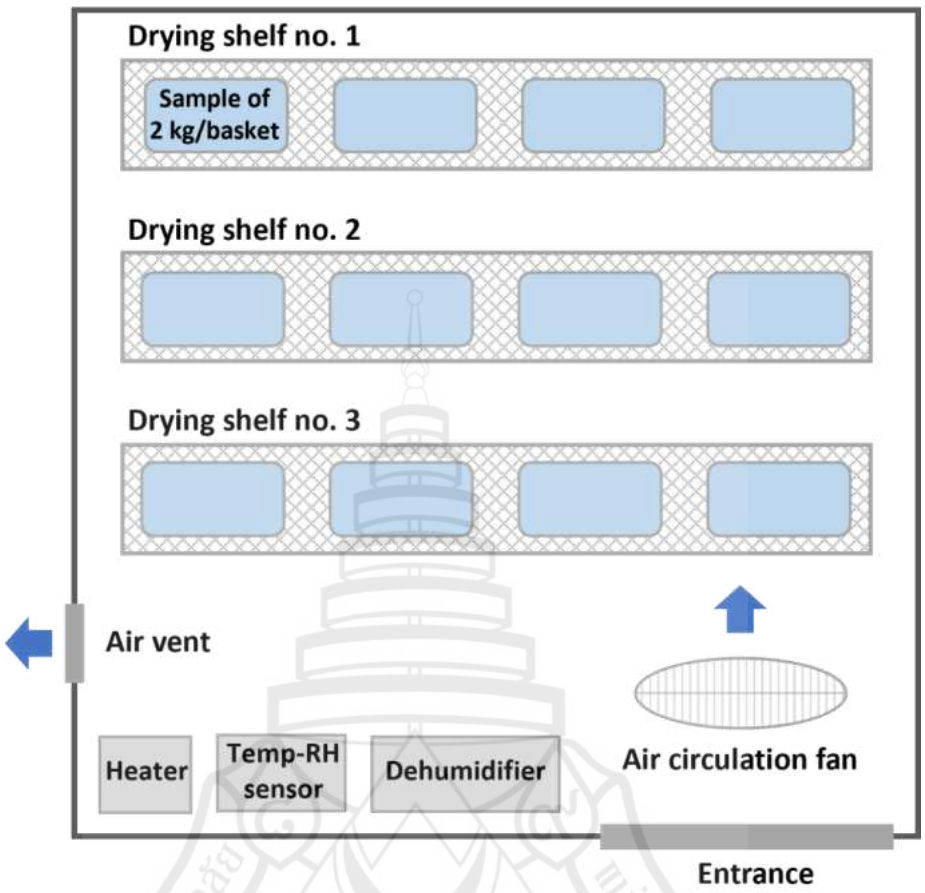
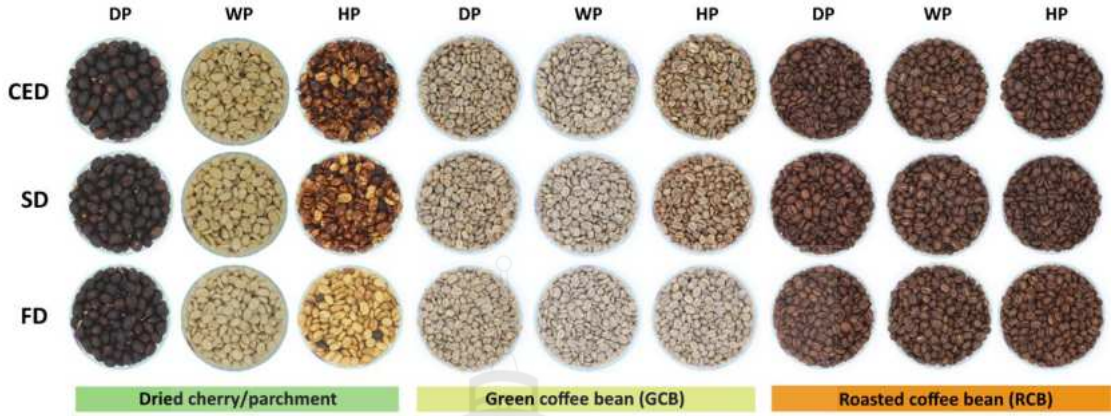


Figure 4.1 Schematic Diagram of Drying Chamber for CED and FD

After drying, the dried coffee cherries and parchment were packed in hermetic bags and stored (25 °C with 50 % RH) for three months before roasting. A 500 g aliquot of each processed GCB hermetic bag underwent roasting using the Specialty Coffee Association (SCA) roasting procedure for the cupping protocol (24). The roasting was conducted using an HB coffee roaster (HB-L2, The Coffee Company, Ltd., Hong Kong, China) under the control of Artisan (2.4.4, freeware) software. The roasting profile was conducted at 208 °C for 8–10 min. Figure 4.2 shows the appearance of the coffee after the post-harvest processing step.



Note CED = controlled-environment drying; SD = sun drying; FD = fast drying; DP = natural process; WP = washing process; HP = honey process.

Figure 4.2 Samples along Coffee Post-Harvest Processing from Dried Cherry, Parchment to Green Coffee Bean (GCB), and Roasted Coffee Bean (RCB)

4.2.2 True Density Determination

The true density was measured using the water displacement method following Chandrasekar and Viswanathan (25). Twenty-five samples were weighed and placed in a 500 mL measuring cylinder filled with water up to 50 mL. The occupied volume was recorded, and the density was calculated using Equation (1):

$$\text{Density} = \text{weight of coffee (g)} / (v_2 - v_1) \text{ volume of coffee (mL)} \quad (1)$$

4.2.3 Color Determination

The color values of GCB were measured using a colorimeter (Color Quest XE, Hunter Associates, Reston, VA, USA) and expressed according to the CIE Lab color scale (26). The colorimeter was calibrated using a standard white tile to obtain the coordinates for the illuminant D65: $L^* = 94.64$, $a^* = -0.80$, and $b^* = 0.07$. L* measures lightness ($L^* = 100$ means white; $L^* = 0$ means black); a^* indicates the contribution of red or green (redness (+) and greenness (−)), and b* determines the role of blue or yellow (yellowness (+) and blueness (−)).

4.2.4 Moisture Content (MC)

The moisture content was determined by drying 3 g of the sample in a vacuum oven at 70 ± 1°C under 5 kPa for 16.0 ± 0.5 h until a constant weight was achieved and calculated using the AOAC 2000 method 979.12 (27) by Equation (2). Moisture content

in dry basis (MC_{db}) and moisture ratio (MR) were expressed in Equations (3) and (4), respectively.

$$MC_{wb} = \text{mass of water (g)/ mass of samples (g)} \times 100 \quad (2)$$

$$MC_{db} = \text{mass of water (g)/ mass of dry matter (g)} \times 100 \quad (3)$$

$$MR = (M_t - M_e)/ (M_o - M_e) \quad (4)$$

where MR is the dimensionless moisture content ratio; Mt is the moisture content at any time (% d.b.); M0 is the initial moisture content (% d.b.), andMe is the equilibrium moisture content (% d.b.)

4.2.5 Water Activity (a_w)

The water activity (a_w) of ground green coffee bean samples was measured at 25 ◦C using a water activity meter (Aqua Lab, Decagon, WA, USA) that included auto analysis (28).

4.2.6 Caffeine, Trigonelline, Chlorogenic Acid, and Caffeic Acid

The samples were extracted in triplicate. Briefly, 1 g of ground coffee was suspended in 15mL of methanol, shaken for one hour without heating, and then filtered through filter paper (Whatman No. 1). The samples were extracted using methanol three times, and the final volume was adjusted to 50 mL. Next, the samples were filtered through a 0.22 μm cellulose ester membrane (Millipore, Brazil). The final extract was diluted with water (1:1) before high-performance liquid chromatography (RP-HPLC) analysis.

Caffeine, trigonelline, chlorogenic acid (CGA), and caffeic acid were determined by reversed-phase high-performance liquid chromatography (RP-HPLC), according to Cordoba et al. (29). Quantitative analyses were carried out using an HPLC (Shimadzu, LabSolutions, Tokyo, Japan) with a diode array detector (UV/VIS). The separation was achieved in a Gemini column C-18 that measured 250 mm × 4.6 mm and 5 μm at 25°C. The mobile phase was modified and used with orthophosphoric acid 0.1 % (A) and methanol (B) HPLC grade. The gradient was adjusted as follows: 0 to 8 min: A/B 96/4; 20 min: A/B 72/28; 25–28 min, A/B 58/42 at a flow rate of 1.5 mL/min. CGA and caffeic acid were detected at 325 nm, caffeine at 275 nm, and trigonelline at 220 nm. The injection volume was 10 μL. The concentrations of bioactive compounds were calculated using a regression equation of their concentrations and the peak area obtained from the HPLC standard (29).

4.2.7 Measurement of Sugar Content (Sucrose, Glucose, Fructose)

The sugar standards used in this study were sucrose, D (+)-glucose, and D (−)-fructose, with 98.9 %, 99.5 %, and 99.9 % purity, respectively. The ultrapure water used in the solutions, sugar extraction, and chromatographic system was purified by a Milli-Q system. Sugar extraction was performed by placing 5 g of ground coffee samples in the tube. The samples were added with 15 mL of Milli-Q water, boiled in a water bath at 80°C for 30 min, and filtered with No.4. The samples were extracted with Milli-Q three times, and the final volume was adjusted to 50 mL. After that, the samples were filtrated by a cellulose ester membrane with a pore size of 0.22 μm before storing at 5°C for further quantification of sugars (30).

The sugars were separated by HPLC following Constantino et al. (30) using a cation exchange column composed of 8 % cross-linked divinylbenzene and Pb^{2+} ions (Aminex HPX-87P, 300 mm × 7.8 mm, 9 μm, Bio-Rad, Hercules, CA, USA) and placed in an oven at 80°C. Ultrapure water was used at the mobile phase at a flow rate of 0.8 mL/min. A manual injector, Rheodyne 7125, containing a 20 μL sampling loop, was used to introduce the samples into the system. A RID-10A refractive index detector was used for sugar detection, and the integration of peaks and area values was obtained using CLASS-VP™ software (v5.0, Shimadzu, LabSolutions, Tokyo, Japan). Sugar identification was carried out according to retention times and the addition of sucrose, glucose, and fructose standards to the samples. Individual quantification of sugars was performed by external standardization using analytical curves comprising six concentrations of a mixture of glucose, sucrose, and fructose.

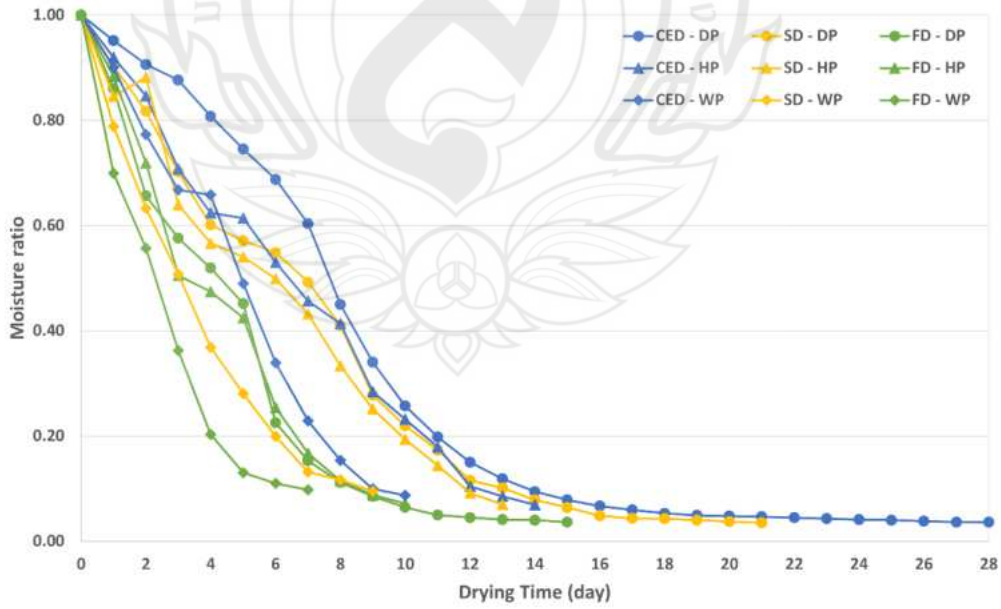
4.2.8 Statistical Analysis

Results from various treatments for true density, color moisture content, water activity, caffeine, trigonelline, chlorogenic acid, caffeic acid, sucrose, and fructose were recorded as mean values with standard deviations (n=3). Analysis of variance (ANOVA) was carriedout using SPSS statistical software (version 20, SPSS Inc., Chicago, IL, USA). Tukey's test ($p \leq 0.05$) was used to compare mean data to identify significant variations between the treatments. Principal component analysis (PCA) was performed using R Statistical Software (v4.1.2, R Core Team, Indianapolis, IN, USA, 2021), and the results of physicochemical properties, biochemical properties, and sugar content data were normalized to exclude dimensional consequences before analysis.

4.3 Results and Discussion

4.3.1 Effect of Drying Techniques on Weight Loss

Figure 4.3 shows the drying characteristics of coffee undergoing different drying conditions. The drying times of each drying technique were significantly different ($p < 0.05$). CED had a longer drying time compared with the others due to a lower drying temperature, as shown in Table 4.1. The final MC values (% w.b.) of the coffee ranged from 9.0 to 12.0%. The MC values of CED were 11.00 ± 0.06%, 11.20 ± 0.10%, and 9.69 ± 0.09% for DP, WP, and HP, respectively, with SD 10.96 ± 0.30 %, 9.44 ± 0.07 %, and 9.52 ± 1.26 % for DP, WP, and HP, respectively, and FD 10.99 ± 0.14, 9.4 ± 1.00, and 9.95 ± 0.54 % for DP, WP, and HP, respectively. Different coffee processing methods influenced the drying time. In CED, a higher initial MC (73.45 ± 2.40 % w.b.) of DP required a longer drying time of 28 days to reach 11.00% w.b. compared to the lower initial MC of WP and HP (51.80 ± 5.23 % and 53.69 ± 3.36 %, respectively). The phenomenon of initial MC on drying time was also found in SD and FD, as shown in Table 4.1.



Note CED = controlled-environment drying; SD = sun drying; FD = fast drying; DP = drying process; WP = washed process; HP = honey process.

Figure 4.3 Drying Characteristics of Coffee Undergoing Different Drying Techniques

FD at high temperatures resulted in higher weight loss compared to the other drying techniques, with a shorter drying period. CED required a longer time to reduce MC. In DP samples (Figure 4.3), the higher drying temperature of FD led to a lower equilibrium moisture content (EMC) compared to other drying techniques. Higher drying temperatures increase the air's ability to retain moisture, resulting in a lower EMC. Increasing the drying temperature or reducing the RH shortened the drying time and lessened the damage caused by unnecessary overfermentation. Fermentation inside the cherry created unique flavor characteristics, whisted by lowering the temperature or increasing the RH. SD required no extra investment costs, as it was dried under natural conditions. However, this method relied on weather conditions. Strong levels of sunlight caused the surface cell structure to break down. In this study, CED was the slowest process for reducing MC, its possible slow drying preventing the loss or degradation of some flavor-precursor compounds, as well as the formation of undesirable components in high-temperature drying such as FD. However, CED requires careful supervision to avoid overfermentation during processing.

4.3.2 Physicochemical Properties of Green and Roasted Coffee Beans

Table 3.2 shows the true density (TD), color, moisture content (MC), and water activity (a_w) of green (GCB) and roasted coffee beans (RCB) under different processing and drying conditions. Drying techniques significantly impacted ($p < 0.05$) coffee TD, color, MC, and a_w of GCB and RCB. However, the lightness (L^*) and yellowness (b^*) did not impact RCB ($p > 0.05$) due to the controlled roasted color level according to the SCA cupping protocol at 63 Agtron.

Table 4.2 The Physicochemical Properties of Green and Roasted Coffee Beans

Sample	TD (g/mL)		*L**			*a**		*b**			MC (% w.b.)		a_w	
	GCB	RCB	GCB	RCB	ns	GCB	RCB	GCB	RCB	ns	GCB	RCB	GCB	RCB
CED-DP	1.21± 0.01 ^{ab}	0.74± 0.02 ^{ab}	51.91± 0.51 ^{bc}	41.60± 0.61		1.85± 0.18 ^{ab}	2.82± 0.12 ^{abc}	8.53± 0.31 ^{ab}	1.54± 0.30		8.48± 0.22 ^{b}	1.99± 0.05 ^{c}	0.52± 0.02 ^{c}	0.40± 0.04 ^{ab}
CED-WP	1.18± 0.02 ^{bcd}	0.71± 0.02 ^{bc}	50.57± 0.21 ^{d}	41.69± 0.12		0.71± 0.17 ^{d}	2.76± 0.11 ^{bc}	7.32± 0.31 ^{b}	1.65± 0.47		10.28± 0.41 ^{ab}	1.74± 0.01 ^{d}	0.61± 0.00 ^{a}	0.39± 0.06 ^{b}
CED-HP	1.23± 0.01 ^{a}	0.75± 0.01 ^{a}	52.70± 0.15 ^{b}	41.35± 0.07		2.48± 0.47 ^{a}	2.67± 0.31 ^{c}	10.02± 1.30 ^{a}	1.83± 0.56		10.37± 0.97 ^{ab}	1.92± 0.07 ^{c}	0.62± 0.00 ^{a}	0.44± 0.02 ^{a}
SD-DP	1.18± 0.02 ^{bcd}	0.73± 0.01 ^{a}	52.14± 0.56 ^{bc}	41.60± 0.23		1.92± 0.01 ^{ab}	2.87± 0.44 ^{abc}	10.00± 0.51 ^{a}	1.84± 0.19		8.57± 0.20 ^{b}	2.18± 0.03 ^{b}	0.53± 0.01 ^{c}	0.45± 0.01 ^{a}
SD-WP	1.20± 0.01 ^{bc}	0.70± 0.01 ^{bc}	52.49± 0.11 ^{bc}	41.85± 0.36		1.10± 0.07 ^{cd}	2.50± 0.16 ^{c}	8.25± 0.29 ^{ab}	1.65± 0.27		9.73± 1.06 ^{ab}	1.95± 0.02 ^{c}	0.58± 0.00 ^{b}	0.38± 0.02 ^{b}
SD-HP	1.16± 0.01 ^{d}	0.70± 0.01 ^{bc}	52.13± 0.04 ^{bc}	41.75± 0.45		2.52± 0.25 ^{a}	2.57± 0.17 ^{c}	10.27± 0.84 ^{a}	1.36± 0.23		11.23± 0.56 ^{a}	1.96± 0.02 ^{c}	0.58± 0.01 ^{b}	0.41± 0.02 ^{ab}
FD-DP	1.19± 0.03 ^{bc}	0.69± 0.02 ^{c}	51.55± 0.35 ^{cd}	42.35± 0.67		2.57± 0.34 ^{a}	3.55± 0.28 ^{a}	9.5± 0.26 ^{ab}	2.44± 0.46		9.25± 0.59 ^{ab}	1.86± 0.09 ^{cd}	0.57± 0.01 ^{b}	0.42± 0.04 ^{ab}
FD-WP	1.17± 0.02 ^{cd}	0.69± 0.02 ^{c}	52.34± 0.23 ^{bc}	41.81± 0.33		0.93± 0.16 ^{cd}	2.64± 0.27 ^{c}	8.19± 0.97 ^{ab}	1.53± 0.23		8.78± 0.06 ^{b}	2.26± 0.02 ^{ab}	0.53± 0.01 ^{c}	0.39± 0.03 ^{b}
FD-HP	1.15± 0.01 ^{d}	0.72± 0.01 ^{abc}	54.07± 0.42 ^{a}	41.24± 0.88		1.82± 0.54 ^{ab}	3.43± 0.35 ^{ab}	9.66± 0.52 ^{ab}	2.46± 0.43		9.41± 0.86 ^{ab}	2.40± 0.07 ^{a}	0.53± 0.00 ^{c}	0.42± 0.04 ^{ab}

Note Data are presented as mean ± SD. Different letters in the same column indicate significant differences among parameters at $p < 0.05$: TD = true density; MC = moisture content; a_w = water activity; CED = controlled-environment drying; SD = sun drying; FD = fast drying; DP = drying process; WP = washing process; HP = honey process; ns = non-significant.

4.3.2.1 True Density (TD)

TD values of GCB and RCB ranged from 1.16 ± 0.01 to 1.23 ± 0.01 g/mL and from 0.69 ± 0.02 to 0.75 ± 0.01 g/mL, respectively. TD values of GCB were similar to previous investigations (31). After roasting, TD reduced due to the loss of moisture content caused by heating (8). CED, GCB, and RCB (1.18 ± 0.02 to 1.23 ± 0.01 g/mL and 0.71 ± 0.02 to 0.75 ± 0.01 g/mL) provided higher TD content than SD (1.16 ± 0.01 to 1.20 ± 0.01 g/mL and 0.70 ± 0.01 to 0.73 ± 0.01 g/mL) and FD (1.16 ± 0.01 to 1.19 ± 0.03 g/mL and 0.69 ± 0.02 to 0.70 ± 0.01 g/mL), respectively. Bustos-Vanegas et al.

(8) concluded that a higher density of coffee beans indicated better quality, with a denser and harder cell structure in the seeds. GCB had greater length, width, and thickness, with a relatively higher average angle (31). Thus, CED might be the best drying technique to improve coffee quality in terms of physical attributes.

4.3.2.2 Color

The maximum L^* of GCB ranged from 51.55 ± 0.35 to 54.07 ± 0.42, 52.13 ± 0.04 to 52.49 ± 0.11, and 50.57 ± 0.15 to 52.70 ± 0.15, for FD, SD, and CED, respectively. The FD had a whitish coffee shading, reflected in the digital image shown in Figure 4.2. The GCB of FD was brighter since less fermentation occurred during drying. Tsai and Jioe (9) claimed that the color of GCB related to the mucilage of the fermentation method performed during coffee processing as bluish, greenish, whitish, yellowish, and brownish. The WP yielded lower a^* (0.71 ± 0.17, 1.10 ± 0.07, and 0.93 ± 0.16 for CED, SD, and FD, respectively) than DP (1.85 ± 0.18, 1.92 ± 0.01, and 2.57 ± 0.34) and HP (2.48 ± 0.47, 2.52 ± 0.25, and 1.82 ± 0.54), respectively. WP exhibited the most greenish color, while DP and HP presented a hint of redness (Figure 4.2). In terms of a^*, different processing methods influenced the character of GCB more than the other drying methods. After roasting, the DP and HP of the FD technique were more brownish than the other processing methods due to increased natural fermentation time (9). The green coffee bean cell structure broke down by FD at a high temperature, while roasting the GCB might easily brunt (8). In terms of b^*, HP from CED showed the highest yellowness, ranging from 9.66 ± 0.52 to 10.02 ± 1.30 compared to DP (8.53 ± 0.31 to 10.00 ± 0.51) and WP (7.32 ± 0.31 to 8.25 ± 0.29). The b^* value might be improved by long-term CED from the browning reaction of the mucilage components. Several yeasts and bacteria grow very rapidly in the coffee mucilage during the drying process. The fructose and glucose in the mucilage produce mannitol, glycerol, and lactic acid (32). Figueroa et al. (33) stated that fermentation broke down the mucilage, which was made up of hemicelluloses, pectin substances, and sugars broken down by enzymes and bacteria in nature. Thus, long-term drying with CED presented more fermentations and increased the yellowness compared to FD and SD.

4.3.2.3 Moisture Content (MC)

The MC of GCB ranged from 8.48 ± 0.22 to 11.23 ± 0.56%, as shown in Table 4.2. The safety range of the moisture level of GCB is 8.0–12.5% (w.b.) (11).

GCB at less than 8% MC could lead to an unpleased appearance, while MC over 12.5% was more vulnerable to microbial development, mycotoxin formation, fungal growth, and sensory changes that reduced coffee quality (10,11). The MC of RCB ranged from 1.74 ± 0.01 to 2.40 ± 0.07%, corresponding to the reported light-medium roasting level of 1.64 ± 0.22 to 2.57 ± 0.00 (34). GCB beans are usually roasted using the SCAA roasting profile. This causes a loss of MC and impacts the physicochemical properties and the formation of several flavor and volatile compounds.

4.3.2.4 Water Activity (a_w)

The a_w of GCB ranged from 0.52 ± 0.02 to 0.62 ± 0.00, indicating a specialty grade of GCB (a_w < 0.7), according to the Specialty Coffee Association of America (SCAA). The a_w content ranged from 0.52 ± 0.02 to 0.62 ± 0.00 in CED, 0.53 ± 0.01 to 0.58 ± 0.00 in SD, and 0.53 ± 0.01 to 0.57 ± 0.01 in FD. The a_w value observed in the connected adsorption isotherm could be explained by water–matrix interactions based on the particular chemical, structural, and cellular characteristics of GCB (12). After roasting, the a_w reduced from 0.38 ± 0.02 to 0.44 ± 0.02. Baggenstoss et al. (35) stated that high a_w content in RCB gave less brittleness. Thus, the RCB process causes a fixed, brittle, and fragile structure that progressively results in the loss of distinctive bean crunchiness and crispiness (12). The lowest a_w of WP could break easily and release energy quickly, resulting in a very brittle and delicate texture of RCB. Thus, during coffee berry drying, physical qualities cause a considerable decrease in the superficial area, volume, and diameter and influence the final cup quality. The drying process influences the aroma level, volatile compounds, sugar, amino acid, a_w, MC, CGA, sulfur-containing substances, sensory quality, and other miscellaneous compounds of sun and mechanically-dried coffee beans (7). Different drying methods altered the physicochemical parameters of GCB and RCB, which are related to the final cupping quality.

4.3.3 Biochemical Properties of Green and Roasted Coffee Beans

Biochemical compounds discovered in coffee, including caffeine, trigonelline, chlorogenic acid (CGA), and caffeic acid (CA), have been identified as contributors to the acidity, bitterness, astringency, and volatile compound formation (13,29). Caffeine, trigonelline, CGA, and CA of GCB and RCB were significantly affected ($p < 0.05$) by post-harvest processes and drying techniques, except for CA in RCB, as shown in Table 4.3.

Table 4.3 The Biochemical Properties of Green and Roasted Coffee Beans

Sample	Caffeine (mg/mL)		Trigonelline (mg/mL)		Chlorogenic Acid (mg/mL)		Caffeic Acid (mg/mL)	
	GCB	RCB	GCB	RCB	GCB	RCB	GCB	RCB ^{ns}
CED-DP	1.01± 0.02 ^{a}	0.76± 0.48 ^{a}	0.68± 0.11 ^{a}	0.23± 0.01 ^{b}	205.38± 2.42 ^{a}	24.44± 3.17 ^{b}	0.45± 1.12 ^{a}	0.19± 0.17
CED-WP	0.91± 0.03 ^{cd}	0.71± 0.01 ^{ab}	0.54± 0.01 ^{bc}	0.22± 0.02 ^{c}	79.61± 2.34 ^{c}	23.37± 0.94 ^{cd}	0.41± 0.39 ^{ab}	0.18± 0.03
CED-HP	0.92± 0.02 ^{ab}	0.64± 0.01 ^{cd}	0.51± 0.04 ^{bc}	0.21± 0.01 ^{d}	109.08± 0.94 ^{bc}	24.05± 3.38 ^{b}	0.39± 0.99 ^{ab}	0.19± 0.01
SD-DP	0.95± 0.02 ^{ab}	0.68± 0.01 ^{bc}	0.61± 0.09 ^{abc}	0.24± 0.01 ^{a}	189.99± 3.13 ^{a}	25.99± 0.56 ^{a}	0.41± 0.30 ^{ab}	0.20± 0.01
SD-WP	0.88± 0.03 ^{cd}	0.72± 0.02 ^{ab}	0.57± 0.03 ^{abc}	0.22± 0.01 ^{c}	76.81± 1.65 ^{c}	24.53± 0.68 ^{bc}	0.38± 0.41 ^{ab}	0.20± 0.01
SD-HP	0.87± 0.04 ^{cd}	0.68± 0.00 ^{bc}	0.48± 0.03 ^{d}	0.21± 0.02 ^{d}	123.82± 0.76 ^{b}	25.65± 0.32 ^{a}	0.30± 0.25 ^{b}	0.19± 0.01
FD-DP	0.90± 0.01 ^{cd}	0.65± 0.00 ^{cd}	0.64± 0.04 ^{ab}	0.23± 0.00 ^{b}	122.42± 0.56 ^{b}	22.77± 0.52 ^{c}	0.40± 0.11 ^{ab}	0.18± 0.02
FD-WP	0.82± 0.01 ^{d}	0.68± 0.01 ^{bc}	0.55± 0.07 ^{bc}	0.22± 0.01 ^{c}	68.35± 5.68 ^{c}	21.20± 1.51 ^{d}	0.45± 0.21 ^{a}	0.19± 0.01
FD-HP	0.86± 0.02 ^{cd}	0.60± 0.02 ^{d}	0.50± 0.02 ^{bc}	0.22± 0.00 ^{c}	103.98± 3.49 ^{bc}	21.53± 0.93 ^{d}	0.37± 0.66 ^{b}	0.18± 0.02

Note Data are presented as mean ± SD. Different letters in the same column indicate significant differences among parameters at $p < 0.05$: CED = controlled-environment drying; SD = sun drying; FD = fast drying; DP, drying process; WP = washing process; HP = honey process; ns = non-significant.

4.3.3.1 Caffeine

The caffeine level of GCB was highest in CED, at 1.01 ± 0.02, 0.91 ± 0.03, and 0.92 ± 0.02 mg/mL for DP, WP, and HP, respectively, followed by SD at 0.95 ± 0.02, 0.88 ± 0.03, and 0.87 ± 0.04 mg/mL, and FD at 0.90 ± 0.01, 0.82 ± 0.01, and 0.86 ± 0.02 mg/mL, respectively. Mengistu et al. (17) demonstrated that GCB caffeine content interacted with mildness and cupping quality. Caffeine is the primary component in coffee and ensures the ultimate quality of the beverage (17). Extending the drying time exhibited higher caffeine concentration in CED than in SD and FD. The lower caffeine content observed in GCB in FD and SD was possibly attributed to the parchment receiving an excessive temperature beyond 40°C during the drying process, as opposed to the uniform drying achieved by mechanical dryers (7). Thus, the application of high temperatures throughout the drying procedure could result in the loss of storage time and structural impairment (36). Comparing coffee processing methods, GCB caffeine content was lower in WP than in DP and HP. WP was fermented under water to dissolve the mucilage layer by enzymes. Sinaga et al. (37) claimed that GCB fermentation reduced caffeine as the enzymes generated by microorganisms degraded caffeine compounds into simpler molecules. Mintesnot and Dechass (38) also reported that WP lost 3% of its caffeine during the soaking step compared to DP. After roasting, DP had 0.76 ± 0.48, 0.68 ± 0.01, and 0.65 ± 0.00 mg/mL of caffeine content for CED, SD, and FD, respectively, and exhibited higher content than WP (0.71 ± 0.01, 0.72 ± 0.02, 0.68 ± 0.01 mg/mL) and HP (0.64 ± 0.01, 0.68 ± 0.00, 0.60 ± 0.02 mg/mL), respectively. The RCB caffeine level was similar to that reported for a coffee brew, ranging from 0.63 to 1.05 mg/L, with caffeine content decreasing as roasting, grinding, and brewing times increased (15). An estimated 30% of the initial caffeine content could be diminished throughout the roasting step (6). In the case of DP, an alkaloid and nitrogenous secondary metabolite might impart a stronger taste, high body, astringency, and bitterness associated with coffee flavor than in WP and HP (6,16).

4.3.3.2 Trigonelline

The highest level of trigonelline of GCB was found in DP, WP, and HP undergoing CED as 0.68 ± 0.11, 0.54 ± 0.01, and 0.51 ± 0.04 mg/mL, followed by FD at 0.64 ± 0.04, 0.55 ± 0.07, and 0.50 ± 0.02mg/mL and SD at 0.61 ± 0.09, 0.57 ± 0.03,

and 0.48 ± 0.03mg/mL, respectively. However, after roasting, the trigonelline content of RCB was high in SD DP, WP, and HP at 0.24 ± 0.01, 0.22 ± 0.01, and 0.21 ± 0.02 mg/mL, respectively, followed by FD at 0.23 ± 0.00, 0.22 ± 0.01, and 0.22 ± 0.00 mg/mL, and CED at 0.23 ± 0.01, 0.22 ± 0.02, and 0.21 ± 0.01mg/mL. Our findings corresponded with the reported range of 0.4–2.4mg/mL for trigonelline in spent coffee grounds (39) and 0.11–0.44mg/mL for cold brew (15). Dong et al. (40) reported that SD preserved caffeine and trigonelline contents better than other methods such as room temperature, solar, heat pump, hot air, and freeze drying due to the longer drying period. Thus, when compared to SD and FD, CED maintained higher levels of trigonelline and caffeine concentrations. DP also maintained a higher trigonelline content than WP and HP. Mintesnot and Dechassa (38) reported that trigonelline levels reduced with wet treatment and were influenced by altitude and processing methods. Trigonelline is a key precursor volatile compound that contributes to aroma and flavor (15,17). RCB showed reduced trigonelline content under CED in comparison to SD and FD. This distinction was attributed to the high trigonelline content in GCB, which, during the degradation stage of roasting, was converted into other volatile compounds, including nicotinic acid, pyridine, pyrroles, 3-methyl-pyridine, and methyl ester (15,17,41). Trigonelline content reduced during roasting, as about 50% of the volatile molecules blew up, resulting in the formation of volatile chemicals (41). Levels of trigonelline in coffee were correlated with various environmental factors, including soil fertility, pH value, and coffee species, which were influenced by the roasting process (17).

4.3.3.3 Chlorogenic Acid (CGA)

Chlorogenic acid (CGA) is the most common phenolic compound found in coffee that is mainly responsible for flavor formation, coffee pigmentation, aroma formation, bitterness, and astringency of coffee beverages (17,38). As shown in Table 3, the CGA content of GCB was highest in DP undergoing CED, SD, and FD at 205.38 ± 2.42, 189.99 ± 3.13, and 122.42 ± 0.56 mg/mL, respectively, followed by HP at 109.08 ± 0.94, 123.82 ± 0.76, and 103.98 ± 3.49 mg/mL and WP at 79.61 ± 2.34, 76.81 ± 1.65, and 68.35 ± 5.68 mg/mL. The CGA contents obtained in this study were close to the range from 86.42 to 61.15 mg/g of total CGA identified in GCB and reported by Moon et al. (42). RCB resulted in a reduction in CGA; the CGA contents from SD were 25.99 ± 0.56, 24.53 ± 0.68, and 25.65 ± 0.32 mg/mL for DP, WP, and HP, respectively.

CED contents were 24.44 ± 3.17, 23.37 ± 0.94, and 24.05 ± 3.38 mg/mL, and FD contents were 22.77 ± 0.52, and 21.20 ± 1.51, 21.53 ± 0.93 mg/mL, respectively. Moon et al. (42) discovered that the amount of CGA decreased by approximately 50% after roasting. The CGA content was measured at 28.12 mg/g for light roast, 18.84 mg/g for medium roast, 2.84 mg/g for city roast, and 0.47 mg/g for French roast, indicating that long roasting times resulted in lower CGA content.

Our results showed that drying and processing influenced the concentration of CGA in both GCB and RCB. In comparison to SD and CED, FD provided a lower CGA value as a result of applying drying temperature at a higher range of 30 to 45°C. This phenomenon was attributed to the instability of CGA isomers during thermal processing, which promoted their degradation at a drying temperature of 50 ◦C (43). Deotale et al. (44). revealed that spray drying, freeze drying, and conductive hydro drying influenced instant coffee's CGA content. CGA reduced during roasting and post-processing, although spray freeze drying using sublimation retained the greatest amount of CGA (44). Mintesnot and Dechassa (38) reported that altitude and processing altered CGA subgroups or individual CGA, which included up to 14% of CGA and affected coffee quality, acidity, and bitterness. Drying conditions influenced coffee seed metabolic activity, causing stress metabolism led to the loss of volatile compounds (43). Thus, the method involving lower temperature and gradual drying was associated with a greater concentration of CGA, with a higher amount in CED compared to SD and FD. DP yielded superior CGA content compared to WP and HP.

4.3.3.4 Caffeic Acid

Caffeic acid (CA) and chlorogenic acid (CGA) are the two main phenolic acids found in coffee, as reported by Li et al. (45). The concentration of CA in GCB was highest in CED at 0.45 ± 1.12, 0.41 ± 0.39, and 0.39 ± 0.99 mg/mL for DP, WP, and HP, respectively, followed by FD at 0.40 ± 0.11, 0.45 ± 0.21, and 0.37 ± 0.66 mg/mL and SD at 0.41 ± 0.30, 0.38 ± 0.41, and 0.30 ± 0.25 mg/mL, respectively. However, there were no significant differences ($p > 0.05$) in RCB, which ranged between 0.18 ± 0.03 and 0.20 ± 0.01 mg/mL. The CA content exhibited a reduction after roasting, corresponding to the decrease in CA from 0.242 to 0.249 mg/g observed in Robusta coffee extract reported by Jeszka-Skowron et al. (13). Moon and Shibamoto (46) observed that CA released the highest quantity of volatile compounds throughout

the process of RCB. The roasting process of coffee resulted in the degradation of CGA isomers into volatile compounds and their conversion into major acids such as CA, which occurred as an ester with quinic acid called 5-caffeolquinic acid (16). On the other hand, GCB from CED gave higher CA values, which were attributed to its higher amount of CGA compared to SD and FD. Hernandex-Ayala et al. (47) demonstrated that CA, pyrrole, and thioglycolic acid exhibited the strongest protection factor against rancidity. The process of coffee roasting leads to the formation of phenolic compounds such as CA, gallic acid, pyrogallol, and purpurogallin. These chemicals serve to counterbalance the reduction in antioxidant capacity caused by the breakdown of CGA (14).

4.3.4 Sugar Content Green and Roasted Coffee Beans

The components of sugar content, such as sucrose (non-reducing sugar), glucose, and fructose (reducing sugar), are crucial for the formation of aroma and flavor during the Maillard reaction and Strecker degradation of the roasting step (44). As a result, sucrose and fructose were identified in GCB, whereas fructose was detected in RCB, and glucose was not detected. Table 4.4 shows that post-harvest processing and drying techniques significantly influenced ($p < 0.05$) sucrose and fructose levels.

Sucrose content in HP was greater for CED, SD, and FD at 9.55 ± 1.76, 7.45 ± 0.61, and 5.55 ± 0.04%, respectively, and higher than DP (6.15 ± 0.04, 5.60 ± 0.33, and 5.23 ± 0.73%) and WP (5.15 ± 0.04, 6.60 ± 0.41, and 4.35 ± 0.37%). Knopp, Bytof, and Selmar (48) reported a range of 7.07% sucrose in arabica GCB. Mintesnot and Dechassa (38) established that altitude and unwashed processing had a substantial effect on the sucrose concentration in GCB. The WP unwashed processing method had an important impact on the complex metabolic activities of the beans during the drying step, particularly influencing sugar content and taste precursors. Sugar concentration plays a crucial role in the coffee cherry, mucilage, and pulp until the coffee reaches the green coffee bean stage (18,19).

Fructose of GCB was found at high levels in DP CED, SD, and FD at 3.75 ± 0.40, 2.20 ± 0.33, and 1.53 ± 0.04%, respectively. WP gave 1.30 ± 0.57, 1.77 ± 0.41, and 1.10 ± 0.08%, while HP recorded 1.20 ± 0.65, 1.70 ± 0.16, and 1.60 ± 0.04%, respectively. DP exhibited greater fructose in comparison to WP and HP as a result of de-pulping, rinsing, and fermentation. Following the fermentation process of

endosperms, the concentrations of sucrose, fructose, glucose, and caffeine reduced, which was caused by the prolonged fermentation period. This led to an increase in acetic acid, ethanol, glycerol, glucuronic acid, lactic acid, mannitol, and succinic acid concentrations (49). Thus, sucrose and fructose contents in HP and DP were greater than in WP. CED showed higher sugar content than the other drying methods. The high sucrose content in GCB presented more intense coffee cupping and flavor precursors (22).

After the roasting process, only fructose contents were found. Fructose contents in the DP of CED, SD, and FD were 2.07 ± 0.41, 1.33 ± 0.25, and 0.96 ± 0.33, respectively, and higher compared to HP (1.15 ± 0.20, 0.95 ± 0.18, and 0.68 ± 0.15) and WP (0.95 ± 0.29, 1.07 ± 0.50, and 0.60 ± 0.08), respectively. During roasting, the Maillard reaction is primarily responsible for the development of aroma in coffee. This involves the reaction between amino acids and reducing sugars, resulting in the formation of nitrogenous heterocycles and brown melanoidins, which contribute to the sweetness of coffee (22).

Table 4.4 Sugar Contents of Green and Roasted Coffee Beans

Sample	Sucrose (%)		Fructose (%)		Glucose (%)	
	GCB	RCB	GCB	RCB	GCB	RCB
CED-DP	6.15 ± 0.04 ^{bc}	ND	3.75 ± 0.40 ^{a}	2.07 ± 0.41 ^{a}	ND	ND
CED-WP	5.15 ± 0.04 ^{bc}	ND	1.30 ± 0.57 ^{bc}	0.95 ± 0.29 ^{bc}	ND	ND
CED-HP	9.55 ± 1.76 ^{a}	ND	1.20 ± 0.65 ^{c}	1.15 ± 0.20 ^{bc}	ND	ND
SD-DP	5.60 ± 0.33 ^{bc}	ND	2.20 ± 0.33 ^{b}	1.33 ± 0.25 ^{b}	ND	ND
SD-WP	6.60 ± 0.41 ^{bc}	ND	1.77 ± 0.41 ^{bc}	1.07 ± 0.50 ^{bc}	ND	ND
SD-HP	7.45 ± 0.61 ^{ab}	ND	1.70 ± 0.16 ^{bc}	0.95 ± 0.18 ^{bc}	ND	ND
FD-DP	5.23 ± 0.73 ^{bc}	ND	1.53 ± 0.04 ^{bc}	0.96 ± 0.33 ^{bc}	ND	ND
FD-WP	4.35 ± 0.37 ^{c}	ND	1.10 ± 0.08 ^{c}	0.60 ± 0.08 ^{c}	ND	ND
FD-HP	5.55 ± 0.04 ^{bc}	ND	1.60 ± 0.04 ^{bc}	0.68 ± 0.15 ^{bc}	ND	ND

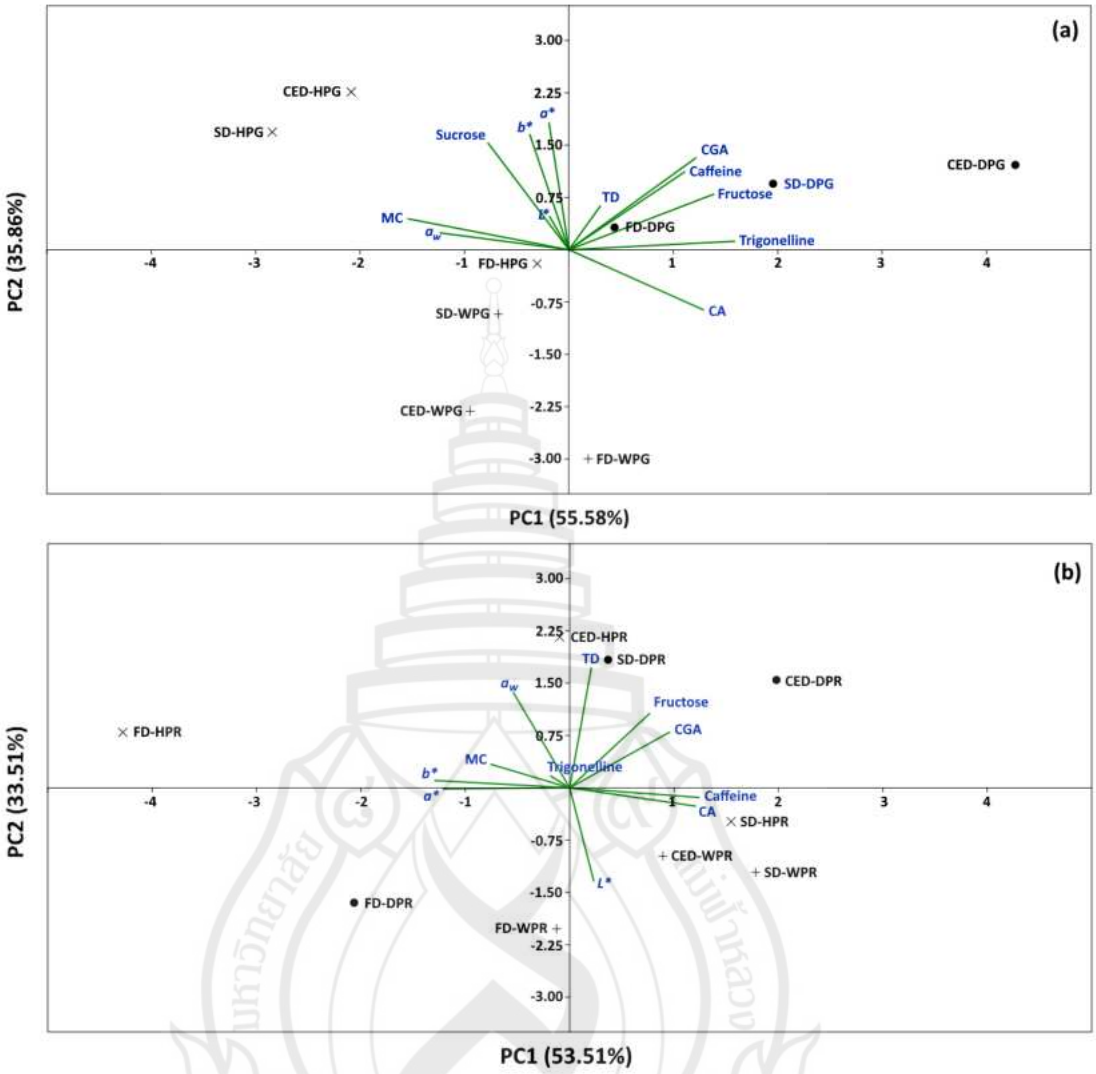
Note Data are presented as mean ± SD. Different letters in the same column indicate significant differences among parameters at $p < 0.05$: CED = controlled-environment drying; SD = sun drying; FD = fast drying; DP = drying process; WP = washing process; HP = honey process; ND = non-detected.

4.3.5 Principal Component Analysis (PCA) of Green and Roasted Coffee Beans

PCA was applied to identify green and roasted coffee physicochemical properties, including TD, L^*, a^*, b^*, MC, a_w, caffeine, trigonelline, CGA, CA, sucrose, and fructose contents from the CED, SD, and FD methods. The PCA score plot in Figure 4.4a indicates that the first two principal components, PC1 (55.58%) and PC2 (35.86%), collectively accounted for 91.44% of the total variance in GCB. The physicochemical parameters of TD, fructose, CGA, caffeine, trigonelline, and caffeic acid were associated with the drying methods of CED-DPG, SD-DPG, and FD-DPG. The drying rates of CED-HPG, SD-HPG, and FD-HPG were much greater and contrasted with sucrose, color L^* a^* b^*, MC, and a_w. The drying methods CED-WPG, FD-WPG, and SD-WPG were correlated with MC, aw, and CA. Therefore, it was inferred that various post-harvest processes had a primary impact on the physical, chemical, and sugar compositions of GCB. When comparing these processes, the CED technique resulted in increased amounts of physicochemical, biochemical, and sugar

contents in GCB. SD resulted in moderate changes in these compounds, while FD exhibited the lowest changes.

The PCA biplot illustrates the relationship between the component of RCB and the ability of selected qualitative indicators to distinguish between different drying and processing methods. PC1 and PC2 were retained based on their combined percentage of 87.02%. The principal components of RCB accounted for PC1 (53.51%) and PC2 (33.51%). CED-DPR, CED-HPR, SD-DPR, CED-WPR, SD-HPR, and SD-WPR were assessed based on a_w, TD, fructose, CGA, caffeine, CA, color L^*, and trigonelline contents. CED-DPR, SD-DPR, and CED-HPR had higher levels of TD, fructose, and CGA, whereas SD-HPR, SD-WPR, and CED-WPR exhibited higher levels of caffeine and CA. By contrast, FD-HPR, FD-DPR, and FD-WPR corresponded to MC, a^*, b^*, and L^*. Thus, RCB had a greater influence on drying techniques than post-harvest processing, and SD had the most equivalent effect on coffee quality as CED compared to FD.



Note CED = controlled-environment drying; SD = sun drying; FD = fast drying; DP = drying process; WP = washed process; HP = honey process; G = green coffee bean; R = roasted coffee bean; CGA, chlorogenic acid; CA, caffeic acid; TD, true density.

Figure 4.4 Biplot of the Relative Physicochemical, Biochemical, and Sugar Contents of Coffee from Different Drying and Post-Harvest Processing Methods, (a) GCB, (b) RCB

4.4 Conclusions

This research investigated the influence of post-harvest processing and drying methods on the physicochemical and biochemical compositions and sugar content of GCB and RCB. CED influenced the quality of GCB by promoting high levels of physicochemical, biochemicals, and sugar content, followed by SD and FD. The quality of RCB relied on the initial GCB. The roasting process decreased the initial qualities (MC, aw, color, TD, caffeine, trigonelline, CGA, CA, sucrose, and fructose) while creating the specific aroma and flavor characteristics. Post-harvest processing was also a key factor in GCB qualities. DP provided the highest biochemical properties on caffeine, trigonelline, GCA, and CA, all of which were linked to the cup quality. HP provided high sucrose and fructose content, which produced a variety of compounds when roasting. WP removed some chemical characteristics during post-harvest processing. For further studies, the optimization of post-harvest processing among these three proposed techniques and their effect on volatile compounds and cup quality should be investigated.

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CHAPTER 5

LIPID OXIDATION CHANGES OF ARABICA GREEN COFFEE BEANS DURING ACCELERATED STORAGE WITH DIFFERENT PACKAGING TYPES[2]

Abstract

The storage conditions of green coffee beans (GCBs) are indispensable in preserving their commercial value. In Thailand, coffee farmers and roasters typically store GCBs for six months to a year before roasting. However, the beans undergo oxidation during storage, influencing both quality and taste. This study investigated changes in GCB lipid oxidation under different accelerated storage conditions (30 °C, 40 °C and 50 °C with 50% RH) and packaging, i.e., plastic woven (PW), low-density polyethylene (LDPE) and hermetic/GrainPro® (GP) bags. Samples were collected every five days (0, 5, 10, 15 and 20 days) and analyzed for lipid oxidation parameters including acid value (AV), free fatty acids (FFA), peroxide value (PV), ρ-anisidine value (PAV), total oxidation value (TOTOX), thiobarbituric acid reactive substances (TBARS), moisture content (MC), water activity (a_w) and color. Primary oxidation was observed, with AV, FFA and PAV gradually changing during storage from 1.49 ± 0.32 to 3.7 ± 0.83 mg KOH/g oil, 3.82 ± 0.83 to 9.51 ± 1.09 mg KOH/g oil and 0.99 ± 0.03 to 1.79 ± 0.14, respectively. Secondary oxidation changes as PV and TBARS were reported at 0.86 ± 0.12 to 3.63 ± 0.10 meq/kg oil and 6.76 ± 2.27 to 35.26 ± 0.37 MDA/kg oil, respectively, affecting the flavor and odor of GCBs. Higher storage temperature significantly influenced a lower GCB quality. GP bags maintained higher GCB quality than LDPE and PW bags. Results provided scientific evidence of the packaging impact on oxidation for GCB under accelerated storage.

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Keywords: Green Coffee Beans, Packaging, Quality, Rancidity, Shelf-life

5.1 Introduction

Coffee is now one of the most popular drinks and is widely consumed daily. Arabica varieties are the most productive, have the highest quality, and are grown at high elevations above 1000 m worldwide (1,2). In 1849, Arabica coffee (Coffea arabica) was introduced to Thailand as Catimor, Caturra, Typica, Bourbon, Catuai, Mundo Novo and others (3,4). The Chiang Rai region of Northern Thailand including Doi Chang, Pang Khon, Mae Chang Tai, Doi Tung and Chiang Mai produces Arabica coffee, with 19,900 ha of farming land mainly located in the highlands (5). Thai coffee has spread to countries including the United States, Canada, the United Kingdom, South Korea, Singapore, Malaysia, Cambodia and Laos. Thai Arabica coffee has a unique profile of intense fruity-floral aroma, acidity, clean-cup, full profile and flavors depending on the processing method (6,7).

However, farmers have faced unstable coffee bean prices, with a lack of market access and the high production costs of hired labor and chemical fertilizers. Sustainable farming practices are required to support local communities and improve farmers' living standards (7). Chuqian (8) also suggested the utilization of advanced processing techniques and equipment to develop a qualified, precise, commercialized industry on a large scale, improve product quality, and conduct more comprehensive investigations and research on problem issues. In Thailand, coffee farmers and roasters typically store green coffee beans (GCB) for six months to a year before roasting. During postharvest and storage, Thai Arabica coffee can be contaminated by fungi that produce mycotoxins such as ochratoxin A (OTA), Aspergillus and Penicillium, particularly on coffee cherries, parchment coffee and green coffee beans (9). Fungi and mold oxidation reactions are found in the coffee processing steps of fermentation, drying and storage, and these microbiota can affect the final taste and sensory qualities of the product. The packaging bags also impact the quality of green coffee beans. Abreu et al. (10) stated that no packaging system can preserve the initial sensory quality of coffee over long-

term storage. This highlights the importance of developing methods to detect and minimize physical, chemical and oxidation changes in green coffee beans during storage before they negatively impact sensory quality (11–14).

It is necessary to maintain and safeguard GCB quality during long-term storage before roasting to maximize market price (15,16). Several compounds that give coffee its sensory characteristics can be produced or degraded during storage (14), and effective methods for preserving the sensory quality of coffee beans during storage are vital (11). Long-term storage and environmental factors alter GCB physical and chemical properties (15). Molds develop and produce toxins that are harmful to consumer health, reducing production quality and impacting market value and human safety (9). Scheidig, Czerny and Schieberle (17) stated that coffee bean storage can affect moisture content, density, odor and aroma, all of which influence flavor. The physicochemical properties of coffee quality, aroma, flavor and taste profiles depend on the variety, plantation environment and farming method involving soil type, climate, husbandry (farming), geography (latitude and altitude), harvesting time, processing, storage, packaging and roasting (18–22).

Accelerated storage techniques are commonly used to control the storage environment by reducing the experimental time of long-term assessments (23). This allows fast aging of food products. The most commonly used accelerating factors are temperature, humidity and light (24,25). Accelerated storage focuses on the sensory, chemical, biochemical and physical changes (24) as very effective tools for studying the changing characteristics of agricultural products and reduction in coffee quality. Cong et al. (25) noted that lipid oxidation impacts the loss of Robusta coffee quality during accelerated storage. Green coffee beans have low moisture content and a high proportion of unsaturated fatty acids. This enhances lipid oxidation that leads to rancid odors, negatively impacting nutritional quality and product secondary oxidation as harmful to human health (25). Coffee has high total lipid content of 50%, comprised of unsaturated fatty acid content higher than saturated fatty acids that easily oxidize, with loss of cellular structure, seed viability and sensory changes. The TBARS value, carbonyl groups and caffeoylquinic acid concentration reduce with loss of color during GCB storage (16). Speer and Kolling-Speer (26) reported that during storage, GCB sensory attributes changed, with production of active lipases, free unsaturated fatty

acids and hydroperoxides associated with lipid oxidation. However, scant research has been conducted on how accelerated storage and packaging impact Thai Arabica GCB quality.

Thus, here, changes in moisture content, water activity, color, fatty acids and lipid oxidation as well as acid value (AV), free fatty acids (FFA), peroxide value (PV), ρ-anisidine value (PAV), total oxidation value (TOTOX), thiobarbituric acid reactive substances (TBARS) in GCB under different accelerated storage conditions were identified. The impact of packaging types, i.e., plastic woven (PW) bags, low-density polyethylene (LDPE bags) and hermetic/GrainPro® (GP) bags on the loss of GCB quality was also assessed.

5.2 Materials and Methods

5.2.1 Sample Preparation

Coffee cherries (*Caffea arabica* L.) for this research were collected from Doi Thep Sadet, Chiang Mai, Thailand during the 2021–2022 coffee cherry harvesting season. Coffee cherries were controlled in the fully ripe stage and processed by washing. The samples were de-pulped to remove the outer skin, the parchment was soaked until pH reached 4.3–4.5 and using a shred drying device until the moisture content was 10–12%. After that, the coffee samples were de-hulled to obtain GCBs and transferred to the laboratory for further analysis.

Samples of 250 g of green coffee beans were packed in plastic woven (PW), low-density polyethylene (LDPE) and GrainPro® (GP) bags (Figure 5.1a–c) and stored in a Constant Climate Chamber (HPP750, Memmert GmbH, Schwabach, Germany) with temperature controlled at 30, 40 and 50 °C and relative humidity (RH) 50%. The properties of packages are shown in Table 5.1. Air permeability was determined using an air permeability tester (FX 3300 LabAir IV, Textest Instruments, Schwerzenbach, Switzerland) according to ASTM D737-04 (27). The packages were cut into 20 × 20 cm2 and results were reported in L/m2 s. The thickness of packages was measured using the thickness gauge (SMD-565J, Teclock, Nagano, Japan). Three replicates were tested and average values were reported. Coffee samples were taken from the

accelerated storage chamber every five days (0, 5, 10, 15 and 20 days), repackaged in polyethylene vacuum sealed packages and stored at −80°C in an ultra-low temperature freezer (MDF-193, SANYO, Tokyo, Japan) until future analysis. Day 0 samples (the control sample) were prepared without any package and used to determine the initial quality parameters of the GCB.

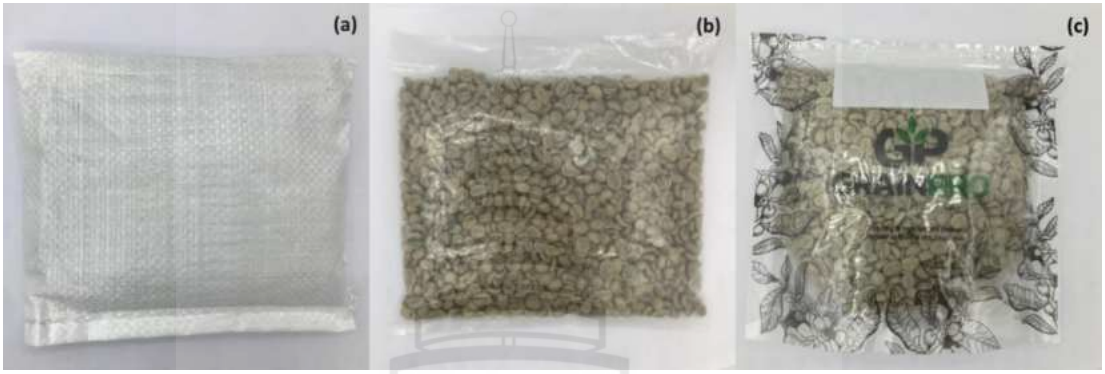


Figure 5.1 Packaging for GCB Storage (a) Plastic Woven Bag (PW), (b) Low-Density Polyethylene Bag (LDPE) and (c) GrainPro® (GP)

Table 5.1 Properties of Packaging Materials

Packaging	Air Permeability ($L/m^2 s$)	Thickness (mm)	Surface Area (m^2)	Supplier
PW	1054.62 ± 4.55	0.127 ± 0.00	0.0445	Siam Makro PCL., Bangkok, Thailand
LDPE	101.47 ± 2.70	0.075 ± 0.00	0.0445	Siam Makro PCL., Bangkok, Thailand
GP	0.538 ± 0.04	0.124 ± 0.00	0.0445	Intergro Co., Ltd., Bangkok, Thailand

5.2.2 Moisture Content (MC)

Moisture content was measured by drying in a hot air oven at 70 ± 1°C for 16.0 ± 0.5 h until constant weight (28) (AOAC 2000 method 979.12) and calculated using Equation (1):

$$\% \text{ Moisture} = (\text{Weight loss on drying (g)} / \text{ Weight of sample (g)}) \times 100 \quad (1)$$

5.2.3 Water Activity (a_w)

Water activity (a_w) was determined using a water activity meter (Aqua Lab, Decagon, WA, USA) at 25 °C with auto analysis on ground GCB samples (29).

5.2.4 Color Determination

Color values of GCBs were analyzed using a colorimeter (Color Quest XE, Hunter Associates, Reston, VA, USA) and reported based on the CIELab color scale (30). The colorimeter was calibrated with a standard white tile to obtain the coordinates for the illuminant D65: L^* = 94.64, a* = -0.80 and b^* = 0.07. L^* measures lightness (L^* = 100 means white, L^* = 0 means black), a^* indicates the contribution of red or green (redness (+) and greenness (−)) and b^* determines the role of blue or yellow (yellowness (+) and blueness (−)).

5.2.5 Lipid Oxidation Determination

Lipid oxidation was determined as lipid, fatty acid and primary oxidation including acid value (AV), free fatty acids (FFA), peroxide value (PV) and secondary oxidation as ρ-anisidine value (PAV) and thiobarbituric acid reactive substances (TBARS).

5.2.5.1 Lipid Content

The lipid content was determined by constant extraction in a Soxhlet apparatus at 105 °C for 2 h using petroleum ether as the solvent (31) (AOAC, 2000 method number 920.39). The lipid content (%fat) was calculated using Equations (2) and (3):

$$\%\text{Fat(wwb)} = ((\text{Weight of can (g)+fat}) - \text{Weight of can}) / \text{Weight of sample(g)}) \times 100 \quad (2)$$

$$\%\text{Fat (dwb)} = (\%\ \text{Fat (wwb)} / (100 - \%\text{moisture})) \times 10 \quad (3)$$

5.2.5.2 Determination of Acid Value (AV) and Free Fatty Acid (FFA)

The AV and FFA were measured by titration following the AOAC method number 940.28 (32). In brief, 1 g of oil sample was weighed into a 250 mL flask and heated to melting point at not more than 10 °C. Then, 50 mL of neutralized alcohol (1:1 v/v) was added and the mixture was boiled in a boiling water bath until a clear solution was obtained. While still hot, the sample was titrated with 0.1 M potassium hydroxide (KOH) with vigorous shaking until a pink color persisted for 30 s. AV was expressed

as milligrams of KOH required to neutralize the FFA present in 1 g of the oil samples (mg KOH/g oil). The AV and FFA were calculated using Equations (4) and (5):

AV = mg KOH required per gram of oil (1 mg of 0.1 KOH = 5.6 mg KOH) (4)

Free fatty acids (%) = ((Volume KOH × Normality KOH) / weight of oil) × 25.6 (5)

5.2.5.3 Determination ρ-Anisidine Value (PAV)

The PAV was measured according to Cong et al. (25). The oil sample (0.6 g) was placed in a 250 mL flask and mixed with 80 mL of 2,2,4-trimethylpentane. Then, 5 mL of the mixed sample solution was added with 1 mL of ρ -anisidine solution, thoroughly mixed and left to react for 10 min in the dark. The absorbance was recorded at 350 nm using a UV-Vis spectrophotometer (GENESYS 180, Thermo Fisher Scientific, Bohemia, NY, USA). The PAV was calculated using Equation (6):

PAV = (25 × (1.2As - Ab)) / weight of oil or fat used for analysis (g) (6)

where As = the absorbance of the fat solution after reaction with ρ-anisidine reagent

Ab = the absorbance of the fat solution.

5.2.5.4 Peroxide Value (PV)

The PV was measured following the AOAC Official Method 965.33 (33). First, 1 g of oil sample (S) and blank (B) were prepared in two 250 mL Erlenmeyer flasks and 30 mL of a mixed solvent of chloroform-acetic acid (2:3 v/v) added. Then, 0.5 mL of saturated KI solution was added to each flask, shaken and allowed to stand in the dark for 1 min. The mixed samples were then immediately added to 30 mL of distilled water to stop the reaction. Finally, the mixture was titrated with 0.002 M sodium thiosulphate until the blue color disappeared. The result was expressed as peroxide milliequivalent per kg oil (meq/kg oil) using Equation (7):

PV (meq/kg samples) = (2 × (Samples − Blank) mL)/weight of oil (g) (7)

5.2.5.5 Total Oxidation Value (TOTOX)

The overall primary and secondary oxidative state of the coffee oil was evaluated by calculating the TOTOX (25) using Equation (8):

$$TOTOX = P - AV + 2PV \quad (8)$$

5.2.5.6 Measurement of Thiobarbituric Acid Reactive Substances (TBARS)

TBARS was measured following Rendon et al. (16). First, 0.2 g of the ground coffee sample was added to 4 mL of 1% (w/v) trichloroacetic acid (TCA) containing 0.08 g of polyvinylpolypyrrolidone (PVPP) and the mixture was homogenized by continuous stirring for 30 min. Then, the mixture was centrifuged at 20,000 rpm for 10 min at 7 °C. Two milliliters of 20% TCA (w/v) solution was added, containing 0.5 mL of 0.5% (w/v) thiobarbituric acid of the supernatant. The reaction mixture was heated for 30 min in a water bath at 90 °C and cooled. The cooled mixture was then centrifuged at 10,000 rpm for 10 min at 10 °C. Quantification was performed by a spectrophotometer (Agilent Technologies, Santa Clara, CA, USA) at 532 and 600 nm using an extinction coefficient of 155 mM^{-1} cm^{-1}, with results expressed as nmol of MDA/g of sample (d.w.).

5.2.5.7 Fatty Acid Profile

The fatty acid profile was determined by gas chromatography-mass spectrometry (GCMS). Ten milligrams of green coffee bean oil sample were placed in a 1.5 mL microcentrifuge tube and 500 µL of 0.5% (w/v) methanolic sodium hydroxide was added, followed by water bath shaking at 60 °C for 20 min. The sample was then cooled at room temperature, 1 mL of n-hexane was added and the mixture was vortexed for 1 min. Then 200 µL of distilled water was added and the mixture was vortexed for 30 s before centrifuging at 4500 rpm for 10 min at 25 °C. After centrifuging, the hexane layer was transferred into another tube and a small amount of anhydrous sodium sulfate was added to dry the residue water in the hexane before filtrating the fatty acids for analysis by GC-MS (6890N, Agilent Technologies, Santa Clara, CA, USA) (34,35) with an HP-5 column (0.25 mm × 30 m × 0.25 µm) and MS detector (5973N Agilent Technologies, Santa Clara, CA, USA). The temperature gradient was set at 150 °C for 10 min at 10 °C/min until reaching 250 °C and then 250 °C for 10 min. Helium was

used as the carrier gas with a constant flow rate of 1 mL/min using injector split mode (150:1) at 220 °C and injector volume 1 µL.

5.2.6 Statistical Analysis

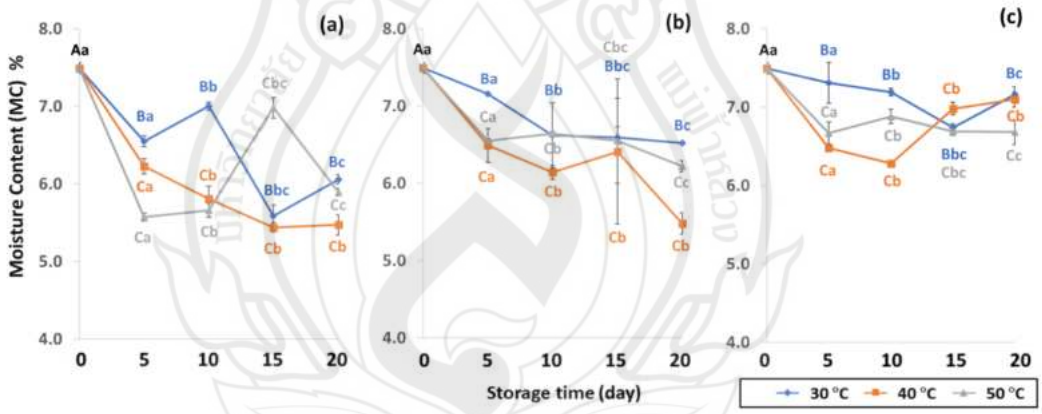
Lipid oxidation, physicochemical properties and oxidation results from different treatments were recorded as mean values ± standard deviations (n = 3). Statistical analysis was performed by analysis of variance (ANOVA) using SPSS statistical software (version 20, SPSS Inc., Chicago, IL, USA). Mean values were compared using Tukey's test ($p < 0.05$) to determine significant differences between the treatments. Principal component analysis (PCA) and hierarchical clustering analysis (HCA) were performed using R Statistical Software (v4.1.2, R Core Team, Indianapolis, IN, USA, 2021) and results were normalized to exclude dimensional consequences before analysis.

5.3 Results and Discussion

5.3.1 Effect of Accelerated Storage on Change of GCB Qualities

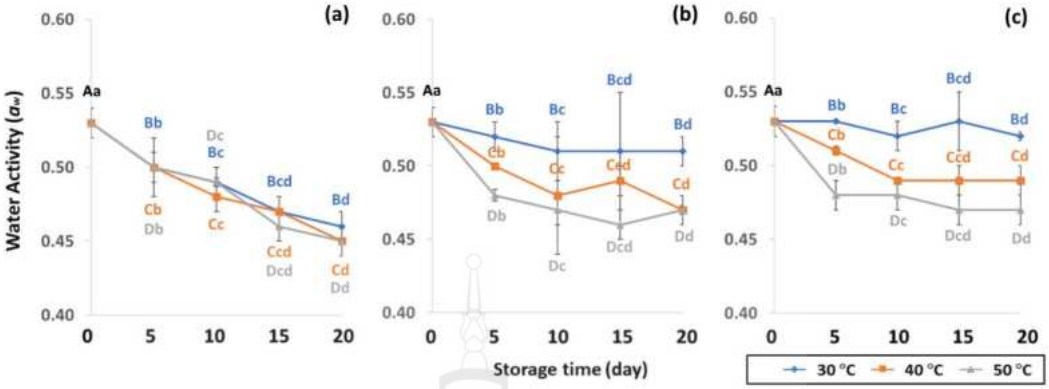
The moisture content (MC), water activity (a_w) and color of GCBs under various packaging and accelerated storage conditions are shown in Figures 5.2 and 5.3. Moisture content (MC), water activity (a_w) and color were significantly different ($p < 0.05$) after accelerated storage in PW, LDPE and GP bags at 30 °C, 40 °C and 50 °C. The initial MC of GCB was 7.49 ± 0.19%. Storage time and temperature influenced the significant decrease of MC ($p < 0.05$). GCB stored at longer storage time with a higher temperature resulted in a more significant decrease of MC. Results revealed that GP bags maintained the MC of GCB better than PW and LDPE bags. According to Erdawati (36), GP bags adequately maintained GCB moisture content for one year and were suitable for GCB storage on a commercial scale under modified and controlled atmospheric conditions (11). GP bags preserved GCB physical characteristics such as MC, shard, color and density, and also retained the contained compounds and chemical properties better than jute or plastic bags (11,14,15). The MC of GCB is an important quality attribute that is regulated by coffee exporting and importing countries, long-term storage and the roasting process (37). The optimal GCB moisture content is

between 9% and 12% (38). The initial MC content of green coffee beans was 7.49 ± 0.19% (w.b.), and lower than the safety range of 8 to 12.5% (w.b.) as the world coffee quality standard (38). Low MC content in GCB causes an undesirable appearance and the beans shrink, leading to poor-quality coffee (37,39,40). Lower MC with high unsaturated fatty acids in GCB forms oxidation reactions, producing rancid odors, loss of quality and secondary product oxidation (25). A previous study reported MC ranging from 5.52 to 7.38% in GCB (41). After 20 days of accelerated storage, MC reduced due to the high storage temperature of 50 °C, with a lower value compared to 30 °C and 40 °C. The GP bags were the best packaging for sustaining MC loss over LDPE and PW (Table 5.3). During the first 5, 10 and 15 days LDPE preserved the MC of GCB better than PW. PW bags allowed the free exchange of gases and water vapor between GCB and the ambient air and did not maintain specialty coffee quality (10). Thus, packaging and storage conditions are related to lipid oxidation and have a direct impact on grain MC.



Note Different capital letters indicate significant differences among temperature at $\rho < 0.05$: Different lower-case letters indicate significant differences among of storage time at $\rho < 0.05$.

Figure 5.2 Effect of packaging on changes in moisture content during accelerated storage conditions (a) PW, (b) LDPE and (c) GP



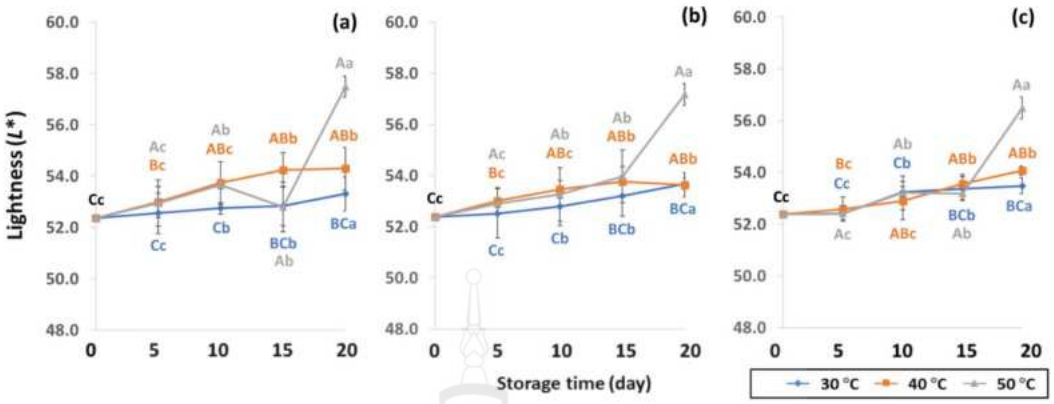
Note Different capital letters indicate significant differences among temperature at $\rho < 0.05$: Different lower-case letters indicate significant differences among of storage time at $\rho < 0.05$.

Figure 5.3 Effect of packaging on changes in water activity during accelerated storage conditions (a) PW, (b) LDPE and (c) GP

In the control samples, a_w content was 0.53 ± 0.01. Longer storage at 50 °C gave lower aw content of PW (0.45 to 0.50), LDPE (0.47 to 0.48) and GP (0.47–0.48), while 30 °C retained higher a_w content for longer than at 40 °C and 50 °C. As a result, GCB in GP bags had a lower change in a_w content than beans packed in PW and LDPE bags. The lower storage temperature of 30 °C was preferable to 40 °C and 50 °C for maintaining a_w that is required to protect the GCB during the drying phase of processing and storage to achieve and maintain the coffee quality (42,43). The a_w of GCB ranged from 0.45 to 0.53 and was similar to 0.45 to 0.55 as reported by Agudelo (44). According to de Oliver et al. (45), the a_w of GCB stored at 22 to 32 °C ranged between 0.95 and 0.99, which supported the growth of *A. carbonarius* and *A. chraceu*s. Lower a_w content than 0.45 did not present enough water to maintain green coffee bean quality (43), while aw content higher than 0.9 produced mold and fungi such as OTA (43,46). As a consequence, a_w is an important parameter for maintaining the physical properties of GCB during storage.

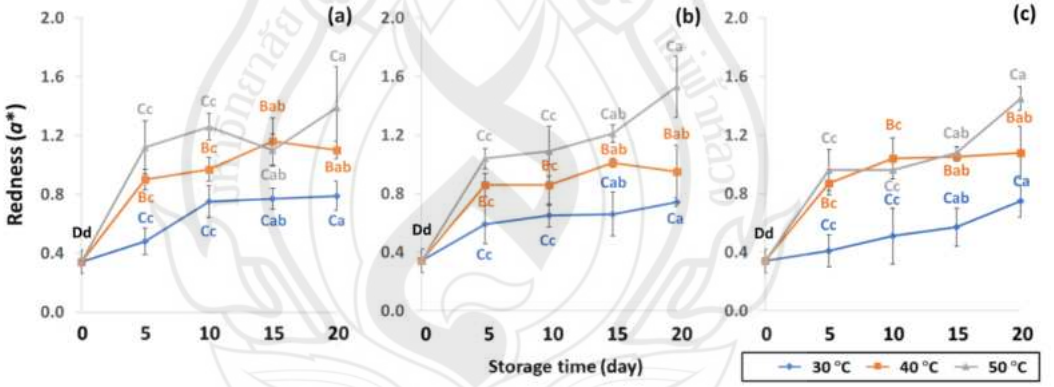
GCB color is an important indicator of freshness, spoilage and homogeneity that influences coffee flavor (18,22). Initial color values of the control GCB were 52.38 ± 0.07, 0.34 ± 0.08 and 10.01 ± 0.07 for L^*, a^* and b^*, respectively (Figures 5.4–5.6).

Longer storage of 20 days increased the lightness of GCB, with GP bags showing less change than LDPE and PW bags. The highest a^* value was recorded at 50 °C. Higher temperatures at longer storage contributed the most redness to GCB. Packaging types were not significantly different for changes of a^* under the same storage conditions (Table 5.3). The b^* values ranged from 10.1 ± 0.01 to 11.28 ± 0.22, with no significant differences under the same temperature conditions, while GCB color changed from bluish green to yellow. After 20 days of accelerated storage, GCB packed in LDPE and PW bags were brighter red and more yellow than those packed in GP bags. Faded GCB color resulted in a slightly bitter taste with woody or smoky notes (18,47). GCB packed in GP bags was described as having a medium bright-greenish-bluish coloration as shiny, translucent and fresh (18,47,48). The color of GCB is related to beverage quality, which strongly suggests that the oxidation process and natural enzymatic biochemical transformation are responsible for coffee flavor and aroma (15). Longer storage at 50 °C showed a significant increase in L^*, a^* and b^* compared to 30 °C and 40 °C. Higher temperatures of accelerated storage gave more brownish and yellowish coloration due to the Maillard reaction, as a strong indication of oxidation and enzymatic reaction. Moreover, after 20 days of storage at 50 °C, the silver skin on top of GCB broke up, making the bean whiter than in other accelerated storage conditions. The change in green coffee color during accelerated storage is related to low moisture content that results in lighter to whiter beans (11,49).



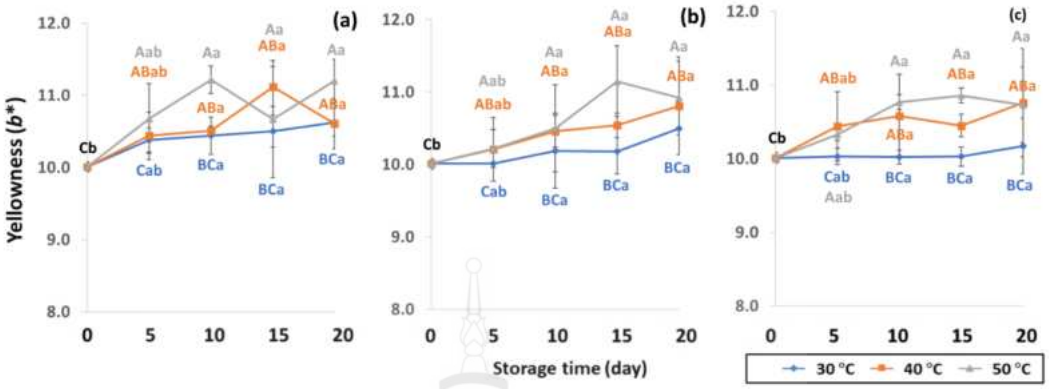
Note Different capital letters indicate significant differences among temperature at $\rho <$ 0.05: Different lower-case letters indicate significant differences among of storage time at $\rho < 0.05$.

Figure 5.4 Effect of packaging on changes in lightness during accelerated storage conditions (a) PW, (b) LDPE and (c) GP



Note Different capital letters indicate significant differences among temperature at $\rho <$ 0.05: Different lower-case letters indicate significant differences among of storage time at $\rho < 0.05$.

Figure 5.5 Effect of packaging on changes in redness during accelerated storage conditions (a) PW, (b) LDPE and (c) GP



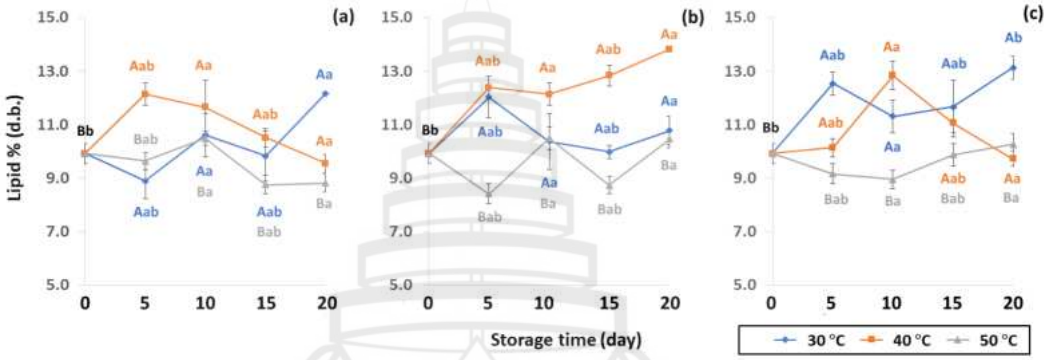
Note Different capital letters indicate significant differences among temperature at $\rho < 0.05$: Different lower-case letters indicate significant differences among of storage time at $\rho < 0.05$.

Figure 5.6 Effect of packaging on changes in yellowness during accelerated storage conditions (a) PW, (b) LDPE and (c) GP

5.3.2 Effects of Accelerated Storage Conditions on GCB Lipid Oxidation

The chemical properties of lipid content were impacted by packaging during accelerated storage. Lipid contributes to beverage quality by influencing texture (crispness, plasticity and viscosity of liquid), mouthfeel (creamy, oily, richness, smoothness, chocolate, butter or baked), appearance (color and opacity) and flavor (aroma and taste, like fruit or vegetable flavors) (50). Lipid content of GCB under accelerated storage ranged from 8.42 to 13.82% (d.b.). These results were in the same range as observed by Speer and Kolling-Speer (26) at 7 to 17%. Lipid content in GCB was also reported in the range of 10–15 % (51,52). Lipid content of GCB packed in PW, LDPE and GP bags was significantly different ($p < 0.05$), as shown in Figure 5.7. The initial value of lipid content in GCB was 9.92 ± 0.38 % (d.b.). During accelerated storage, lipid content ranged from 8.76–12.18%, 8.42–13.82% and 8.96–13.14% for PW, LDPE and GP bags, respectively, with LDPE providing the highest lipid content. The increasing trend of lipid content at 40 °C of LDPE was observed. However, there was no previous report on the increase of the lipid content of GCB during storage. On the other hand, Hou and Chang (53) reported that lipid content of soybeans stored for nine months increased from 17.18% to 20.36%. The destruction of phospholipids

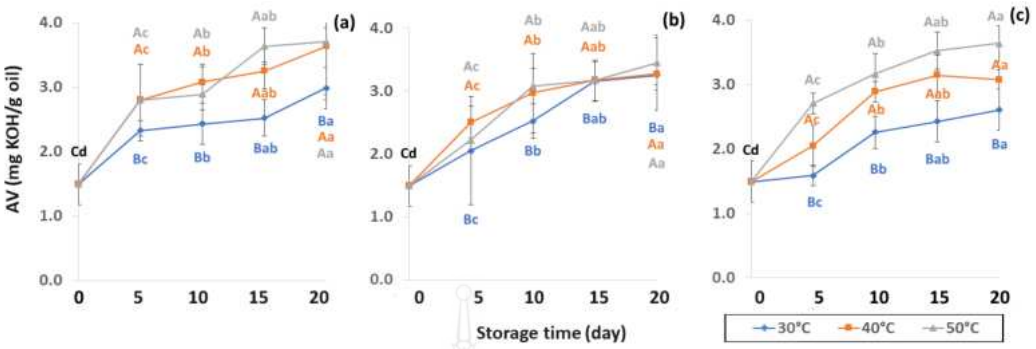
during storage forms compounds that may become extractable in petroleum ether. Storage temperature at 50 °C showed lower lipid content, resulting in lipid oxidation causing product off-flavor, loss of aroma and taste (19,50). Coffee lipid content is not only related to storage but is also impacted by particle size, surface area, choice of solvent and duration of extraction, processing, drying method and geographical origin (19,47,54,55). Storage conditions and packaging types significantly influenced changes of GCB lipid oxidation of GCB ($p < 0.05$) (Table 5.4).



Note Different capital letters indicate significant differences among temperature at $\rho < 0.05$: Different lower-case letters indicate significant differences among of storage time at $\rho < 0.05$.

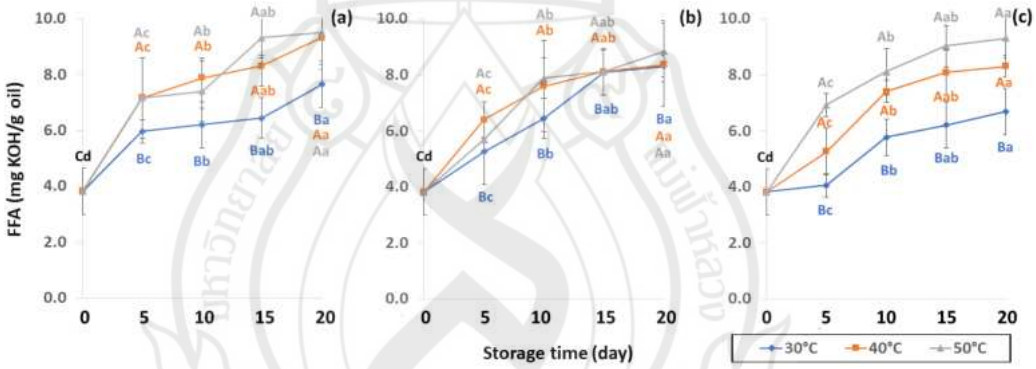
Figure 5.7 Effect of packaging on changes in lipid content during accelerated storage conditions (a) PW, (b) LDPE and (c) GP

Lipid oxidation, which is colorless and odorless, comprises the occurrence of primary oxidation, i.e., acid value (AV), free fatty acid (FFA), and peroxide value (PV), while secondary oxidation, i.e., ρ-anisidine value (PAV) and thiobarbituric acid reactive substances (TBARS) produce odors and off-flavors that decrease coffee quality. Initial values of primary oxidation in the control samples were AV (1.49 ± 0.32 mg KOH/g), FFA (3.82 ± 0.83 mg KOH/g), and PV (0.86 ± 0.12 meq/kg oil), as shown in Figures 5.8–5.10. AV is defined as primary oxidation, which reflects total acidity and the number of fatty acids (56). The AV of GCB significantly increased during storage for 20 days ($p < 0.05$). When GCB was conditioned at a higher temperature, AV and FFA levels rose faster. Arabica AV of GCB was higher than Robusta GCB at 0.79 to 1.28 (25), while AV was reported in various ranges of 3.89 mg KOH/g oil (57), 2.0 mg KOH/g (58) and 6.41 to 9.2 mg KOH/g (59).



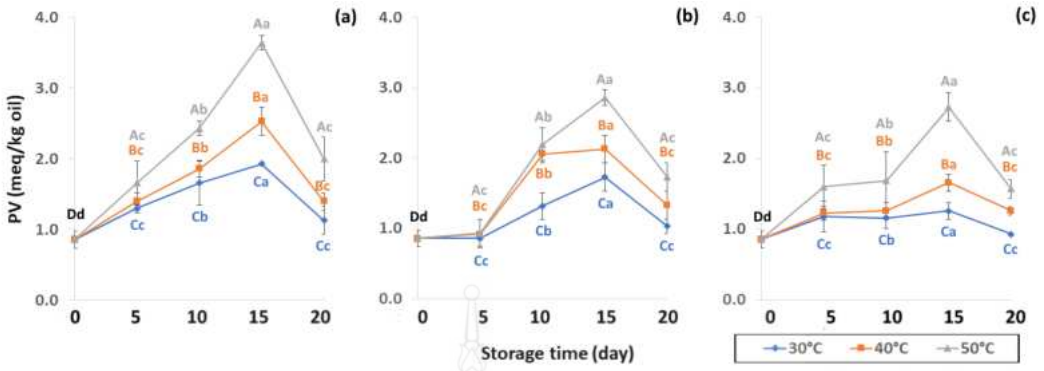
Note Different Capital Letters Indicate Significant Differences among Temperature at $\rho < 0.05$: Different Lower-case Letters Indicate Significant Differences among of Storage Time at $\rho < 0.05$.

Figure 5.8 Effect of Packaging on Changes in Acid Value (AV) during Accelerated Storage Conditions (a) PW, (b) LDPE and (c) GP



Note Different capital letters indicate significant differences among temperature at $\rho < 0.05$: Different lower-case letters indicate significant differences among of storage time at $\rho < 0.05$

Figure 5.9 Effect of packaging on changes in free fatty acid (FFA) content during accelerated storage conditions (a) PW, (b) LDPE and (c) GP



Note Different capital letters indicate significant differences among temperature at $\rho < 0.05$: Different lower-case letters indicate significant differences among of storage time at $\rho < 0.05$.

Figure 5.10 Effect of packaging on changes in peroxide value (PV) during accelerated storage conditions (a) PW, (b) LDPE and (c) GP

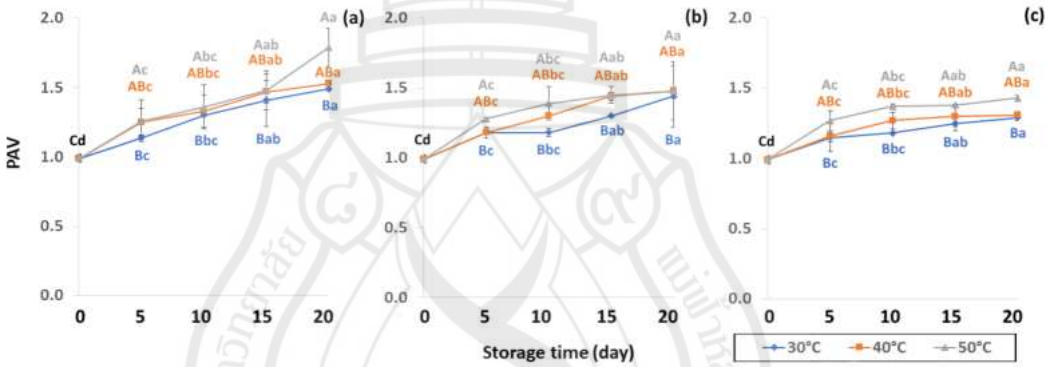
FFA contents of GCB were reported at 3.57 to 10.48 mg KOH/g oil by Dong et al. (59). FFA content formed after hydrolysis degradation of lipid molecules is measured by AV to specify the degree of rancidity in oil hydrolysis (25). Panpraneecharoen and Chumanee (60) considered PV and FFA as important parameters to determine the chemical quality of extracted coffee oil since both increased the oxidation reaction and reduced oil stability and degradation. Base-catalyzed esterification converts FFA extracted from oil into fatty acid methyl ester (FAME), an important parameter for maintaining product quality, with susceptibility to oxidation increased by high FFA (56). Cong et al. (25) reported that FFA content can be used to measure the hydrolytic rancidity of triglycerides caused by enzymatic or spontaneous hydrolysis. FFA is also commonly used as an indicator of fat hydrolysis.

The PV increased until 15 days of storage (Figure 5.10) with an increase in hydrogen peroxide concentration. The high PV of coffee oil samples indicated low oxidative rancidity. The initial presence of free radicals in coffee promotes free radical formation associated with the pyrolysis reaction, therefore PV increases during storage as a result of lipid oxidation (61). PV can be used as an oxidative index for the early stages of lipid oxidation with a slower increase to secondary oxidation. Initial PV concurred with Hong and Dong (62) who recorded 0.97 meq/kg of GCB. The PV

increased until day 15 and was then affected by secondary oxidation, similar to results reported by Budryn et al. (63), where PV slowed down after nine weeks of regular storage. During the oxidation process, an abundance of primary products, peroxides and hydroperoxides are formed in oils via autoxidation (25). PV is one of the most important initial products of autooxidation (64) that is related to oxidation caused by air at room temperature. Oxygen reacts with unsaturated fatty acids resulting in loss of flavor quality such as hay, grassy, green, fishy or sour as well as change in color and texture (64,65). The PW bags showed faster lipid oxidation than LDPE and GP bags. The PV increased from 5 to 15 days and then decreased at 20 days, indicating the beginning of secondary oxidation. The GP bags gave a lower oxidation reaction than LDPE and PW bags (Table 5.4). Storage at high temperature of 50 °C accelerated the coffee lipid oxidation reaction.

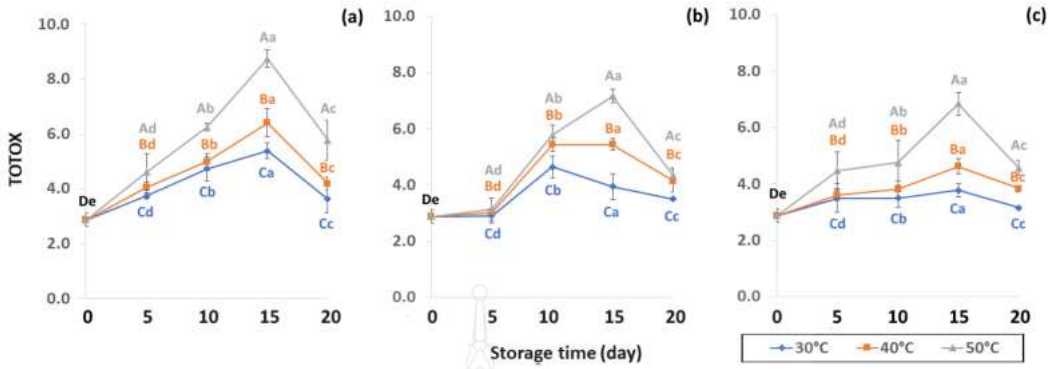
Initial values of secondary oxidation in the control samples were 0.99 ± 0.03, 2.87 ± 0.24 and 6.76 ± 2.27 MDA/g DW for PAV, TOTOX and TBARS, as shown in Figures 5.11–5.13. The PAV was similar to EI-Anany et al. (66) on roasted coffee oil (1.02). The initial TBARS value was also similar to Rendon et al. (16) at 8.8–10.2 MDA/g. PAV and TBARS are secondary terms for photooxidation and enzymatic oxidation that change relative to coffee flavor, taste, color and sensory characteristics (25,65,67). PAV oxidation products arise from lipid decomposition by hydroperoxide to carbonyl, ketone and aldehyde compounds (67). Acevedo et al. (68) suggested that PAV implies increased rancidity that impacted the quality, with increased oxidation of aldehydes and ketones in the end product. Results showed that greater amounts of secondary ethanol extract were generated at higher storage temperature. PAV contributes to the rancid flavor of oil, which can be detected by texture and mouthfeel. PAV with high concentration of secondary ethanol enhanced the oil flavor during storage (25), while TBARS increased significantly ($p < 0.05$) during accelerated storage (Figure 5.13). Dilnawaz et al. (69) found that increased TBARS was attributed to GCB extract containing many bioactive phytochemicals, polyphenols and flavonoids. TBARS are useful for determining secondary oxidation products that react with off-flavors such as ketones, esters, pyridines and other compounds. TBARS are malonaldehyde products that highly correlate to sensory scores (16,25). To inhibit secondary oxidation, GP was shown to be the optimal packaging to maintain GCB

quality. The TOTOX value includes data from primary and secondary oxidation analyses and indicates the overall oxidation stage of the oil under consideration (25). The TOTOX value of GCB was calculated using PV and PAV. The change in TOTOX value followed the same trend as PV. According to Equation (8), the TOTOX values were approximately 2.5 times higher than those of PV. The maximum values of TOTOX were found to be 8.74 ± 0.33, 7.17 ± 0.25 and 6.84 ± 0.41 for PW, LDPE and GP, respectively, on 15 days under 50 °C. The TOTOX value gradually increased after storage and decreased when secondary oxidation began (Figure 5.12). TOTOX results showed that LDPE and GP bags had better capability to maintain GCB quality at the beginning of storage than PW. However, at a longer storage time, GP was preferable to prevent change in GCB quality.



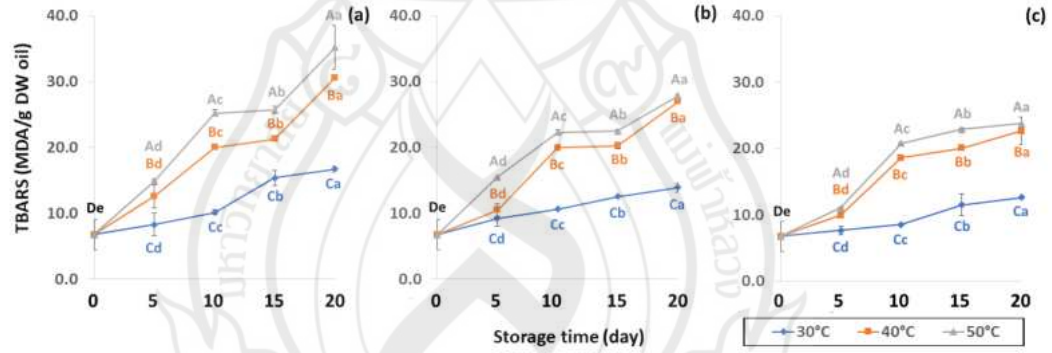
Note Different capital letters indicate significant differences among temperature at $\rho < 0.05$: Different lower-case letters indicate significant differences among of storage time at $\rho < 0.05$.

Figure 5.11 Effect of packaging on changes in ρ-anisidine value (PAV) during accelerated storage conditions (a) PW, (b) LDPE and (c) GP



Note Different capital letters indicate significant differences among temperature at $\rho < 0.05$: Different lower-case letters indicate significant differences among of storage time at $\rho < 0.05$.

Figure 5.12 Effect of packaging on changes in TOTOX content during accelerated storage conditions (a) PW, (b) LDPE and (c) GP



Note Different capital letters indicate significant differences among temperature at $\rho < 0.05$: Different lower-case letters indicate significant differences among of storage time at $\rho < 0.05$.

Figure 5.13 Effect of packaging on changes in TBARS during accelerated storage conditions (a) PW, (b) LDPE and (c) GP

5.3.3 Effects of Accelerated Storage Conditions on GCB Fatty Acid Profile

Changes in fatty acid composition under different accelerated storage conditions are shown in Table 5.2. GCB oil contained five major fatty acids as palmitic acid (C16:0), linoleic acid (C18:2), oleic acid (C18:1), stearic acid (C18:0) and arachidic acid (C20:0). Primary fatty acids of the control sample were C16:0 (35.64 ± 0.55 %) and C18:2 (41.61 ± 0.60 %), followed by C18:1 (10.00 ± 0.14 %), C18:0 (7.25 ± 0.04 %) and C20:0 (3.13 ± 0.02 %). The main fatty acids presented in coffee oil were saturated fatty acids (palmitic acid C16:0, stearic acid C18:0 and arachidic acid C20:0) and unsaturated fatty acids (linoleic acid C18:2 and oleic acid C18:1). Palmitic acid and linoleic acid were the two most abundant acids in GCB, similar to reports by several previous studies (22,70–72).

Fatty acids are essential components of coffee flavor and aroma that influence coffee quality (73). Unsaturated fatty acids (USFA), i.e., C18:2 and C18:1, were more prevalent than saturated fatty acids (SFA), including C16:0, C18:0 and C18:3. The amount of USFA decreased during storage, while SFA increased. Packaging type had no significant effect on change in total fatty acids (TFA) at the same storage time (Table 5.5). Longer storage caused a reduction in C18:0, C18:1 and C18:2, with an increase in C16:0 and C20:0 due to the oxidation reaction during accelerated storage. The high content of USFA provided less intense acidity, fragrance, body and flavor. Therefore, SFA including C16:0, C18:0 and C20:0 were likely discriminators of the sensory quality of specialty coffee (73,74). High polyunsaturated fatty acids negatively impact final coffee quality because the double bonds are easily broken down, promoting the formation of undesired odor compounds (25).

5.3.4 Principle Component Analysis (PCA)

Statistical analyses were performed to determine whether the oxidative parameters of coffee could be discriminated between packaging type and storage period. A dataset of moisture content, aw and oxidative parameters was used to perform PCA. For a storage temperature of 30 °C, the first two components of PCA explained 82.21% of the total variance (Figure 5.14). The control treatment is located on the left-hand side of the graphic, while storage values at 5 and 10 days are located at the center, and storage values for 15 and 20 days are located on the right-hand side of the graphic. GP packages were discriminated from other packages at the same storage time of 20

days (PC1 65.3 %). For storage at 40 °C and 50 °C, the first two components of the PCA explained 82.34 % and 76.93 % of the total variance, respectively. The GP package was discriminated by PC1 (70.76 %) from WP and LDPE. At 50 °C, GCB storage values at 5 and 10 days were distinguished from longer storage by PC1 (59.73 %). The biplot (Figure 5.14a) also shows that FFA, PAV, SFA, TBARS, TOTOX and PV had positive loadings on PC1, while USFA, a_w, MC and TFA had negative loadings on PC1. The loadings showed the same trend at higher storage temperatures of 40 °C and 50 °C. PV, TOTOX, PAV, AV, TBARS, SFA and TFA had positive loadings on PC1, while USFA, MC, and a_w had negative loadings. The PCA results showed that GCB data could be grouped based on storage time, while packaging type also influenced changes in the oxidative parameters. GCB packed in GP bags showed some minor overlap in the biplots with GCB packed in PW and LDPE bags at shorter storage times.

Table 5.2 Effect of Packaging on Changes in Fatty Acids during Accelerated Storage Conditions

Fatty Acid (%)	Packaging	Control	30 °C, 50% RH				40 °C, 50% RH				50 °C, 50% RH			
		Day 0	Day 5	Day 10	Day 15	Day 20	Day 5	Day 10	Day 15	Day 20	Day 5	Day 10	Day 15	Day 20
C16:0	PW	35.64	35.41	35.10	35.44	36.35	36.35	35.38	35.76	37.31	35.88	37.23	36.99	37.84
		±0.55Cc	±0.02Cc	±0.22Cb	±0.13Ca	±0.05Ca	±0.13BCa	±0.03BCa	±0.03BCa	±0.58BCa	±0.05Ac	±0.13Ab	±0.25Aa	34.84Aa
	LDPE	35.65	35.53	36.06	35.18	35.66	35.21	35.19	35.83	37.49	36.04	36.81	37.76	36.79
		±0.06Cc	±0.08Cc	±0.37Cb	±0.04Ca	±0.71Ca	±0.22BCa	±0.71BCa	±0.21BCa	±0.36BCa	±0.04Ac	±0.41Ab	±0.08Aa	±0.07Aa
	GP	35.66	35.31	35.12	35.60	35.19	35.76	37.32	37.11	37.01	37.60	37.01	37.23	37.24
		±0.06Cc	±0.04Cc	±0.04Cb	±0.06Ca	±0.05Ca	±0.04BCa	±0.19BCa	±0.01BCa	±0.04BCa	±0.02Ac	±0.04Ab	±0.05Aa	±018Aa
C18:0	PW	7.25	8.09	7.89	8.21	8.11	7.30	7.88	6.92	7.34	6.68	6.72	6.42	7.96
		±0.04Bbc	±0.01Ab	±0.01Ac	±0.01Ac	±0.02Aa	±0.04Bb	±0.04Bc	±0.04Bc	±0.37Ba	±0.02Cb	±0.17Cc	±0.03Cc	±0.03Ca
	LDPE	7.25	7.70	7.56	8.21	8.01	7.96	7.90	7.27	7.37	6.69	6.25	6.53	7.37
		±0.04Bbc	±0.02Ab	±0.08Ac	±0.15Ac	±0.03Aa	±0.07Bb	±0.25Bc	±0.06Bc	±0.37Ba	±0.02Cb	±0.06Cc	±0.01Cc	±0.13Ca
	GP	7.25	8.12	8.05	7.73	8.22	7.68b	6.44	7.07	7.50	6.47	6.45	6.85	6.97
		±0.04Bbc	±0.05Ab	±0.02Ac	±0.04Ac	±0.02Aa	±0.01Bb	±0.06Bc	±0.02Bc	±0.50Ba	±0.01Cb	±0.02Cc	±0.05Cc	±0.07Ca
C18:1	PW	10.00	10.07	9.57	10.12	9.76	9.58	9.71	9.30	8.82	8.87	9.58	9.11	8.95
		±0.14Aa	±0.07ABbc	±0.21ABab	±0.10ABbc	±0.04ABc	±0.22Bbc	±0.05Bab	±0.23Bbc	±0.29Bc	±0.06Cbc	±0.22Cab	±0.83Cbc	±0.46Cc
	LDPE	10.00	9.49	9.83	9.48	9.45	9.35	9.76	9.52	9.09	8.97	9.23	8.80	8.85
		±0.14Aa	±0.03ABbc	±0.34ABab	±0.06ABbc	±0.11ABc	±0.11Bbc	±0.37Bab	±0.23Bbc	±0.14Bc	±0.06Cbc	±0.05Cab	±0.08Cbc	±0.73Cc
	GP	10.00	9.70	9.98	9.59	9.84	9.86	9.26	9.23	8.71	8.55	9.55	8.82	9.03
		±0.14Aa	±0.06ABbc	±0.10ABab	±0.08ABbc	±0.51ABc	±0.02Bbc	±0.01Bab	±0.40Bbc	±0.02Bc	±0.05Cbc	±0.05Cab	±0.39Cbc	±0.65Cc

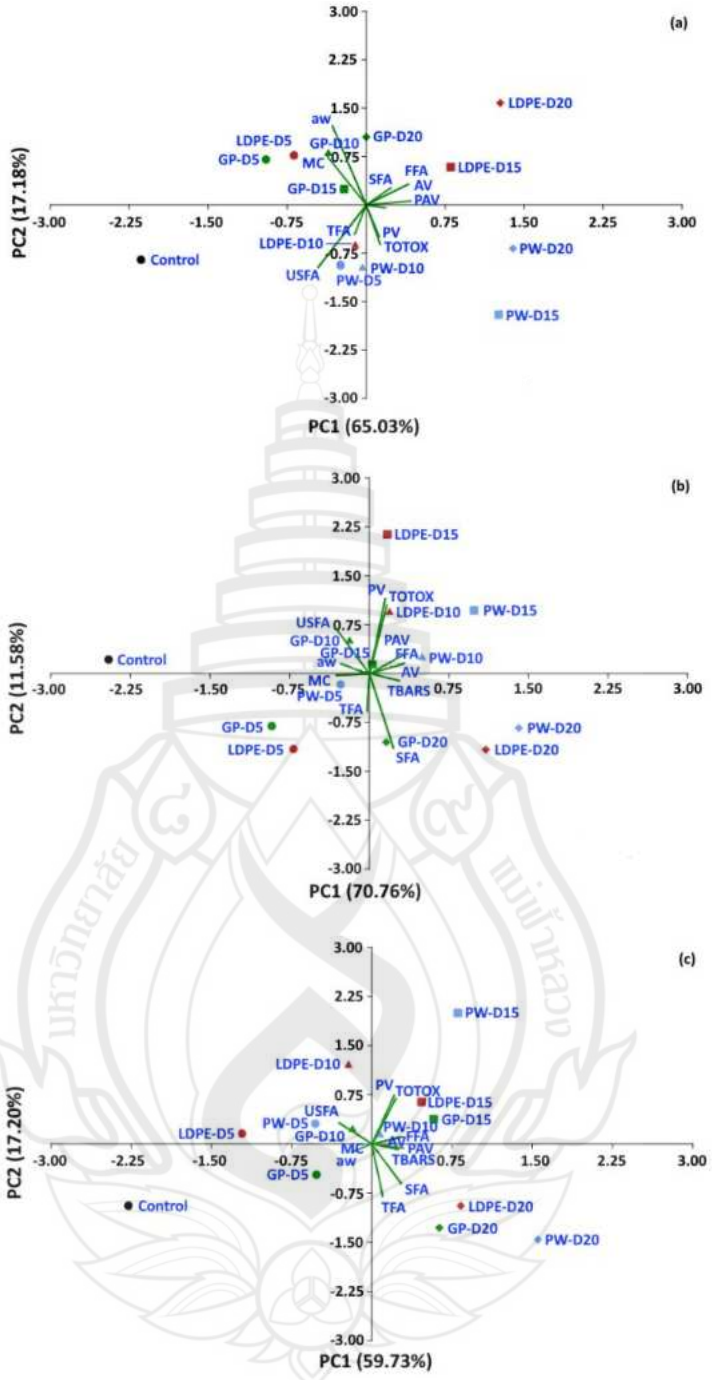
Table 5.2 (continued)

Fatty Acid (%)	Packaging	Control	30 °C, 50% RH				40 °C, 50% RH				50 °C, 50% RH			
		Day 0	Day 5	Day 10	Day 15	Day 20	Day 5	Day 10	Day 15	Day 20	Day 5	Day 10	Day 15	Day 20
C18:2	PW	41.61	40.64	41.15	39.91	40.28	40.69	40.32	40.99	41.00	41.39	40.72	41.25	40.44
		±0.60Aa	±0.56Cbc	±0.04Cab	±0.13Cbc	±0.56Cc	±0.31BCbc	±0.13BCab	±0.85BCbc	±0.04BCc	±0.35Bbc	±0.03Bab	±0.17Bbc	±0.04Bc
	LDPE	41.61	40.93	40.82	40.58	40.13	41.13	40.64	41.02	40.61	41.33	41.05	41.46	40.23
		±0.60Aa	±0.02Cbc	±0.26Cab	±0.04Cbc	±0.10Cc	±0.10BCbc	±0.05BCab	±0.22BCbc	±0.04BCc	±0.02Bbc	±0.01Bab	±0.46Bbc	±0.12Bc
	GP	41.61	40.58	40.22	40.75	40.70	40.56	40.54	41.01	41.01	41.80	40.63	41.34	40.79
		±0.60Aa	±0.04Cbc	±0.07Cab	±0.10Cbc	±0.10Cc	±0.09BCbc	±0.37BCab	±0.40BCbc	±0.01BCc	±0.01Bbc	±0.01Bab	±0.07Bbc	±0.15Bc
C20:0	PW	3.13	3.79	3.58	3.90	3.62	3.33	3.89	2.87	2.92	2.75	2.90	2.53	2.97
		±0.02Bb	±0.01Aa	±0.02Ab	±0.01Ab	±0.02Aa	±0.06Ba	±0.01Bb	±0.01Bb	±0.18Ba	±0.03Ca	±0.13Cb	±0.03Cb	±0.03Ca
	LDPE	3.13	3.42	3.28	3.89	3.63	3.93	3.82	3.15	2.81	2.69	2.61	2.57	3.49
		±0.02Bb	±0.01Aa	±0.12Ab	±0.03Ab	±0.01Aa	±0.07Ba	±0.20Bb	±0.11Bb	±0.15Ba	±0.10Ca	±0.05Cb	±0.01Cb	±0.41Ca
	GP	3.13	3.73	3.78	3.47	3.92	2.55	2.91	3.00	2.60	2.75	2.98	2.98	3.51
		±0.02Bb	±0.01Aa	±0.02Ab	±0.01Ab	±0.02Aa	±0.02Ba	±0.02Bb	±0.01Bb	±0.03Ba	±0.01Ca	±0.05Cb	±0.05Cb	±0.47Ca
SFA	PW	46.03	47.29	46.92	47.21	47.17	46.98	47.14	47.54	47.57	46.65	46.60	46.78	47.82
		±0.12Bc	±0.02Ab	±0.22Aa	±0.15Aa	±0.05Aa	±0.04Ab	±0.02Ab	±0.01Ab	±0.77Aa	±0.08Ab	±0.08Ab	±0.27Ab	±0.01Aa
	LDPE	46.03	46.65	46.89	47.27	47.30	47.11	46.91	46.25	47.67	45.42	45.66	46.86	47.65
		±0.12Bc	±0.08Ab	±0.17Aa	±0.01Aa	±0.08Aa	±0.08Ab	±0.26Ab	±0.05Ab	±0.58Aa	±0.01Ab	±0.51Ab	±0.08Ab	±0.35Aa
	GP	46.03	47.17	46.95	46.80	47.33	47.09	46.30	47.08	47.50	46.66	46.21	47.06	47.72
		±0.12Bc	±0.06Ab	±0.01Aa	±0.02Aa	±0.01Aa	±0.05Ab	±0.26Ab	±0.01Ab	±0.46Aa	±0.05Ab	±0.06Ab	±0.09Ab	±0.58Aa

Table 5.2 (continued)

Fatty Acid (%)	Packaging	Control	30 °C, 50% RH				40 °C, 50% RH				50 °C, 50% RH			
		Day 0	Day 5	Day 10	Day 15	Day 20	Day 5	Day 10	Day 15	Day 20	Day 5	Day 10	Day 15	Day 20
USFA	PW	51.61	50.71	50.71	50.03	50.04	50.27	50.03	50.29	49.83	50.36	50.31	50.36	49.39
		±0.74Aa	±0.49Bb	±0.17Bb	±0.04Bb	±0.52Bc	±0.53Bb	±0.08Bb	±0.80Bb	±0.25Bc	±0.41Bb	±0.25Bb	±0.66Bb	±0.50Bc
	LDPE	51.61	50.41	50.65	50.06	49.58	50.48	50.40	50.54	49.70	50.30	50.28	50.26	49.07
		±0.74Aa	±0.04Bb	±0.08Bb	±0.03Bb	±0.06Bc	±0.06Bb	±0.01Bb	±0.33Bb	±0.01Bc	±0.10Bb	±0.18Bb	±0.04Bb	±0.84Bc
	GP	51.61	50.28	50.20	50.53	50.29	50.40	50.40	50.27	50.23	50.51	50.18	50.16	49.82
		±0.74Aa	±0.02Bb	±0.01Bb	±0.01Bb	±0.01Bc	±0.60Bb	±0.36Bb	±0.41Bb	±0.40Bc	±0.08Bb	±0.05Bb	±0.32Bb	±0.50Bc
TFA	PW	97.63	97.99	97.63	97.23	97.21	97.24	97.17	97.24	97.83	97.39	97.66	97.15	98.16
		±0.85Aa	±0.51Ab	±0.05Ab	±0.11Aab	±0.57Aab	±0.49Ab	±0.07Ab	±0.09Aab	±0.52Aab	±0.32Bb	±0.52Bb	±0.68Bab	±0.51Bab
	LDPE	97.63	97.06	97.54	97.32	96.88	97.59	97.30	96.79	97.36	95.72	95.94	97.12	96.72
		±0.85Aa	±0.12Ab	±0.09Ab	±0.02Aab	±0.15Aab	±0.09Ab	±0.58Ab	±0.06Aab	±0.06Aab	±0.75Bb	±0.09Bb	±0.55Bab	±0.06Bab
	GP	97.63	97.44	97.14	97.33	97.62	97.49	96.70	97.35	97.74	97.17	96.39	97.22	97.54
		±0.85Aa	±0.01Ab	±0.01Ab	±0.02Aab	±0.02Aab	±0.55Ab	±0.62Ab	±0.40Aab	±0.07Aab	±0.13Bb	±0.02Bb	±0.23Bab	±0.08Bab

Note Data are presented as mean ± SD. Means with different capital letters in the same row indicate significant differences among temperature at $p<0.05$: Different lower-case letters in the same row indicate significant differences among storage time at $p<0.05$: PW = plastic woven; LDPE = low-density polyethylene; GP = GrainPro®; RH = relative humidity; C16:0 = palmitic acid; C18:0 = stearic acid; C18:1 = oleic acid; C18:2 = linoleic acid; C20:0 = arachidic acid; SFA = saturated fatty acids; USFA = unsaturated fatty acids; TFA = total fatty acids

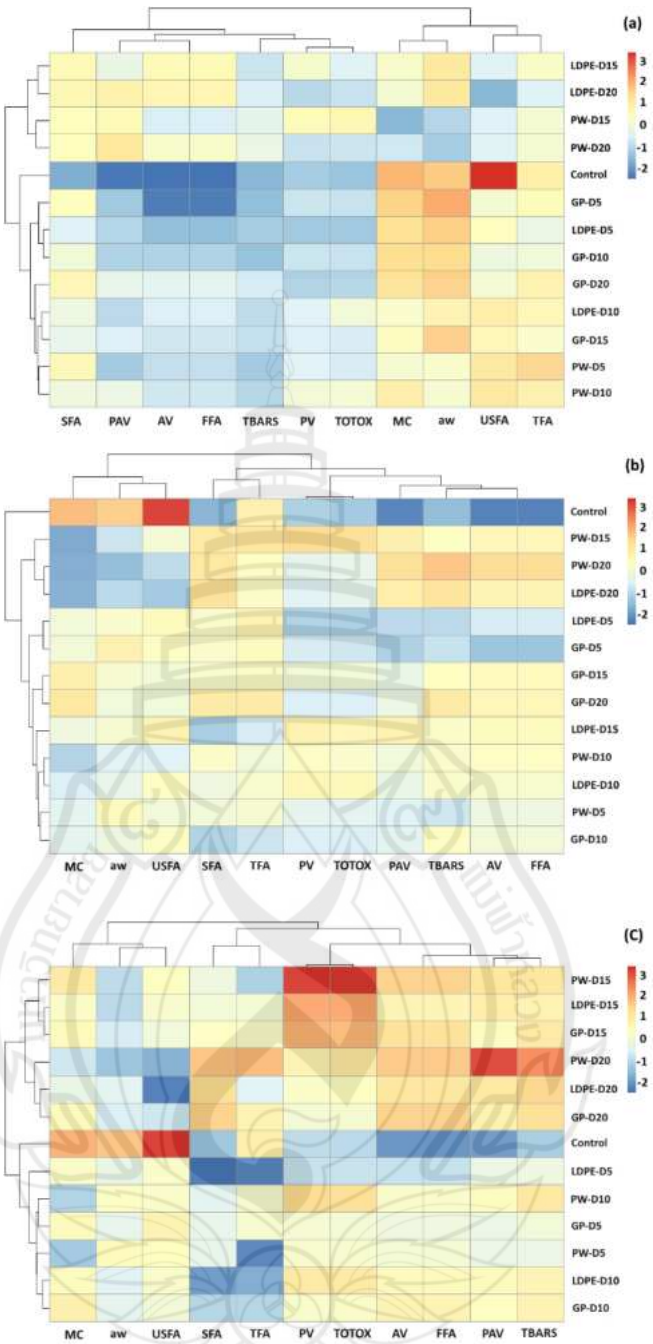


Note PW= plastic woven = LDPE, low-density polyethylene; GP = GrainPro®; a_w = water activity; MC = moisture content; PV = peroxide value; AV = acid value; PAV = *ρ*-anisidine value; TBARS = thiobarbituric acid reactive substances; TOTOX = total oxidation value; TFA = total fatty acids; FFA = free fatty acids; SFA = saturated fatty acids; USFA = unsaturated fatty acids.

Figure 5.14 Biplot of the oxidation-related parameters of GCB under accelerated storage at (a) 30 °C, (b) 40 °C and (c) 50 °C

5.3.5 Agglomerative Hierarchical Clustering (AHC) Analysis

According to the PCA results, overlaps were found for all storage temperatures (Figure 5.15). The effects of packaging influenced changes in GCB chemical components. Hierarchy clustering analysis (HCA) was performed to justify groups of GCB under different storage conditions. The clustering results were similar to those of the PCA biplot. At accelerated storage of 30 °C, GCB was grouped into three clusters. The first cluster was GCB with the control treatment, while the second cluster was GCB samples stored for 5 and 10 days with all packaging types. GCB packed in GP packages at 15 and 20 days were also classified into the second group. These results showed that the GP package delayed the change of oxidation reaction of GCB compared to PW and LDPE bags. The GCB stored at 15 and 20 days were classified into the third cluster, except for GP packaging. The control treatment for GCB stored at 5 to 10 days and GP packed at 15 and 20 days were characterized by MC, a_w, USFA and TFA. GCB stored at longer storage times of 15 and 20 days were characterized by SFA, PAV, AV and FFA. At accelerated storage of 40 °C and 50 °C, clear clusters were formed between the control treatment and stored GCB. The GP packaging exhibited superior capability to delay the change of oxidative parameters. Moreover, oxidative parameters of PV, TOTOX, PAV and TBARS characterized GCB stored for longer time periods.



Note PW = plastic woven; LDPE = low-density polyethylene; GP = GrainPro®; aw = water activity; MC = moisture content; PV = peroxide acid; PAV = *p*-anisidine value; TBARS = thiobarbituric acid reactive substances; TOTOX = total oxidation Value; TFA = total fatty acids; FFA = free fatty acids; SFA = saturated fatty acids; USFA = unsaturated fatty acids.

Figure 5.15 HCA of the oxidation-related parameters of GCB under accelerated storage at (a) 30 °C, (b) 40 °C and (c) 50 °C

5.4 Conclusions

Changes in physical and chemical characteristics of GCB after undergoing accelerated storage with different packaging types were investigated. Different degrees of lipid oxidation were observed. Higher temperatures and longer storage time lead to a higher degree of lipid oxidation and quality change of GCB. PV, AV, PAV, TOTOX, TBARS, FFA and SFA values increased, while MC, a_w and USFA decreased during storage. PCA and HCA portrayed the influences of storage conditions and packaging types on change in GCB quality. Hermetic (GP) packaging was optimal for maintaining GCB quality, while selecting proper packaging delayed changes in GCB quality.

5.5 Supplementary

Table 5.3 The Effect of the Type of Packaging on Physical Properties

Packaging	MC (%)	a_w	*L**	*a**	*b**
Control	7.49±0.07^{a}	0.53±0.01^{a}	52.38±0.07^{b}	0.34±0.08^{b}	10.01±0.07^{b}
PW	6.02±0.55^{d}	0.48±0.02^{c}	53.64±1.42^{a}	0.98±0.27^{a}	10.70±0.41^{a}
LDPE	6.45±0.46^{c}	0.49±0.02^{b}	53.62±1.30^{a}	0.93±0.28^{a}	10.47±0.47^{a}
GP	6.85±0.32^{b}	0.50±0.02^{b}	53.26±1.15^{a}	0.89±0.30^{a}	10.43±0.43^{ab}

Note Data are presented as mean ± SD. Means with different letters in the same column indicate significant differences at $p<0.05$. PW, plastic woven; LDPE, low-density polyethylene; GP, GrainPro®; MC moisture content, a_w, water activity; *L**, lightness; *a**, redness, and *b**, yellowness

Table 5.4 The Effect of the Type of Packaging on Oxidation Reaction

Packaging	Lipid	AV	FFA	PV	PAV	TOTOX	TBARS
Control	9.92±0.38^{b}	1.49±0.32^{b}	3.82±0.83^{b}	0.86±0.12^{c}	0.99±0.03^{b}	2.87±0.24^{c}	6.76±2.28^{d}
PW	10.26±1.28^{ab}	3.01±0.58^{a}	7.70±1.48^{a}	1.91±0.69^{a}	1.40±0.19^{a}	5.21±1.45^{a}	19.70±8.09^{a}
LDPE	11.05±1.64^{a}	2.90±0.55^{a}	7.43±1.45^{a}	1.59±0.63^{b}	1.35±0.14^{a}	4.50±1.29^{b}	17.70±6.33^{b}
GP	10.90±1.61^{a}	2.77±0.64^{a}	7.10±1.42^{a}	1.46±0.47^{b}	1.34±0.20^{a}	4.20±1.00^{b}	15.86±6.00^{c}

Note Data are presented as mean ± SD. Means with different letters in the same column indicate significant differences at $p<0.05$. PW, plastic woven; LDPE, low-density polyethylene; GP, GrainPro®; AV, acid value; FFA, free fatty acid; PV, peroxide value; PAV, p-anisidine value; TOTOX, total oxidation value; and TBARS thiobarbituric acid reactive substances.

Table 5.5 The effect of the type of packaging on fatty acids

Packaging	C16:0	C18:2	C18:1	C18:0	C20:0 ^{ns}	SFA	USFA	TFA
Control	35.65	41.61	10.00	7.25	3.13	46.03	51.61	97.63
	±0.06^{c}	±0.60^{a}	±0.14^{a}	±0.04^{b}	±0.02	±0.12^{b}	±0.74^{a}	±0.85^{a}
PW	36.34	40.74	9.45	7.49	3.25	47.14	50.20	97.24
	±1.01^{ab}	±0.54^{b}	±0.50^{b}	±0.63^{a}	±0.48	±0.57^{a}	±0.55^{b}	±0.81^{ab}
LDPE	36.13	40.83	9.31	7.40	3.27	46.80	50.14	96.94
	±0.90^{b}	±0.41^{b}	±0.39^{b}	±0.62^{ab}	±0.51	±0.73^{a}	±0.50^{b}	±0.69^{b}
GP	36.46	40.83	9.44	7.30	3.23	46.99	50.27	97.26
	±0.94^{a}	±0.43^{b}	±0.48^{b}	±0.66^{b}	±0.49	±0.47^{a}	±0.32^{b}	±0.44^{ab}

Note Data are presented as mean ± SD. Means with different letters in the same column indicate significant differences at $p<0.05$. PW, plastic woven; LDPE, low-density polyethylene; GP, GrainPro®; RH, relative humidity; C16:0, palmitic acid; C18:0, stearic acid; C18:1, oleic acid; C18:2, linoleic acid; C20:0, arachidic acid; SFA, saturated fatty acids; USFA, unsaturated fatty acids, TFA, total fatty acids, and *ns*, no significant

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CHAPTER 6

APPLICATION OF ATR-FTIR FOR GREEN ARABICA BEAN SHELF-LIFE DETERMINATION IN ACCELERATED STORAGE[3]

Abstract

Coffee bean oxidation is associated with enzymatic and non-enzymatic browning, the degradation of desirable aromatic compounds, the development of undesirable flavors, increased susceptibility to microbial spoilage, and volatile compound losses. This study investigated natural dry process (DP) and honey process (HP) green coffee beans stored in GrainProR bags for 0, 5, 10, and 20 days under accelerated storage conditions at 30 °C, 40 °C, and 50 °C with relative humidity of 50%. A kinetic model was used to estimate the shelf-life of the green coffee beans. DP recorded durability of 45.67, 29.9, and 24.92 days at 30 °C, 40 °C, and 50 °C, respectively, with HP 60.34, 38.07, and 19.22 days. Partial least squares (PLS) analysis was performed to build the models in order to predict the shelf-life of coffee based on peroxide (PV) and thiobarbituric acid reactive substances (TBARS) values. In terms of prediction with leave-one-out cross-validation (LOOCV), PLS provided a higher accuracy for TBARS (R2 = 0.801), while PV was lower (R2 = 0.469). However, the auto-prediction showed good agreement among the observed and predicted values in both PV (R2 = 0.802) and TBARS (R2 = 0.932). Based on the variable importance of projection (VIP) scores, the ATR-FTIR peaks as 3000–2825, 2154–2150, 1780–1712, 1487–2483, 1186–1126, 1107–1097, and 1012–949 cm^{-1} were identified to be the most related to PV and TBARS on green coffee beans shelf-life. ATR-FITR showed

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potential as a fast and accurate technique to evaluate the oxidation reaction that related to the loss of coffee quality during storage.

Keywords: Infrared Spectroscopy, Multivariate Analysis, Oxidation, Rancidity

6.1 Introduction

The global production and consumption of coffee are supported by a comprehensive market analysis, appreciated for its rich flavor, aroma, and stimulating properties (1). Arabica has fallen 7.1% to 94 million bags, while Robusta is set to rise 5.1% to 73 million bags (2). Several factors influence the final quality of coffee, including climate change (3), post-harvest (4), coffee processing (5–7), and storage (8–10), which negatively impact coffee quality assessment and the sensory characteristics of coffee, as well as the obtaining of optimal and market prices (11). Additionally, maintaining the quality of coffee throughout its shelf-life presents a significant challenge for Thai coffee producers, distributors, and consumers.

As coffee ages, it undergoes chemical changes that degrade its sensory attributes, leading to a loss flavor, aroma, and overall appeal (8–11). Also, the quality of the coffee could change while it is being stored, causing mold to grow and harmful compounds to develop. This could affect consumer health, manufacturing costs, and safety, depending on the beans' physicochemical properties, oxidation reactions, storage time, and environmental conditions (11–13). Thus, moisture content, density, lipid oxidation, and other chemical changes affect coffee odor, flavor, aroma, and overall sensory attributes (14–16). To maintain the quality during storage, GrainProR was applied, and it presented better results than other packaging (16,17). However, coffee still undergoes oxidation when exposed to air, light, and heat, resulting in the formation of volatile compounds such as aldehydes and ketones that are related to off flavors and rancid aromas (10,18,19), as well as the characteristic rich and nuanced flavor of coffee deteriorating, resulting in a flat taste (15). Furthermore, accelerated storage tests that measure peroxide (PV) and thiobarbituric acid reaction substances (TBARS) values provided insights into the extent of lipid oxidation. Monitoring these

values helps to assess the coffee's susceptibility to oxidative degradation and provides a quantitative means to evaluate shelf-life (15,20). A kinetic model helps to predict shelf-life using accelerated storage tests. Using an Arrhenius model shows how temperature influences degradation processes, enabling accurate predictions of shelf life under different conditions (15,20,21). Thus, understanding the factors influencing coffee deterioration and accurately assessing its shelf-life are crucial for ensuring product quality and consumer satisfaction. The applied shelf-life under accelerated storage could be subjective, time-consuming, and impractical for large-scale productions.

The adequate packaging, storage, and utilization of green coffee beans and roasted coffee beans are essential while applying non-destructive methodologies for inspecting, testing, and assessing the coffee characteristics without causing damage to the original parts (22,23). The FTIR spectrum can detect primary vibrations within the mid-infrared range, specifically between 4000 and 400 cm^{-1}. These vibrations arise when molecules absorb overtones and combinations of fundamental vibrational bands (24–26). Fourier transform infrared spectroscopy (FTIR) is a non-destructive technique that is used to assess the physical and chemical attributes, reactions, aroma compounds, sensory quality, and overall quality of green and roasted coffee beans (27,28). According to Barrios-Rodriguez et al. (27), the ATR-FTIR method could be used as an extra way to tell the difference between, and describe the taste outcomes of, different coffee processing (natural, semi-dry, and washed processes) and roasting conditions (medium and dark roasted). Additionally, ATR-FTIR has presented a valuable formation of the chemical composition of green and roasted coffee, e.g., water activity, moisture content, caffeine, lipid, chlorogenic acid (CGA), carbohydrate, trigonelline, and other compounds (24,29); the classification of the coffee variety (30); the fermentation technique (31); the geographical location (32,33); defects (34,35); adulterants (36); the determination of antioxidants (37,38); the quality of specialty coffee (39); and sensory characteristics (40,41). However, there is limited reporting on the use of ATR-FTIR on coffee shelf-life at the present. By employing ATR-FTIR, researchers and coffee producers can gain valuable insights into the chemical changes occurring in coffee over time, helping them determine its shelf-life and optimize storage conditions to maintain quality. The inherent chemical fingerprint of coffee, ATR-FTIR

allows for the rapid and non-destructive analysis of key components involved in coffee degradation.

In order to establish a direct relationship between the spectral characteristics and the shelf-life based on PV and TBARS values, multivariate analysis was applied. According to Tandee et al. (42), the calibration model was developed using partial least squares (PLS) regression. The predictive model PLS is effectively utilized in various applications, e.g., discriminating defects of coffee (43), classifying sensory attributes (40), and characterizing chemical compositions (44,45). Thus, the efficacy of PLS regression with FTIR data could develop robust and accurate calibration models for predicting coffee shelf-life from PV and TBARS values, ultimately enhancing quality control and product development processes in the coffee industry. Hence, the objective of this study was to investigate the shelf-life of green Arabica coffee beans from both natural and honey processes based on lipid oxidation reactions by their shelf-life determination with ATR-FTIR under accelerated storage conditions.

6.2 Materials and Methods

6.2.1 Sample Preparation

The coffee cherries (*C. arabica* L. cv. Catimor) used in this study were obtained from Doi Thep Sadet, Chiang Mai, Thailand during the 2021/2022 coffee cherry harvesting season at an altitude of 1300 to 1400 m, latitude 18.95156 north and longitude 99.3484 east. The freshness of the coffee cherries was carefully observed and controlled throughout the processing stage. All unnecessary materials such as dust, dirt, leaves, twigs, and floating cherries were removed, and whole coffee cherries were dried to a moisture content (MC) of 10±1% to produce the dry process (DP) samples. After de-pulping to get rid of the outer peel, the honey process (HP) samples were immediately dried until the MC reached 10±1%. Then, 250 g of green coffee bean samples were placed into GrainPro® bags as shown in Figure 6.1. GrainProR bags have the following specifications: an air permeability rating of 0.538 ± 0.04, a thickness of 0.124 ± 0.00 mm, and a surface area of 0.0445m^2. The measurement of air permeability was carried out using an approved air permeability tester (FX 3300 Lab Air IV, Textest

Instruments, Schwerzenbach, Switzerland) in compliance with the guidelines provided in ASTM D737-04. The parcels were divided into 20 × 20 cm^2 pieces, and the results were recorded in units of L/m^2. The thickness of the packages was measured using a thickness gauge (SMD-565J, Teclock, Nagano, Japan). The coffee bags were stored in a Constant Climate Chamber (HPP750, Memmert GmbH, Schwabach, Germany) with the temperature controlled at 30 °C, 40 °C, and 50 °C at 50% RH. Coffee samples were removed from the chamber every 5 days (0, 5, 10, 15, and 20 days). The samples were then packed into polyethylene vacuum-sealed packets and kept at −80 °C in an ultra-low temperature freezer (MDF-193, SANYO, Osaka, Japan) before quality determination. The day 0 samples, which served as the control, were created without packaging. Figure 6.2 shows the appearance of the green coffee beans at day 20.

Figure 6.1 Packages for Green Coffee Bean Storage. GrainPro® Bags (a) Natural Process, and (b) Honey Process

Figure 6.2 Green Coffee Bean Storage in GrainPro® Bags after 20 Days under Accelerated Storage Condition

6.2.2 Moisture Content (MC)

Moisture content (MC) was measured by drying the coffee beans in a hot air oven at 70 ± 1 °C for 16.0 ± 0.5 h to achieve constant weight according to the AOAC method 979.12 (46) and calculated using Equation (1). The samples were taken in three replicates and expressed as percentages on a wet basis (%w.b.):

$$\% \text{ Moisture} = (\text{Weight loss on drying (g)} / \text{Weight of sample (g)}) \times 100 \quad (1)$$

6.2.3 Water Activity (a_w)

The water activity (a_w) of the ground green coffee bean samples was determined using a water activity meter (Aqua Lab, Decagon, WA, USA) at 25 °C with auto-analysis. a_w values were recorded as the mean of the three replicates (47).

6.2.4 Coffee Oil Extraction

Coffee oil samples were prepared using solvent extraction as described in previous studies (15,16). Petroleum ether (400 mL) in a 500 mL Erlenmeyer flask was used to extract a 50 g sample of green coffee powder, utilizing an ultrasonic water bath (SS 304 Automatic UltrasonicWater Bath, ASK-06A LAB Instruments, Hyderabad, India) at room temperature up to 25 °C for 30 min. The petroleum ether was then evaporated using a vacuum rotary evaporator after the samples had been filtered using Whatman Paper No. 4. A 50 mL sample vial constructed of amber borosilicate glass

was then used to transfer the extracted oil from the collected oil. The vial had a rubber cap to create a tight polytetrafluoroethylene seal. The oil was kept at 2 °C until subjected to additional examination.

6.2.5 Lipid Extraction Determination

6.2.5.1 Peroxide Value (PV)

The PV was measured following the AOAC Official Method 965.33 (47). One gram of oil sample (S) and a blank (B) were first prepared in two 250 mL Erlenmeyer flasks. Then, 30 mL of a mixed solvent of chloroform–acetic acid (2:3 v/v) was added. Next, each flask received 0.5 mL of saturated KI solution and was shaken and left to stand in the dark for 1 min. The reaction was stopped by adding 30 mL of distilled water to the combined samples. The mixture was then titrated with 0.002 M sodium thiosulfate until the blue tint disappeared. The outcome was recorded in milliequivalents of peroxide per kilogram of oil (meq/kg of oil) using Equation (2):

$$\text{PV (meq/kg samples)} = (2 \times (\text{Samples} - \text{Blank})\ \text{mL}) / \text{weight of oil (g)} \quad (2)$$

6.2.5.2 Measurement of Thiobabituric Acid Reactive Substances (TBARs)

The measurement of TBARS followed Rendon et al. (4). First, 4 mL of 1% (w/v) trichloroacetic acid (TCA) containing 0.08 g of polyvinylpolypyrrolidone (PVPP) and 0.2 g of the ground coffee sample were combined. The mixture was then continuously homogenized for 30 min before centrifuging for 10 min at 7 °C at 20,000 rpm. A 20 % TCA (w/v) solution was added, and the supernatant contained 0.5 mL of 0.5 % (w/v) thiobarbituric acid. The reaction mixture was placed in a water bath for 30 min before cooling and centrifuging at 10,000 rpm, 10 °C for 10 min. Quantification was performed by a spectrophotometer (Agilent Technologies, Santa Clara, CA, USA) at 532 and 600 nm using an extinction coefficient of $155 mM^{-1}\ cm^{-1}$, with results expressed as nmol of MDA/g of sample (d.w.).

6.2.6 Shelf-Life Prediction

Kinetic models were utilized to calculate the shelf-life prediction of green coffee beans (15,20), and integrated using the Arrhenius equation. This related the rate of time to three specific temperatures (30 °C, 40 °C, and 50 °C) under accelerated storage

conditions with 50% RH. Equations (3)–(6) are presented below. The kinetic parameters were estimated using Microsoft Excel (version 2405):

$$\text{Zero-order model: } PV = k_0 t + PV_0 \quad (3)$$

$$\text{First-order model: } PV = kt + \ln(PV_0) \quad (4)$$

$$\text{Arrhenius equation: } \ln(k) = -E_a/RT + \ln(k_0) \quad (5)$$

$$\text{Shelf-life prediction: } SL = (\ln(PV) - \ln(PV_0))/(k_0 e(-E_a/RT)) \quad (6)$$

where k_0 and k are the reaction rate constants. PV and PV_0 are the PVs at storage time. t is the initial value. k_0 is a pre-exponential factor, and E_a is the activation energy (J mol^{-1}). T is the absolute temperature, R is the molar gas content (8.3144 J K^{-2} mol^{-2}), and SL is the shelf-life prediction.

6.2.7 FTIR Spectroscopy Analysis

A Fourier Transform Infrared (ATR-FTIR) spectrophotometer (Cary 630, Agilent Technologies, Santa Clara, CA, USA) (24,27) was used to conduct the analysis. The coffee samples were ground using a grinder to achieve a particle size of 200 ± 25 μm. The spectrophotometer was outfitted with a deuterated L-alanine doped triglycine sulfate (DLATGS) detector and a diamond attenuated total reflectance (ATR) sample attachment. All measurements were conducted within the 4000 to 400 cm^{-1} spectral region at a resolution of 4 cm^{-1} and 16 scans in a dry atmospheric environment at room temperature (20 ± 0.5 °C).

6.2.8 Statistical Analysis

The results of MC, aw, PV, and TBARS were recorded as mean values of three replicates with standard deviations (n=3). Analysis of variance (ANOVA) was carried out using SPSS statistical software (version 20, SPSS Inc., Chicago, IL, USA). Tukey's test ($p \leq 0.05$) was used to compare the mean data and identify significant variations between the treatments. MATLABR (version 7.9.2009, MathWorks, Natick, MA, USA) was used to perform partial least squares (PLS) regression and principal component analysis (PCA) using ATR-FTIR data along with other parameters, e.g., MC, a_w, PV, and TBARS, and shelf-life.

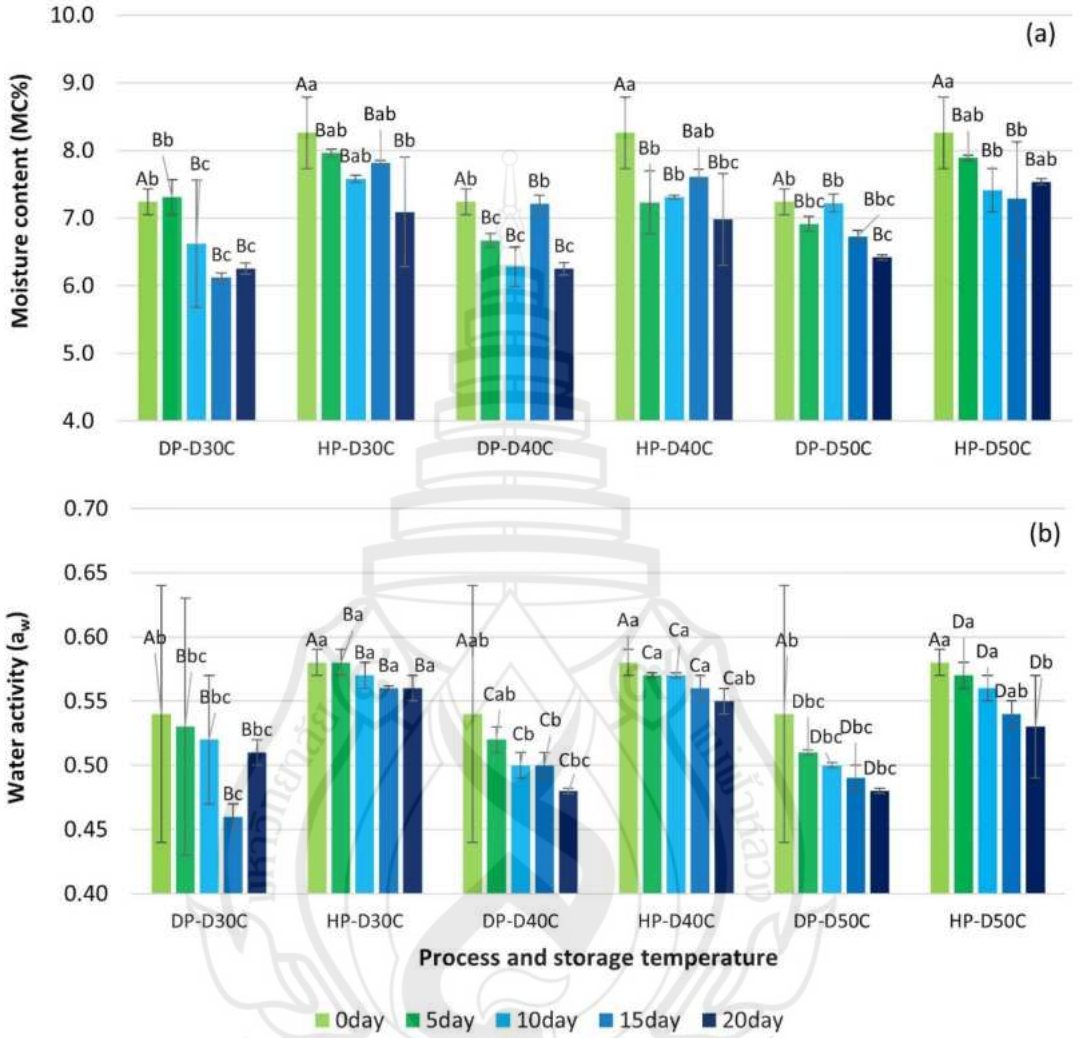
6.3 Results and Discussion

6.3.1 Moisture Content and Water Activity Parameter of Green Coffee Beans

Under accelerated storage in GrainPro® bags, the moisture content (MC) and water activity (a_w) values of green coffee beans from the natural process (DP) and honey process (HP) are shown in Figure 6.3a,b. The MC and aw values of green coffee beans from different processing conditions significantly reduced ($p < 0.05$) after 20 days of accelerated storage in GrainPro® bags at 30 °C, 40 °C, and 50 °C. Achata et al. (48) stated the most important attributes when assessing the quality and stability of dried food shelf-life as MC and a_w. The MC of DP and HP coffee beans ranged from 7.31 ± 0.26 to 6.12 ± 0.07 and from 8.26 ± 0.53 to 7.09 ± 0.81, respectively, after 20 days of storage. The optimal MC of a green coffee bean is between 9% and 12%; hence, the sample was lower than the normal MC ranges. Green coffee beans with low MC produce the unsatisfactory results of an unpleasant aroma and poor-quality beans (16). Under storage, MC is impacted by chemical interactions and oxidative deterioration in the packaging, leading to rancid aromas, quality loss, and secondary oxidation (16,49).

The a_w reductions in DP and HP coffee beans ranged from 0.54 ± 0.04 to 0.46 ± 0.01 and 0.58 ± 0.01 to 0.53 ± 0.04, respectively. By contrast to the HP procedure, DP coffee beans gave the most significant reduction in aw during a 20-day storage period. The storage of samples at a lower temperature of 30 °C resulted in a higher aw content compared to storage at 40 °C and 50 °C. This finding concurred with Michalak et al. (50), who also observed elevated a_w levels at a significantly lower temperature of 25 °C. Orfanou et al. (51) found that shelf-life was significantly influenced by storage temperature and aw. Values of a_w below 0.52 significantly affected the sensory attributes of coffee including aroma intensity, fragrance quality, aftertaste, and the formation of off flavors (51). The shelf-life was around 20 days when the a_w value was below 0.36 (21). Manzocco and Nicoli (52) presented empirical findings indicating that the parameter aw exhibited temperature dependency, resulting in alterations to both the apparent activation energy and the frequency factor within the framework of the

modified Arrhenius equation. When the a_w value is between 0.52 and 0.8, an Arrhenius-type correlation exists between the rate of H3O+ generation and the temperature (52).



Note Different capital letters indicate significant differences in temperature at p<0.05: Different lowercase letters indicate significant differences in storage time at p<0.05: DP-D30C = natural process storage at 30°C, HP-D30C = honey process storage at 30°C, DP-D40C = natural process storage at 40°C, HP-D40C = honey process storage at 40°C, DP-D50C = natural process storage at 50°C; HP-D50C = honey process storage at 50°C.

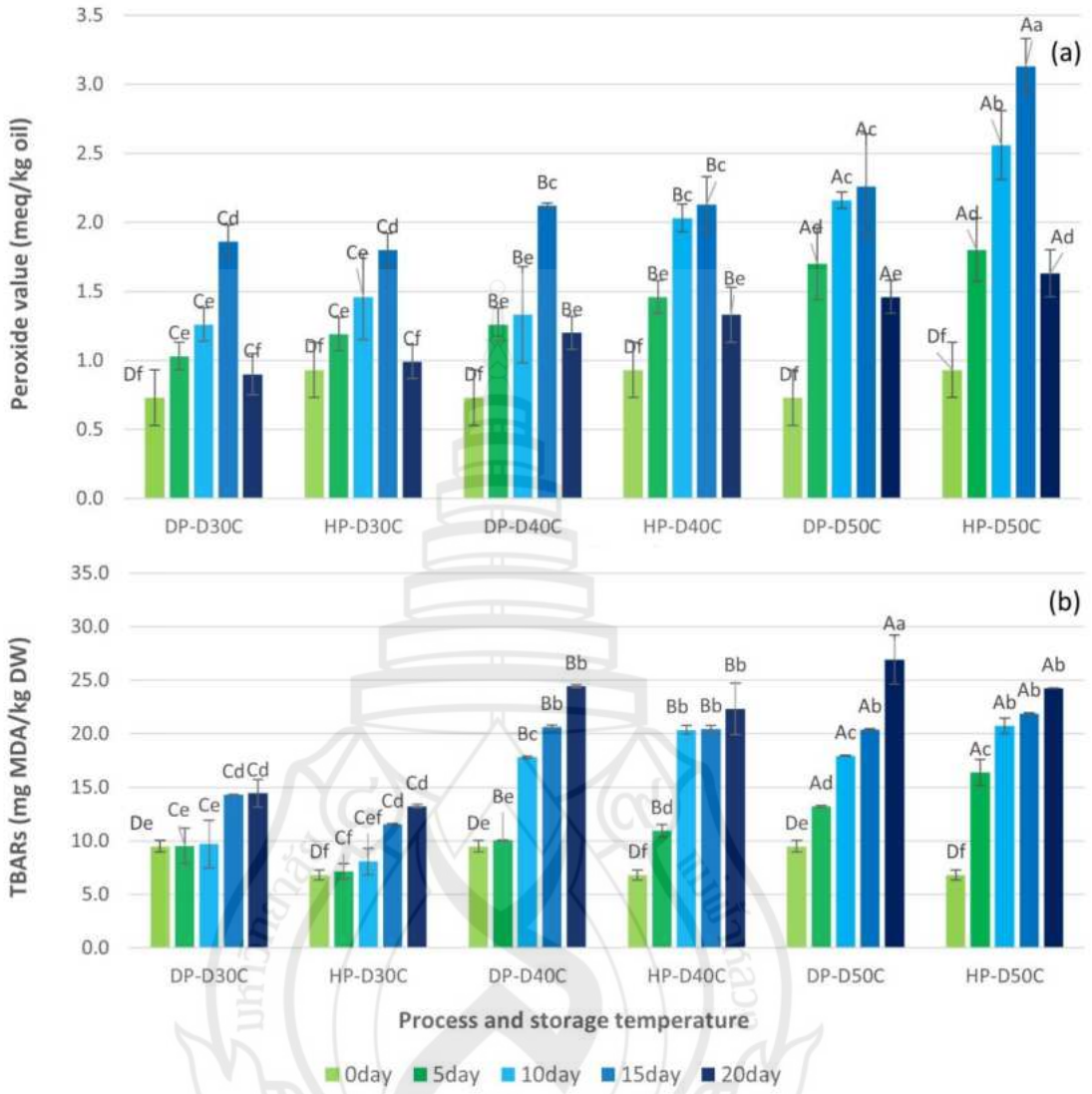
Figure 6.3 Effect of Storage Conditions on Changes in (a) Moisture Contents and (b) Water Activity during Accelerated Storage Conditions

6.3.2 Oxidation Reactions of Green Coffee Beans

Shelf-life, volatile loss, physical collapse, loss of pleasant fragrance components, and off-flavors are all impacted by the rate of coffee oxidation reactions (20). The two most significant lipid oxidation statistics were PV and TBARS (15,20). Figure 6.4 shows the PV and TBARS values for DP and HP. Aung Moon et al. (16) also reported that PV and TBARS values of the washed process changed with increasing storage temperature and storage time. The PV developed as a primary reaction, while TBARS presented as secondary oxidation. Parvathy et al. (53) recorded the main sources of lipid oxidation as PV and TBARS, giving unfavorable alterations to flavor, aroma, texture, color, and nutritional value. The peroxide value (PV) concentration of DP and HP varied within the ranges of 0.73 ± 0.20 to 2.26 ± 0.06 and 0.93 ± 0.20 to 3.13 ± 0.20 meq/kg oil, respectively. The PV values obtained from DP and HP after 20 days of accelerated storage were below 3.13 meq/kg oil. Anese et al. (21) also reported PV values below 2 meq/kg oil, while Yoon et al. (54) reported PV values below 3 meq/kg in a milk beverage mixed with coffee extract. The PV value increased until 15 days before physical changes occurred, causing a disagreeable scent and off-flavor. The PV is a major product generated in oil by auto-oxidation processes with an increase in hydroperoxide reported by Cong et al. (15). PV production occurs exponentially, with accumulation until subsequent reactions produce breakdown products such as aldehydes (15,55). PV increases due to the introduction of highly reactive radical species into the product, which promotes oxidation (55). This may lead to a reduction in the quality of the coffee and its ability to be stored for extended periods.

The highest PV content was found in HP, followed by DP. HP reacted with mucilage dried coffee on both skin-dried and parchment-dried coffee, producing yellow, red, and black honey coffee (5,56). Microorganisms devoured sugars and other substances on the mucilage section and then broke them down into byproducts that were absorbed into the cellular structure of the green coffee bean, leading to a more yellow-brown bean than the washing procedure (57,58). The TBARS contents of DP and HP ranged from 9.48 ± 0.55 to 26.92 ± 2.28 and 6.81 ± 0.46 to 24.25 ± 0.03 mg MDA/kgDW, respectively. The value of TBARS increased during accelerated storage, consistent with the outcome described by Rendon et al. (4). Thiobarbituric acid (TBA) and malonaldehyde (MDA) were formed during the final stage of lipid oxidation by the

breakdown of hydroperoxides obtained from fatty acids with three or more double bonds and reacted in the TBARS test (4,15). Following 20 days of accelerated storage, the TBARS values of DP and HP were comparatively higher than those reported by Aung Moon et al. (16) for washed processing. DP and HP may develop a more undesirable odor and a greener appearance. As a result, the fungi and mold that produced the auto-oxidation, photo-oxidation, and enzymatic oxidation reactions had a higher impact on HP and DP during storage. After three months of storage, Borem et al. (9) noted that DP green coffee beans packed in permeable paper bags had sensory quality damage, with a cardboard or old crop flavor. However, HP changes were noted during the ninth month of storage. Natural coffee loses its sensory qualities faster than pulped natural coffee or honey (9). TBARS was consistent with coffee bean respiration being interrupted during storage at temperatures lower than 40 °C and 50 °C. TBARS are lipid oxidation byproducts that combine with proteins to create polymers (4). TBARS levels are more sensitive to ketones, esters, pyridines, and other chemicals (15).



Note Different capital letters indicate significant differences in temperature at $p<0.05$: different lowercase letters indicate significant differences in storage time at $p<0.05$: DP-D30C = natural process storage at 30 °C; HP-D30C = honey process storage at 30 °C; DP-D40C = natural process storage at 40 °C; HP-D40C = honey process storage at 40 °C; DP-D50C = natural process storage at 50 °C; HP-D50C = honey process storage at 50 °C.

Figure 6.4 Changes in the Oxidation Reactions of Green Coffee Beans during the Natural and Honey Processes; (a) Peroxide Value, and (b) TBARS

6.3.3 Shelf-Life of Green Coffee Beans

A kinetic model and Arrhenius equations were used to investigate the shelf-life of green coffee beans. This approach has been used to predict the shelf-life of green coffee beans (15), coffee brew (59), and capsule packaging (60). Table 6.1 shows the shelf life of green coffee beans calculated based on the different lipid oxidation parameters, e.g., PV and TBARS. The shelf-life of DP at 30 °C, 40 °C, and 50 °C was 35.57, 25.64, and 21.10 days, with HP 51.50, 33.88, and 15.26 days, respectively. The secondary oxidation of TBARS, the shelf-life of DP was 10.1, 4.25, and 3.82 days, and HP was 8.84, 4.19, and 3.96 days at 30 °C, 40 °C, and 50 °C, respectively. Green coffee beans stored at 30 °C had a longer shelf-life than those stored at 40 °C and 50 °C, with HP processing showing a longer shelf-life than DP processing at 30 °C. HP drying with parchment and mucilage can dehydrate moisture content and reduce water activity faster during drying and storage, thereby impacting the transition to a whiter bean, the shade size, and the yellowish color (8). HP and DP had lower shelf-life at high-temperature storage of 50 °C. By contrast, the aw impact on the kinetics of shelf-life deterioration was attributed to the involvement of non-enzymatic browning (61).

Table 6.1 Shelf-Life of Green Coffee Beans with Different Processing Methods and Storage Temperatures.

Temperature	Process	PV		TBARS	
		R^2	Shelf-Life (Days)	R^2	Shelf-Life (Days)
30°C	DP	0.95	35.57 ± 1.69^{b}	0.99	10.01 ± 0.27^{a}
	HP	0.89	51.50 ± 1.83^{a}	0.99	8.84 ± 0.44^{ab}
40°C	DP	0.91	25.65 ± 1.67^{c}	0.96	4.25 ± 0.10^{c}
	HP	0.90	33.88 ± 2.00^{b}	0.92	4.19 ± 0.23^{c}
50°C	DP	0.87	21.10 ± 3.71^{cd}	0.98	3.82 ± 0.10^{c}
	HP	0.99	15.26 ± 0.63^{d}	0.93	3.96 ± 0.16^{c}

Note Data are presented as mean ± SD. DP = natural process; HP = honey process. a–d: Mean values with different superscript within the same columns indicate significance among different processing, temperature, and time at (p<0.05).

6.3.4 ATR-FTIR Spectra of Green Coffee Beans

The FTIR technique was used to explore the physicochemical structures of DP and HP, as well as their mixtures at different temperatures (30 °C, 40 °C, and 50 °C) and storage times (0, 5, 10, 15, and 20 days). The absorbance region of green coffee beans ranged from 4000 to 400 cm^{-1}. The same peak structure line-up was shown in the infrared spectra of DP (Figure 6.5a–c), and HP (Figure 6.5d–f) under varied accelerated storage conditions. The spectrogram showed the main regions of 12 absorbance peaks at wavenumbers 3313, 3010, 2854, 1745, 1645, 1458, 1377, 1248, 1157, 1049, and 715 cm^{-1}. Fagan and O'Donnell (62) divided the wavenumbers into two groups: a functional group, 4000 to 1450 cm^{-1}, and a fingerprint group, 1450 to 400 cm^{-1}.

The absorbance peak at 3313 cm^{-1} was attributed to the stretching of O-H bonds in relation to a_w and MC (24,62). This peak was also connected with the stretching vibration of O-H bonds in hydroperoxides 3444 cm^{-1} (37), as well as the stretching of O-H bonds in alcohols and water (3280 cm^{-1}) by Tsiaka et al. (63). After a 20-day storage period, the coffee beans exhibited decreased MC and aw values. HP showed the smallest loss, followed by DP. DP involved longer sun drying than the other process, which caused a decrease in O-H stretching associated with water molecules, with reduced MC and aw (24,29). During drying, fermentation occurs, leading to the creation of hydroperoxides and causing a decrease intensity of the O-H stretching peak at 3444 cm^{-1} (37). Using a regulated fermentation process (DP technique) reduced the production of alcohols, thereby impacting O-H stretching 3280 cm^{-1} (37).

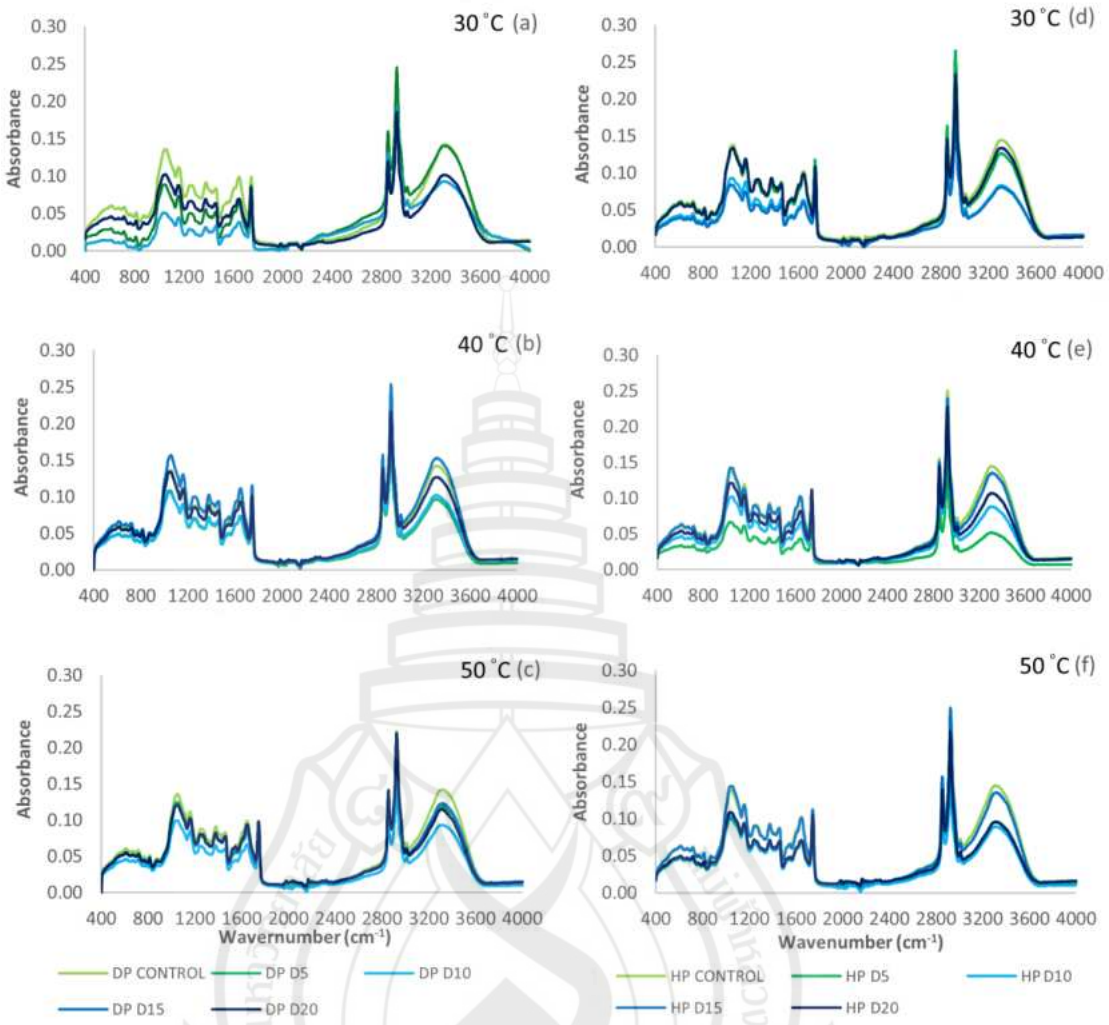
The wavenumber peaks observed within the range of 3010 cm^{-1} were associated with the symmetric vibration of C-H stretching in cis double bonds 3009 cm^{-1} as reported by Raba et al. (37). These peaks might also be attributed to C-H stretching in aromatic rings (3130–3010 cm^{-1}) as described by Tsiaka et al. (63). The efficacy of the DP and HP methods diminished over 20 days of accelerated storage. The peaks at 2925 and 2854 cm^{-1} were attributed to the antisymmetric stretching of CH_2 and CH_3 groups in lipids as reported in previous studies (27,62,63). Raba et al. (37) provided a description of the asymmetric and symmetric stretching vibrations of the C-H bond inside the aliphatic CH_2 group of the fatty acid backbone and also discussed the C-H symmetrical stretching of methyl groups (2850 cm^{-1}) as reported by Wang and Lim

(29). Conversely, the vibration of the C-H bonds in both caffeine and lipid molecules may exert an influence (24,39). When comparing the processing methods, DP at 50 °C resulted in a significantly decreased peak between 2925 and 2854 cm^{-1}. No substantial alteration was observed in the chemical characteristics of HP. Extended periods of drying can cause an elevation in lipid oxidation and degradation, leading to a reduction in the intensity of CH_2 and CH_3 stretching vibrations, hence accelerating the observed alterations and reductions. The utilization of HP techniques may result in reduced drying durations, with less significant alterations in the aforementioned peaks. The potential impact of temperature on CH_2 and CH_3 stretching vibrations may be mitigated to a certain degree by the stability of lipids throughout these processes (62,63). The potential influence of coffee and its interaction with lipids on these peaks could result in variances in the reported decreases (27).

The absorbance peak at 1745 cm−1 corresponded to the stretching of the C=O bond in lipids (62), the stretching of the C=O bond in aliphatic esters (63), and the stretching vibration of ester carbonyl functional groups in triglycerides (O-C=O) (37), as well as in chlorogenic acids (CGAs) and caffeine (28). The peak at 1645 cm−1 was associated with the C=C stretching vibration in cis-olefins (cis RHC=CHR) (61), as well as in caffeine (1650 cm−1) and trigonelline (1600–1300 cm−1) (24). The HP samples demonstrated greater intensity at wavenumbers 1745 and 1645 cm−1 in comparison to the DP samples. The higher peak seen in the HP samples indicated the enhanced preservation and accessibility of vibrations, highlighting the capacity to facilitate beneficial chemical modifications in the molecules under investigation, specifically in relation to the conformation and interactions of ester carbonyl functional groups.

Within the fingerprint regions, distinct absorbance peaks at specific wavenumbers 1458, 1377, 1248, 1157, 1049, and 715 cm^{-1} were related to chlorogenic acids (1450–1150 cm^{-1}), C-H scissoring bend of CH2 (1485–1445 cm^{-1}), OH bend in organic acids (1381–1376 cm^{-1}), saccharose (1237 cm^{-1}), C-N stretch (1241–1218 cm^{-1}), C-O stretch in organic acids (1161– 1153 cm^{-1}), arabinogalactans (1065–1020 cm^{-1}), cellulose or quinic acid (1082–1033 cm^{-1}), carbohydrate (1500–700 cm^{-1}), overlapping of aliphatic CH2 rocking vibration, and the out-of-plane vibration of cis-disubstituted olefins (722 cm^{-1}), respectively (24,27,37,62,63). Consequently, the DP

peak exhibited the least amount of content at 30 °C in the fingerprint group, whereas HP displayed relatively lower content compared to 40 and 50 °C. At a lower temperature of 30 °C, certain interactions decreased favorability, leading to a decrease in the concentration of molecules linked to specific absorbance peaks in DP. However, when exposed to temperatures ranging from 40 and 50 °C, these interactions exhibited a greater propensity toward green coffee beans, resulting in an augmented concentration of chemicals in DP. The impact of temperature fluctuations on the performance of HP diminished, depending on specific processing techniques or inherent chemical stability. Thus, the ATR-FTIR absorbance peak area could be continuously affected by physicochemical composition, metabolic features, lipid oxidation, and the presence of important compounds, e.g., carbohydrates, proteins, lipids, caffeine, CGAs, and trigonelline, corresponding to the functional group and fingerprint group peaks.



Note D = days, DP = dry process, HP = honey process.

Figure 6.5 ATR-FTIR spectra of DP Green Coffee Bean Storage at (a) 30 °C, (b) 40 °C, and (c) 50 °C and HP storage at (d) 30 °C, (e) 40 °C, and (f) 50 °C

6.3.5 Multivariate Analysis of Coffee Shelf-Life Under Accelerated Storage

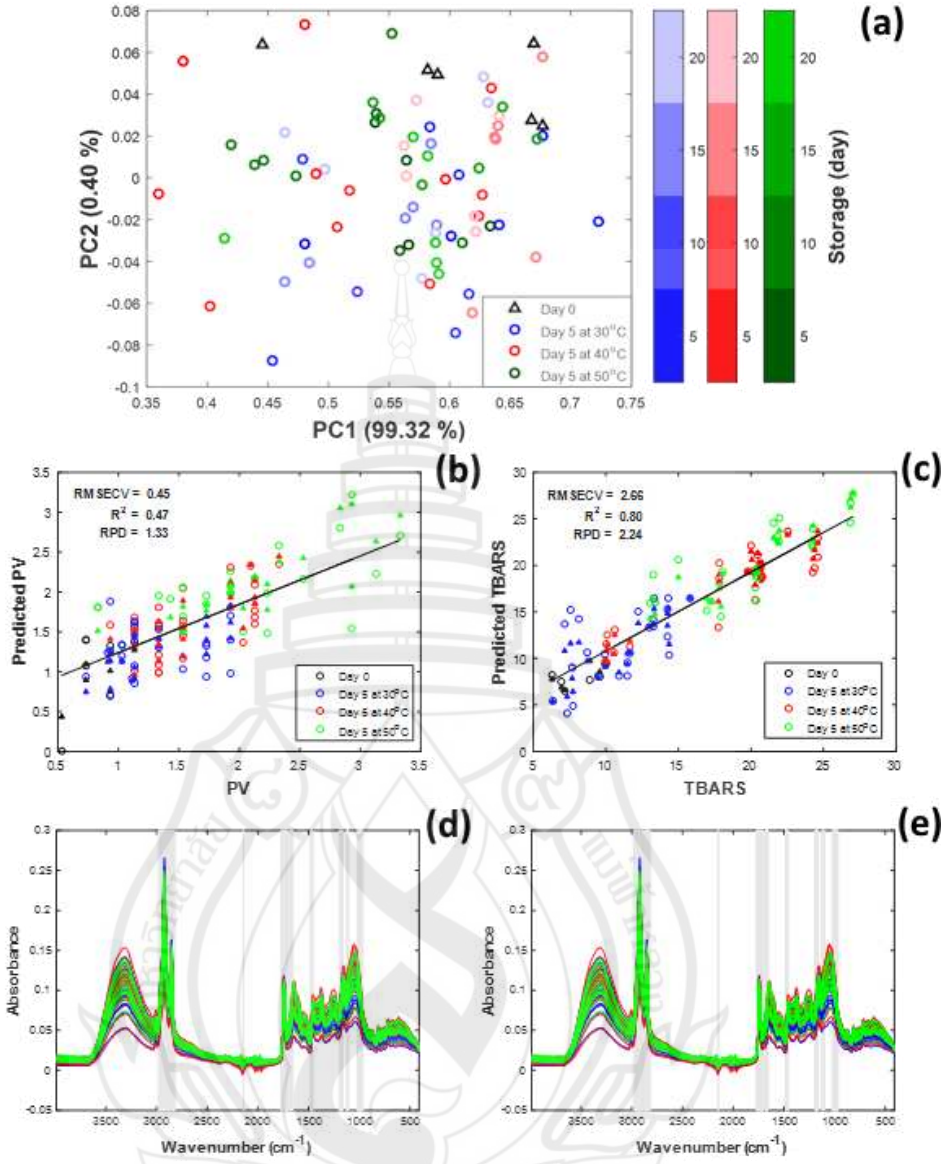
The score plot of the lipid oxidation is shown in Figure 6a, representing 99.72% of the total variation. A difference between the storage duration and temperature was observed. This meant that PCA could be used to find the basic structure in the ATR-FTIR data of 1869 peaks, with a wavenumber range of 401 to 4000 cm^{-1} and a PV and TBARS of variation in the dataset at 26 samples across three replications (78 samples). The control samples clustered on the top right of the plane showed the similarity of the samples prior to storage. When the accelerated storage proceeded, the clustering of data

points at the center of the plane showed an increase in oxidative reactions, resulting in an increase in PV and TBARS, while the shelf-life was lower.

Based on the experimental data, PLS models were established; the performance values and PLS parameters are shown in Table 6.2. In both cases, the R2 values were greater in the auto-prediction of 0.802 for PV and 0.932 for TBARS. This showed a good explanation among the prediction results and the input variables. But when leave-one-out crossvalidation (LOOCV) was used with SNV and 1st derivative pre-processing, the PV had a lower R2 of 0.469, while the TBARS had a higher R2 of 0.801. The root mean square error of cross validation (RMSECV) was 0.449 and 2.658 for PV and TBARS, respectively. In this case, the PLS results showed that ATR-FTIR was better at measuring the oxidation reactions of TBARS than PV. This might be due to the characteristics of the primary oxidation of PV that are lower when the storage time increases, while TBARS gradually increases (Figure 6.4). Figure 6.6b,c show the plots obtained between the observed and predicted values for the models of the oxidation reactions of PV and TBARs. It was evident that the impact of a high storage temperature (50 and 40 °C) provided a high content of predicted PV and TBARS when compared to control and storage in lower conditions with a shorter storage time. As a result, the study used the PLS model, which it achieved by locating and removing outliers. These techniques were effective in predicting and establishing a relationship between ATR-FTIR data and oxidation reactions on shelf-life parameters.

The partial least squares–variables important of projection (PLS-VIP) plots for PV and TBARS are shown in Figure 6.6 d & e. It is crucial to acknowledge that the PLS-VIP indicates the significance of the parameters in the context of the oxidation data prediction. The size of VIP parameters can be used to determine how significant the variables are or how influential they are for the prediction model (42). Based on the PLS-VIP, ATR-FTIR peaks of 3000–2825, 2154–2150, 1780–1712, 1487–2483, 1186–1126, 1107–1097, and 1012–949 cm^{-1} were identified to be strongly influential for the model prediction of PV and TBARS. Additionally, the observations were reached at 3000–2854 and 1745 cm^{-1} peaks, which decided the impact of the moisture content and water activity during the accelerated storage, and 2925 to 2854 cm^{-1} was considered to be the C-H asymmetric and symmetric stretching of CH2 and CH3 in the lipids, caffeine, aliphatic compounds, and fatty acids (61,62). On the other hand, these aspects

contributed to organic molecules such as lactone, aliphatic esters, aldehydes, ketones, aliphatic acids, and carboxylic acid, which played a role in extending the longevity of unroasted coffee beans (29,39). In the past, researchers have looked into how the C=O bond in compounds like caffeine, trigonelline, and chlorogenic acid affects their ATR-FTIR absorbance spectra, finding a peak between 1645 and 1458 cm^{-1} (27,39,64). The absorbance peak at 1377, 1157, and 1049 cm^{-1} could be related to the vibrational modes of O-H bonds in organic acids, the presence of C-O ester groups, the stretching of C-N bonds in organic acids, and the composition of the cellulose ester group in green coffee beans. These vibrational modes affect the production of quinic acid (27,29,63). Thus, in turn, this has implications for the extended preservation of the beans. As a result, the identified ATR-FTIR peaks, along with other characteristics, give us a lot of information about the chemical changes that happen during accelerated storage. Subsequent research endeavors should focus on the utilization of these discoveries to optimize coffee storage and improve methods related to quality management.



Note PV = peroxide value; TBARs = thiobabituric acid reactive substances. PCA = principal component analysis; LOOVC = Leave-one-out crossvalidation; RMSCV = root mean square error of cross validation; R^2 = coefficient determination; RPD = residual prediction deviation.

Figure 6.6 PCA Score Plot of PC1 against PC2 with the Oxidative Parameters during Accelerated Storage (a). The Correlation Graphs Present the Expected and Predicted PV (b) and TBARS (c) Values (Circle Symbols Present the LOOVC, while Triangle Symbol presents the Auto-prediction). The Overlap Variables Important of Projection (VIP) Scores (Highlighted Zone means VIP $\geq$ 1) with FTIR Spectrum of PV (d) and TBARS (e)

Table 6.2 Relevant Information and Results Obtained for the PLS Models

Response	Samples	Processing	LVs	LOOCV			Auto-prediction		
				RMSECV	R^2	RPDCV	RMSE	R^2	RPD
PV	78	SNV and 1st derivative	10	0.449	0.469	1.332	0.264	0.802	2.260
TBARS	78	SNV and 1st derivative	10	2.658	0.801	2.237	1.546	0.932	3.846

Note LVs = number of latent variables used; LOOCV = leave-one-out cross-validation; RMSE = root mean square error; RPD = residual predictive deviation; cv = cross-validation; PV = peroxide value; TBARs = thiobabituric acid reactive substances.

6.4 Conclusions

The shelf-life of green coffee beans stored in GrainPro® bags was investigated by assessing the levels of lipid oxidation, namely, peroxide and TBARS. At a storage temperature of 30 °C, the shelf-life of the honey coffee process was longer than the natural process. Long periods of green coffee bean storage were conducted at low temperatures. ATR-FTIR spectroscopy and lipid oxidation parameters were utilized for the assessment and management of green coffee bean quality. Green coffee beans with a longer shelf-life exhibited a correlation with a lower temperature of 30 °C compared with 40 °C and 50 °C. According to PLS, the models showed acceptable prediction results for TBARS on green coffee beans. Moreover, the PLS-VIP revealed that the important wavenumber ranges of 3000–2825, 2154–2150, 1780–1712, 1487–2483, 1186–1126, 1107–1097 and 1012–949 cm^{-1} are considered related to the lipid oxidations. Thus, the correlation between oxidation reactions and ATR-FTIR analysis in green coffee beans provided the evidence demonstrating the influence of processing treatments on the shelf-life of coffee beans, which could be used to monitor the quality of coffee.

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CHAPTER 7

COMPARATIVE ANALYSIS OF POST-HARVEST PROCESSING AND DRYING TECHNIQUES ON THE CUPPING QUALITY OF THAI ARABICA COFFEE[4]

Abstract

Climate variability poses significant challenges to Thai Arabica coffee. Unstable weather has negatively impacted the quality of Northern Thai Arabica, leading to issues with quality consistency and reduced market competitiveness for Thai coffee growers. Enhancing refining postharvest processing methods is crucial for improving the overall quality of Thai coffee. This study investigated the impact of drying techniques i.e., controlled environmental drying (CED), sun drying (SD), and fast drying (FD), alongside processing methods i.e., dry processing (DP), washed processing (WP), and honey processing (HP), on the pH, total titratable acidity (TA), total soluble solids (TSS), volatile compounds, and cupping scores of roasted coffee beans. Results showed significant differences ($p < 0.05$) among the drying methods and processing techniques regarding the pH, TA, TSS, volatile compounds, and cupping scores of the roasted beans. CED-DP and CED-HP obtained the highest cupping scores of 83.17±1.26 and 83.33±0.58, respectively. CED gave high levels of total ester and heterocyclic N, FD gave high total acetate, and SD gave high total acid, alcohol, aldehyde, furan, ketone, and pyrazine which link to the sensory attributes.

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Principal component analysis (PCA) of the chemical compound group explained 87.97% of the cumulative variance, revealing distinct associations between processing methods and sensory attributes. DP samples were aligned with acidity, overall, TA, TSS, and total esters and aldehydes, while WP samples were aligned with characteristics such as uniformity, clean cup, acid, alcohol, and pyrazine and HP samples were linked to the sensory characteristics of sweetness, aftertaste, body, flavor, balance, fragrance/aroma, pH, acetate, ketone, furan, and heterocyclic N. These findings offer actionable insights for Thai coffee producers to improve coffee quality by selecting the proper postharvest processing for desired characteristics, despite climatic challenges.

Keywords: Multivariate Analysis, Sensory, Specialty Coffee, Volatile Compound

7.1 Introduction

In Northern Thailand's Chiang Rai is a region of major Thai Arabica coffee production. For a decade, Thai coffee farms grow diverse varieties including Catimor, Caturra, and Typica. A mix-variety coffee produces complex cupping characteristics that created the uniqueness of Chiang Rai coffee. Since climate change with rising temperatures and water scarcity now impacts product quality, Thai Arabica production region also faced with these changes which affected directly to Thai coffee industry (1, 2, 3, 4). To address these issues, farmers are prioritizing post-harvest processing and drying of coffee cherries to reduce moisture levels from 55–60% to a more stable 9–12% for storage. Previous research indicated that drying methods such as controlled environment drying, sun drying, and fast drying combined with processing styles (natural/dry, washed, and honey processing) significantly influenced the coffee's moisture content, density, chemical composition, and sensory attributes (5). Traditional sun drying, while economical, is time-intensive and climate-dependent, often leading producers to choose mechanical drying for greater consistency (6). Optimizing these drying and processing techniques is essential for maintaining Thai coffee quality amid environmental pressures. To measure coffee quality grade, the Specialty Coffee

Association (SCA) cupping protocol is essential for evaluating sensory attributes such as aroma, acidity, body, flavor, and aftertaste which are critical quality markers in specialty coffee (1,7). By providing a standardized scoring system, the SCA cupping protocol ensures consistent evaluation, enabling comparison across diverse coffee origins, processing methods, and drying techniques.

Previous research suggests that sensory scores often correlate with chemical attributes like titratable acidity (TA), pH, and total soluble solids (TSS), establishing links between flavor notes and measurable compounds (8, 9, 10). pH, TA, and TSS are key indicators of coffee quality that significantly impact sensory attributes assessed through cupping. TA is a reliable measure of perceived acidity because it accounts for both dissociated and non-dissociated acids that contribute to fruity and sour notes (11), while pH, which generally decreases with darker roasts, helps to balance acidity and bitterness by tracking organic acid breakdown during roasting (12). TSS, measured in degrees Brix, reflects sugars and other soluble compounds, correlating with body and sweetness which enhance flavor intensity (13). Each factor provides insights into the influence of post-harvest drying and processing on the coffee's sensory qualities and volatile compounds, making them essential for optimizing desired flavor profiles and guiding best practices. This connection is crucial for scientifically validating how post-harvest processes affect sensory outcomes and chemical profiles. A study by Ref. (14) examined various drying methods and found that each impacted the pH, TA, and TSS of the coffee and also controlled the release of volatile compounds through the Maillard reaction and lipid oxidation.

Volatile compounds are fundamental to coffee's aroma and flavor, which are pivotal to quality and consumer preferences (9, 15). These compounds vary depending on coffee seed composition (9), fermentation processes (16), roasting profiles (17), packaging, and storage (18, 19). Specific drying and post-harvest processing methods such as sun drying, heat pump drying, and freeze drying also impact volatile profiles and sensory outcomes (14). Natural processing can heighten fruity esters, while washed processing enhances acidic profiles (20). During roasting, compounds like pyrazines, aldehydes, and ketones form through Maillard reactions, with pyrazines contributing nutty and roasted aromas, while aldehydes and esters impart green and fruity notes in lighter roasts (21, 22). Recent studies have shown that freeze drying preserves bioactive

compounds and pyrazines in Arabica coffee (23). Volatile compounds, particularly pyrazines, ketones, aldehydes, heterocyclic nitrogen compounds, acetates, acids, alcohols, esters, and furans are key to coffee's distinctive aroma and flavor, which define consumer preferences and quality (15). Different drying techniques, especially freeze drying, preserve many of these volatile compounds including bioactive pyrazines, acids, and ketones and enhance both the aroma complexity and antioxidant properties in Arabica coffee (23).

The solid-phase microextraction-gas chromatography/mass spectrometry (SPME-GC-MS) technique is widely regarded as a robust and reliable analytical method for assessing the volatile compound profile in coffee, particularly for quality studies (15, 24, 25). This method allows precise measurement of volatiles directly from the headspace, preserving the integrity of the aroma compounds without sample alteration (15). Pyrazine, ketone, aldehyde, heterocyclic N, acetate, acid, alcohol, esters, and furan were the main volatile groups found in coffee, with different post-harvest processing and drying techniques (14, 15). Principal component analysis (PCA) in conjunction with SPME-GC-MS further enhances this approach by enabling a comprehensive examination of complex data sets. PCA can identify patterns and correlations between specific volatiles and processing conditions, enabling a more detailed understanding of how processing methods impact coffee aroma and flavor characteristics (15, 24, 25, 26, 27). This analytical combination is particularly effective for sensory analysis and optimizing coffee production practices to align with consumer preferences, making SPME-GC-MS with PCA an invaluable tool in quality control and research of coffee's sensory attributes.

This study tends to understand the effect of the control environment drying (CED), a new drying technique that becoming a trend of Thai coffee processors (5), on the quality of coffee in terms of sensory attributes, chemical and volatile compounds compared to the conventional drying techniques. With the expectation of producing a better coffee quality that maximizes the desirable flavor attributes to meet specific quality standards and consumer preferences for unique coffee profiles. However, the relationships between volatile compounds, chemical properties, and cupping scores from different coffee processing and drying methods remain unclear. Understanding the formation and retention of volatile compounds across different drying and

processing methods is essential because they directly affect coffee's sensory attributes and overall quality, highlighting the importance of further research into optimizing these methods for quality enhancement. This study investigated the effect of different drying techniques as sun drying (SD), controlled environment drying (CED), and fast drying (FD) together with different post-harvest processing methods such as dry processing (DP), washed processing (WP), and honey processing (HP) on the volatile compounds in coffee to better understand how to control and enhance the complex flavor of Thai Arabic coffee. This study may help the Thai coffee producer overcome the challenges posed by climate variability.

7.2 Materials and Methods

7.2.1 Sample Preparation

Coffee cherries of mixed varieties (Arabica Catimor, Caturra, Catuai, and Bourbon) were collected during the 2022-2023 harvesting season from Doi Chang, Chiang Rai, Thailand at altitudes between 1,250 and 1,300 m. The harvested cherries were floated and washed to remove impurities before undergoing three distinct processing methods: DP, WP, and HP. The DP method involved drying whole coffee cherries, while WP and HP required pulping. For WP, the cherries were submerged in water until a pH of 4.3 to 4.5 was reached, followed by mucilage removal, while for HP, the cherries were dried with their mucilage intact. The initial moisture contents were 73.45%, 53.69%, and 51.80% for DP, HP, and WP, respectively.

Subsequent drying methods including SD, CED, and FD were applied until moisture levels reached 9-12%. For CED, the temperature was kept in the range of 20-30°C with RH ranged of 50-55%, while FD was conducted at the temperature range 30-40°C with RH ranged 50-55%, as explained by Aung Moon et al. (5). Following drying, the samples were stored in hermetic bags at 25°C and 50% RH for three months (Figure 7.1). Roasting, under Specialty Coffee Association standards, was carried out at 208°C for 8-10 min to obtain light-medium roasting (Agtron 63 ± 3). Artisan software and an HB coffee roaster ensured consistency for subsequent quality analyses.

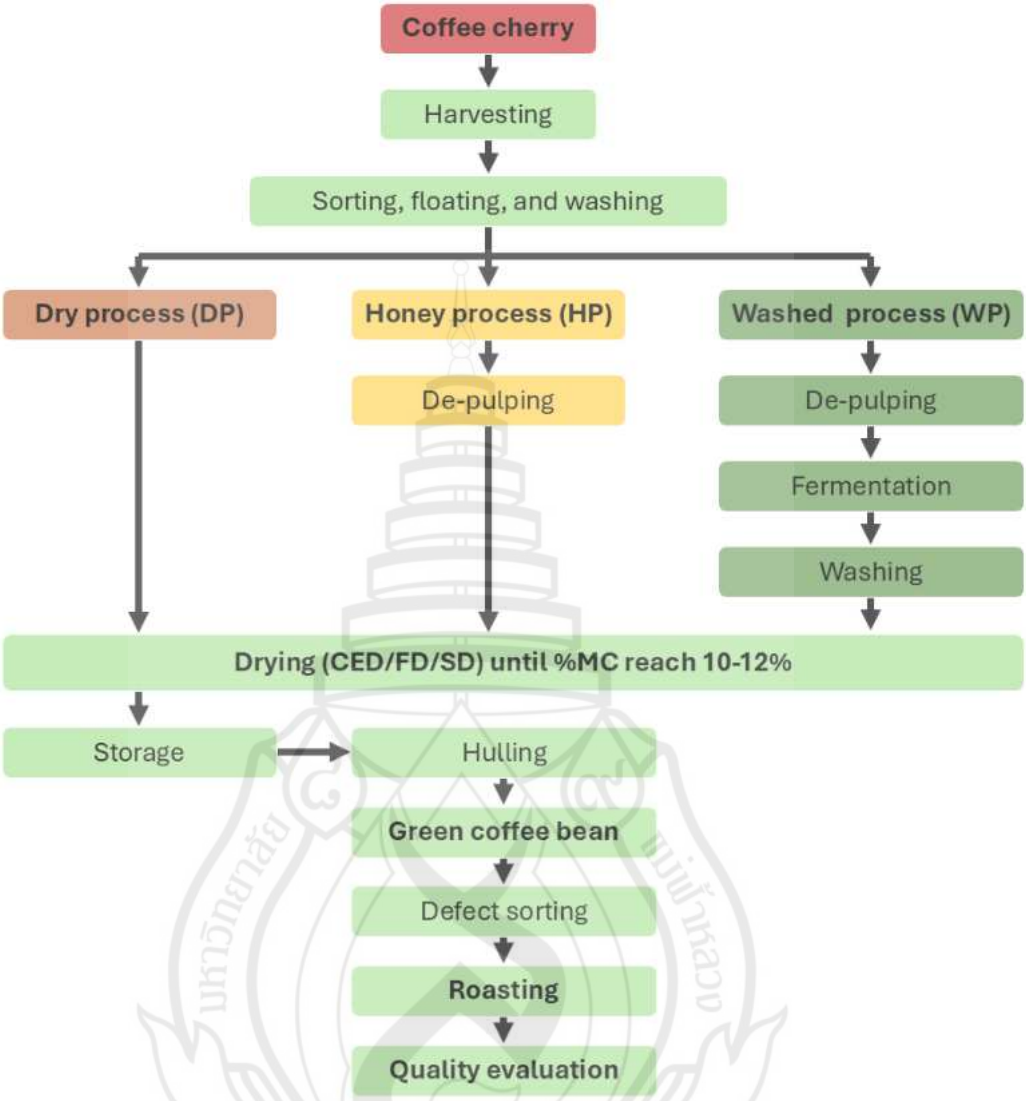


Figure 7.1 Flow Diagram for Three Coffee Processing

7.2.2 pH, TSS, and TA

Aliquots of 2.25 g of ground samples were mixed with 10 mL of hot water at 80°C, cooled to room temperature, and then measured for pH by a pH meter (Eutech pH 700-meter, Thermo Fisher Scientific, Waltham, MA, USA) (28). TSS was determined using a refractometer (HI96801 Refractometer, Hanna Instruments Inc., Woonsocket, RI, USA). For the TA analysis, 10 g of ground coffee samples was mixed with 75 mL of 80% ethanol in an Erlenmeyer flask with a stopper, kept for 16 h and filtered using Whatman No.4 filter paper. Then, 25 mL of the extract was diluted to 100 mL with distilled water and a 40 mL aliquot of each sample was titrated with 0.1 N

sodium hydroxide (NaOH) added with three drops of phenolphthalein indicator (11). The results were expressed as a percentage and calculated using Eq. (1).

$$\%TA = \frac{\text{Volume of 0.1 NaOH (mL)} \times \text{Normality of 0.1NaOH} \times 90 \times 100}{\text{weight of sample} \times 1000} \quad (1)$$

7.2.3 Cupping Analysis

The cupping standard followed the Specialty Coffee Association (SCA) protocol (7). Coffee cupping was evaluated by three Q-graders and two trained panelists. The cupping protocol is an internationally recognized method for evaluating coffee quality in a standardized and objective manner. Using this protocol, certified Q-Graders assess key sensory attributes such as fragrance/aroma, flavor, aftertaste, acidity, body, balance, uniformity, clean cup, sweetness, and overall score. Each attribute is scored on a 100 points scale, ensuring consistency and comparability across different coffees and processing methods. Coffee with a final score of less than 80 was considered below specialty grade, whereas coffee with a score above 80 was regarded as specialty quality and classified as very good (80.00-84.99), excellent (85.00-89.99), and outstanding (90.00-100.00). The cupping test attributes ranged from 6.00 to 10.00, categorized as good (6.00-6.75), very good (7.00-7.75), excellent (8.00-8.75), and outstanding (9.00-10.00). The samples were roasted, with cupping within 24 h. Roasting levels were light to medium and the ground coffee color was recorded as 63±2 Agtron. For each sample, five cups were prepared with 8.25 added with 150 mL of hot water at 93°C. The ground sample size was 20 mesh, with grinding immediately before cupping and no more than 15 min before infusion with water. The water used was clean and odor-free with total dissolved solids 125-175 g/mL. Cupping samples were added with hot water to evaluate aroma, flavor, acidity, body, balance, aftertaste, sweetness, uniformity, cleanliness, and overall within 45 min using the SCA cupping form. The sensory evaluation protocol (Protocol No. EC 24083-14) was approved by the Mae Fah Luang Ethics Committee on Human Research (COE No. 93/2024).

7.2.4 Volatile Compounds

The volatile compounds of coffee were evaluated by solid-phase microextraction-gas chromatography/mass spectroscopy (SPME-GC-MS) or headspace (15, 29). Exactly 100 mg of ground samples were weighed and placed in 5

mL vials. The coffee samples were equilibrated for 10 min at 40°C, followed by 20 min fiber contact and 5 min injection using a 1 cm 50/30 µm DVB/ Carboxen/ PDMS StableFlex fiber. 3-Heptanone was added as the internal standard, using 20 µL of a 0.01% methanol solution. The GC analysis was conducted using a 30 m length Zebron ZB-WAX column with 0.25 mm internal diameter and 1 µm film thickness**.** The analysis was carried out using a gas chromatograph (Trace Ultra) coupled to a mass spectrometer (PolarisQ, ThermoElectron, San Jose, CA, USA), an RTX-5MS column (5% diphenyl, 95% dimethyl polysiloxane) 30 m 0.25 mm I.D. (Restec, Ireland) with helium as the carrier gas (1 mL/min). The GC injector was operated at 250°C in the spitless mode and the GC oven utilized a constant flow of 1.6 mL/min. The GC oven program was set as follows: 40°C held for 5 min, followed by increase to 180°C at a rate of 3°C/min. The rate was then set at 10°C/min until the temperature reached 250°C, which was held for 5 min. The ion source (detector) and interface temperatures were 300°C and 275°C, respectively. Mass spectra were acquired in the electron impact mode at 70 eV, using a m/z range of 50-350 and 2 s scan time. The volatile compounds were identified by comparing the mass spectra against the NIST database when reference compounds were not available. The identification was carried out by comparing the linear retention indices (LRI) of volatiles under the experimental conditions described above with data from the literature. The results were presented as the relative percentage of each compound peak area to the total GC-MS peak area. All the measurements were carried out in duplicate.

7.2.5 Statistical Analysis

The results from the various treatments for group of acetate, acid, alcohol, aldehyde, ester, furan, heterocyclic N, ketone, pyrazine, fragrance/aroma, flavor, aftertaste, acidity, body, sweetness, clean cup, balance, overall, pH, TA, and TSS were recorded as mean values with standard deviations (n=3). Analysis of variance (ANOVA) was carried out using SPSS statistical software (version 20, SPSS Inc., Chicago, II, USA). Tukey's test ($p \leq 0.05$) was used to compare mean data to identify significant variations between the treatments. Principal component analysis (PCA) was performed using R Statistical Software (v4.1.2, R Core Team, Indianapolis, IN, USA,

2021). The results of the chemical properties, each volatile compounds, and cupping parameters data were normalized to exclude dimensional consequences before analysis.

7.3 Results and Discussion

7.3.1 Chemical Characteristics of Roasted Coffee Beans

The values of pH, TSS, and TA of roasted coffee beans, presented in Table 7.1, were significantly different ($p < 0.05$) depending on drying and coffee processing techniques. The pH values of FD roasted coffee beans varied from 5.19±0.02 to 5.25±0.01, with higher values than SD (5.16±0.00 to 5.18±0.01) and CED (5.13±0.01 to 5.17±0.02), respectively. The pH values were similar to Ref. (30) who reported a pH range of 5.02±0.00 to 5.45±0.01 for light roasted coffee with pH at 5.23 for medium roasted Panamanian coffee (31), and 5.27 for light and 5.53 for medium roasted (32). A study Ref. (33) explained that the recommended coffee pH was 4.95 to 5.20 to make the coffee palatable without excessive bitterness or acidity for product acceptance by consumers. The range of light and medium roasted levels of coffee brew had the highest sourness due to the maximum level of aliphatic acid before the decomposition of chlorogenic acids, trigonelline, caffeine, tocopherols, diterpenes, carbohydrate, protein, fat, and minerals (12, 32, 34). Thus, CED techniques enhanced aliphatic acids compared to SD and FD techniques. FD-WP, FD-DP, and FD-HP gave the highest pH content, with the lowest acidity or reduced sourness/crisp acidity compared to the other techniques. The increase in pH of the coffee extract was related to the ester bond of chlorogenic acids which broke down into ester bond structures of caffeic acid and quinic acid during roasting (12). The range of pH values was associated with the origin of the coffee genotypes, processing, fermentation, and roasting profiles (30, 33, 35).

TA was the highest in CED, ranging from 2.40±0.21 to 3.26±0.97% compared to SD (1.67±0.20 to 2.01±0.19%) and FD (1.35±0.34 to 1.54±0.50%). The TA values were similar to those reported by Ref. (11) as 1.2±0.1 to 5.2±0.35%. TA in coffee brew is a more reliable indicator for correlating the coffee acidity than the pH value (34). Both pH and TA can be used to measure coffee brew acidity as sourness (10, 11). The acidity of coffee is often described as brightness when favorable, and contributes to the

coffee's liveliness, sweetness and fresh-fruit character, or sour when unfavorable as an unpleasant taste (10). The TA value of the CED technique including DP, WP, and HP had the highest acidity levels compared to SD and FD. CED preserves citric, malic, and acetic organic acids by minimizing the degradation or evaporation of these compounds. Conversely, SD and FD at higher temperatures cause more rapid degradation of these acids, leading to lower TA. High TA content gives high cup quality through the reactions occurring with acid during roasting (10). The increase in TA was related to the formation of total aliphatic acid at the maximum level with low pH (34). Thus, CED at low temperatures reduced the activity of enzymatic reactions and retained more acids. SD and FD accelerated enzymatic breakdown and reduced the concentration of acids. CED allowed slow fermentation, giving acids like lactic acid more time to develop and maintain their cell structure, with slower removal of moisture content in fruit than SD and FD. FD produced the highest oxidation stress at higher temperatures and less controlled conditions, giving lower acidity than SD and CED.

The TSS were 1.77±0.06 °Brix for DP under all drying techniques, followed by HP (1.37±0.06 to 1.73±0.06 °Brix) and WP (1.20±0.00 to 1.60±0.00 °Brix). The processing methods of TSS were not significantly different ($p \geq 0.05$) for the CED, SD, and FD techniques. TSS content of 0.85-1.15 °Brix was reported for coffee beverages by Ref. (20), 1.93-2.50 °Brix for roasted coffee (14), and 2.43-2.7 °Brix (36). The TSS represents the sugar concentration in coffee and the small number of dissolved compounds including sugar, organic acids, vitamins, amino acids, proteins, pigments, phenolic compounds, pectin, and minerals (13, 33, 35, 36). The TSS content provides the sweetness in coffee and contributes to determining its flavor (33), which is linked to a large number of instrumental and sensory attributes. A positive correlation with °Brix was observed for the concentration of total solids, headspace intensity, concentration of caffeine, 3-CQA and 5-CQA, and TA (14, 20, 36). The correlation was greater with an increase in sensory attributes as aroma intensity, body, roasty flavor, bitter flavor, bitterness, and astringency in aftersensation. During roasting, organic acid losses and chemical volatilization as pyrolysis reactions trigger soluble solid losses and coffee cell breakages which allow the re-solubilization of celluloses, carbohydrates, and protein (30). Thus, DP allowed the retention of higher dissolved compounds than HP and WP.

Low pH and high TA are linked with a brighter, more vibrant flavor while excessively high acidity may cause undesirable sourness (30, 33, 35). The CED method, which yielded lower pH and higher TA, correlates with enhanced positive acidity and fresh-fruit notes. Additionally, TSS represents the sugar and dissolved compounds that contribute to sweetness and body, enhancing flavor intensity (14, 20, 36). Thus, these chemical markers help explain the observed sensory differences, demonstrating that optimized processing methods can improve overall cup quality.

Table 7.1 pH, TSS and TA of Roasted Coffee Beans

Drying technique	Processing	pH	TSS (°Brix)	TA (%)
CED	DP	5.17 ± 0.02^{b}	1.77 ± 0.06^{a}	3.00 ± 0.55^{ab}
	WP	5.17 ± 0.01^{b}	1.50 ± 0.10^{c}	3.26 ± 0.97^{a}
	HP	5.13 ± 0.01^{c}	1.67 ± 0.06^{ab}	2.40 ± 0.21^{abc}
SD	DP	5.16 ± 0.00^{b}	1.77 ± 0.06^{a}	2.01 ± 0.20^{bc}
	WP	5.18 ± 0.01^{ab}	1.60 ± 0.00^{bc}	1.67 ± 0.33^{c}
	HP	5.16 ± 0.01^{b}	1.73 ± 0.06^{ab}	1.87 ± 0.19^{bc}
FD	DP	5.20 ± 0.02^{a}	1.77 ± 0.06^{a}	1.48 ± 0.20^{c}
	WP	5.25 ± 0.01^{a}	1.20 ± 0.00^{d}	1.54 ± 0.50^{c}
	HP	5.19 ± 0.02^{ab}	1.37 ± 0.06^{c}	1.35 ± 0.34^{c}

Note Data are presented as mean ± SD. Different letters in the same column indicate significant differences at $p<0.05$. CED, controlled environment drying; SD, sun drying; FD, fast drying; DP, dry processing; WP, washed processing; HP, honey processing; TSS, total soluble solids; and TA, total titratable acidity.

7.3.2 Cupping Profile of Coffee

The cupping quality followed SCA protocols and was assessed by three Q Arabica graders and two panelists. Figure 7.2 displays the outcomes of the cupping tests including fragrance/aroma, flavor, aftertaste, acidity, body, and overall ratings. All parameters of coffee drying techniques and processing methods were significantly different ($p < 0.05$). Sweetness, uniformity, and clean cup received a score of 10,

indicating an outstanding evaluation. CED, SD, and FD showed no significant differences ($p \geq 0.05$) based on the cupping score. None of the samples were categorized as defective beans. The cupping scores and tasting notes of the coffee samples by Q-graders are shown in Table 7.2. The highest final scores were recorded in CED-HP (83.33±0.58) and CED-DP (83.17±1.26), followed by SD-HP (81.42±0.58), SD-DP (81.25±2.14), and SD-WP (80.08±1.38). Scores below the specialty grade included FD-HP (79.83±1.46), FD-WP (79.17±0.76), and CED-WP (78.92±1.28).

Comparing CED-DP against SD-DP and FD-DP, (Figure 7.2(a)) demonstrates that CED-DP received a "very good specialty", with ≥ 7.5 for fragrance/aroma, flavor, aftertaste, acidity, body, balance, and overall ratings. SD-DP was also given a high score ranging from 7.00 to 7.50 in the "very good specialty" grade range, while FD-DP scored ≤ 7 in aftertaste, body, and balance. FD-DP was weakest in odor notes as spice and smoke in fragrance/aroma, astringent in aftertaste, watery, dry in body, and bitterness in balance. SD-DP was noted as bitterness in aftertaste, thin, dry in body, taste, and bitter as cool down in balance, while CED-DP was watery in body, and bitterness in balance. Thus, CED-DP was the weakest compared to SD and FD for natural/dry processing. DP was linked to taste notes as flowery, fruity, passion fruit, tropical fruit, apple, candy, raisin, orange, nutty and ripe fruit in both fragrance/aroma and flavor. Figure 7.2(b) shows that for WP, SD-WP presented a better final score than FD and CED. SD-WP presented a very good specialty grade due to the high level of aroma, acidity, balance, and overall, with a low score in flavor (6.75±0.28). CED-WP had minimal scores in flavor, acidity, body, balance and overall, while FD-WP had a reduced score for fragrance/aroma and overall. CED-WP was noted as weak odor like spice, hay, smoky, long smoky aftertaste, water with an astringent body and sour-bitter balance. The WP samples presented a lower final score compared to DP and HP due mainly to the nutty group as sweetness, honey, caramel, cocoa, chocolate, and tea-like. Results in Figure 7.2(c) indicate that the final score of CED-HP was the highest among all the samples, and characterized by "very good specialty quality", attributed to its distinctive fragrance/aroma (7.75±0.00), flavor (7.75±0.00), and aftertaste (7.67±0.14). FD-HP exhibited scores of ≤ 7 in acidity, body, balance, and overall, with FD-HP presenting the highest fragrance/aroma score (7.92±0.38). The FD-HP final score was below the specialty quality with a flat aftertaste, watery, astringent body, and sour-bitter

in balance. The SD-HP was in between CED and FD with weakness, a bit dry in aftertaste, clean with soup of body, and bitterness in balance. The HP fragrance/aroma and flavors were grain in brown sugar, fruity, flowery, syrup, sweet, dry fruit, cocoa, raisin, butter, nutty, and honey taste notes. Thus, CED was better suited for valuable specialty coffee quality in DP and HP methods than in SD and FD techniques. WP was suggested to use with SD and FD with reduced drying time but lower quality of coffee grade. Coffee quality is influenced by post-harvest drying and processing techniques. The cupping session demonstrated the critical impact of drying and processing on coffee quality, providing actionable insights for producers and buyers aiming to improve specialty offerings.

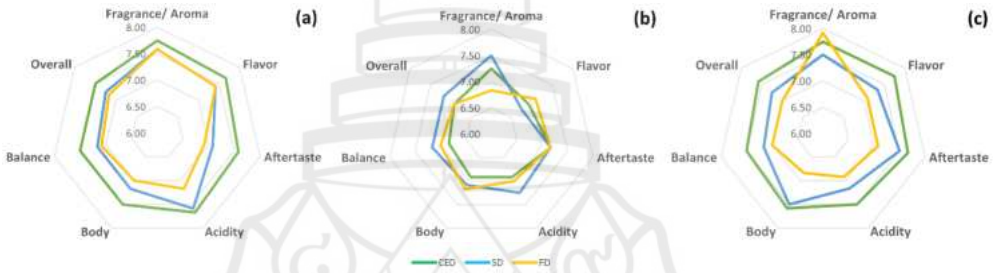


Figure 7.2 Cupping Scores of Roasted Coffee (a) Dry Processing (DP); (b) Washed Processing (WP); and (c) Honey Processing (HP). CED, Controlled Environment Drying; SD, Sun Drying; FD, Fast Drying; DP, Dry Processing; WP, Washed Processing; and HP, Honey Processing

Table 7.2 Cupping Scores and Tasting Notes of the Coffee Samples

Sample	Cupping score	Fragrance/Aroma	Sensory descriptor
CED-DP	83.17±1.26[a]	Flowers, Plum, rose, sweet, raisin, dry fruit, Passion fruit, apple, candy	Rose, stone fruit, dark chocolate, Sweet, bitterness aftertaste, complex acidity, smooth, watery, silky body
CED-WP	78.92±1.28[c]	Brown sugar, fruit, spice, nutty, cocoa nib, caramel	Hay, orange peel, smoky, sweet aftertaste, acidity, smooth, watery, astringent body
CED-HP	83.33±0.58[a]	Fruity, brown sugar, red-yellow fruit, flowery, nut, syrup sweet, dry fruit, honey, Prum, raisin	Rose, strawberry, nutty, honey, sweet, clean aftertaste, complex, juicy, smooth, silky body, balance
SD-DP	81.25±2.14[b]	Sweet, rose-like, berry-like, chocolate, butter, passion fruit, pineapple, grainy	Rose, berry, sweet syrup, black tea, grapefruit, sweet, bitterness aftertaste, juicy, complex, savory, crisp acidity, smooth, dry, astringent body
SD-WP	80.08±1.38[b]	Cherry, spicy, tropical fruit, orange, honey, nutty	Citrus, nut, dark chocolate, black tea, popcorn, sweet, short aftertaste, juicy, clean
SD-HP	81.42±0.58[b]	Chocolate, almond, sweet, berry, nutty, raisin, cocoa, butter	Nutty, dark chocolate, tea-like, sweet, dry aftertaste, complex, acidity, bitter
FD-DP	80.33±1.70[b]	Pineapple, Ripe fruit, Red Flower, Spice	Fruity, passion fruit, lychee, smoke, citrus, dry, astringent aftertaste, juicy, lemon, smooth, watery
FD-WP	79.17±0.76[c]	Brown sugar, nutty, cocoa, flower, cocoa nip, nut, black tea	Nutty, toast, sweet, clean, sweet, acidity, balance
FD-HP	79.83±1.46[c]	Honey, nutty, pea, berry, orange, honey, citrus, candy, flower	Lemon, nutty, black tea, candy, sweet, fade, flat, juicy, smooth, watery, astringent, sour-bitter balance

Note Data are presented as mean ± SD. Different letters in the same column indicate significant differences at $p<0.05$. CED, controlled environment drying; SD, sun drying; FD, fast drying; DP, dry processing; WP, washed processing; HP, honey processing.

7.3.3 Volatile Compounds of Roasted Coffee

Table 7.3 shows the SPME-GC-MS results of the three drying techniques (CED, SD, and FD) on the volatile compounds identified in roasted coffee using the three processing methods (DP, WP, and HP) according to Caporaso et al. (15). Twenty-nine volatile compounds impacted the coffee aroma in the nine drying and processing technique combinations. The identified aroma compounds were classified into nine categories: ten pyrazine, eight ketone, three aldehyde, three heterocyclic N, one acetate, one acid, one alcohol, one ester, and one furan. The drying techniques (CED, SD, and FD) applied in the coffee processing (DP, WP, and HP) significantly impacted the retention of volatile compounds, which in turn affected the aroma and flavor profiles of the final coffee quality.

The main volatile compounds in Doi Chang coffee were 2,5-dimethylpyrazine as 22.46±0.32 to 26.12±2.24% followed by pyrazine (20.78±0.12 to 24.51±0.71%), pyridine (18.50±2.48 to 24.58±2.84%), 2-methyl-pyrazine (6.68±1.16 to 9.59±2.28%), and 1-methyl-1H-pyrrole (5.29±3.39 to 9.38±1.38%). Higher concentrations were found in pyrazine groups as 2,5-dimethylpyrazine, characterized by its nutty, roasted, and grassy aromas (15, 21, 27). Other notable compounds contained pyrazine, which contributed roasted, nutty, sweet, cooked, spinach, rancid, and earthy/musty notes, and 2-methyl-pyrazine, recognized for its nutty scent (15, 27, 37). The main pyrazine groups represented in coffee were similar to those previously reported by Guclu et al. (27) in Turkish coffee and as the most abundant components in cold brew (38). Pyrazines are the main volatiles in coffee beverages formed by the condensation of two aminocarbonyl molecules such as amino acids or amino sugar moieties via the Maillard reaction. These contribute to aroma production by thermal processes during roasting (27). Pyrazine is abundant in coffee and is formed by reactions between carbohydrates and α-amino acids (39). Several studies reported that roasting temperature, time, brew composition, and extraction methods influenced the production of pyrazine (27, 37, 38). Conversely, pyridine and 1-methyl-1H-pyrrole as heterocyclic N chemical groups present less favorable descriptors such as sour, putrid, fishy, amine, bitter, roasted, pungent, burnt, and smoky and have a sharp and unpleasant aroma (15, 16, 40, 41). Pyridine is formed by the reaction of NH abstraction from pyrazine groups, mainly C-C bond scissions with CH_2 abstraction. 3-Ethyl-2,5-dimethypyrazine is transformed

into ethyl pyrazine, 2,6-dimethylpyrazine or 2,3-dimethylpyrazine, then converted to 4-methlpyrimidine and oxidized to 3-methylpyridine (40). By contrast, lower concentrations of other compounds provide distinct yet slightly pungent notes as fruity and malty due to the formation of aldehyde and furan groups as acetaldehyde, 2-methylbutanal, and 3-methylbutanal (15, 16, 37, 41). 3-Hydroyxy-2-butanone and acetols of the ketone group have sweet, buttery, creamy or caramel-like taste notes, while ester groups as ethyl propanoate have sweet, fruity, rum, and juicy taste notes, with acid groups as propanoic acid (pungent, acidic, cheesy, and vinegar), and alcohol groups as 2-furanmethanol (caramel-like, burnt, and smoky) (15). The pyrazine compound, 2-ethyl-6-methylprazine has flowery, fruity, and hazelnut-like taste notes (15). The aroma characteristics of Doi Chang coffee were presented as sugar browning, nutty, caramelly, and chocolaty, with dry distillation as pungent, smoky, and ashy and also enzymatically as flowery, fruity, and herby.

7.3.4 Effect of Post-Harvest Processing and Drying Techniques on the Main Volatile Groups

Chemical groups influenced by CED, SD, and FD volatile compounds had higher contents of pyrazine ranging from 56.89±2.01 to 61.13±0.26%, followed by heterocyclic N (23.89±2.85 to 32.40±2.89%), aldehyde (4.00±0.11 to 5.88±0.12%), ketone (3.44±2.38 to 5.78±0.67%), and small amounts of alcohol (0.02±0.02 to 1.85±2.61%), ester (0.12±0.16 to 0.56%), acetate (0.09±0.13 to 0.50±0.02%), acid (0.05±0.04 to 0.21±0.09%), and furan (0.05±0.07 to 0.16±0.01%), as shown in Table 7.4. The contained volatile compounds were significantly different (p<0.05) depending on drying techniques (CED, SD, and FD) and processing methods (DP, WP, and HP).

7.3.4.1 Pyrazine

In Table 7.4, the highest pyrazine content was presented in CED-WP and FD-WP at 61.19±2.84% and 61.13±0.26%, respectively followed by SD-WP (59.77±2.21%), FD-HP (59.42±2.62%), SD-HP (58.56±0.99%), CED-DP (59.45 ± 0.5 %), SD-DP (58.28±2.96%), CED-HP (56.89±2.01%), and FD-DP (57.69±0.30%). The coffee processing methods were related to pyrazine compounds more than to the drying methods. Pyrazine content was not significantly different (p<0.05) with drying methods CED, SD, and FD followed by the same processing step. WP had higher pyrazine content than HP and DP. In wet post-harvest processing methods, fermentation and

mucilage removal play more crucial roles in the development of pyrazines than mechanical mucilage removal (42).

Our results suggested that higher pyrazine in WP than in DP and HP related to fermentation time, microbial activity, and drying conditions. Without a thick layer of mucilage, the beans dried more uniformly and maintained specific precursors on their surfaces which potentially increased the efficiency of the Maillard reaction and improved pyrazine levels. Different drying methods such as drying, shade drying, and mechanical drying led to variations in pyrazine levels which influenced the coffee's aroma and flavor (43). Pyrazine is mainly related to the Maillard reaction, a non-enzymatic browning reaction that occurs between reducing sugars and amino acids, and thermal degradation of sugar during roasting as caramelization to give rich coffee flavor profiles (21, 27). Higher amounts of pyrazine compounds were presented in 2,5-dimethylpyrazine as the odorant description "nutty, roasted, grassy", pyrazine "cooked, spinach, rancid, peanuts, strong", 2-methylpyrazine "nutty" and 2,3-dimethylpyrazine "chocolate, cocoa, roasted, nutty, and fried" (15, 16, 41). The small amount of pyrazine in 2,6-dimethylpyrazine gave odorant description "chocolate, cocoa, roasted, nutty, and fried", ethyl pyrazine "nutty, peanut, and butter", 2-ethyl-6-methypyrazine "flowery, fruity, hazelnut-like", 2-ethyl-5-methylpyrazine "coffee-like", 2-ethyl-3-methylpyrazine "nutty, and peanut", and 2,3-diethylpyrazine "raw, nutty, and green pepper" (15, 16, 41). Thus, WP as a fermentation and drying condition effectively preserved and increased the levels of pyrazine precursors compared to HP and DP.

7.3.4.2 Heterocyclic nitrogen compounds

The highest heterocyclic N was found in CED-HP and SD-DP at 32.40±2.89% and 31.69±0.52%, followed by FD-HP (31.34±0.11%), FD-DP (30.82±0.76%), SD-HP (30.15±1.01%), and CED-DP (29.91±0.54%). Heterocyclic N was lowest in SD-WP (23.80±2.85%), with FD-WP (27.91±0.48%) and CED-WP (29.31±0.68%). Heterocyclic N is essential to the complex aroma and flavor profile of coffee (44, 45). Compounds that have nitrogen atoms in their ring structures form primarily during the Maillard reaction and Stecker degradation as coffee beans are roasted (15, 46). Heterocyclic N compounds include pyridine, pyrroles, imidazole, indoles, and quinoline (47, 48). WP presented the lowest concentration of heterocyclic N compared to DP and HP. When comparing drying techniques, CED of WP and HP

were higher in heterocyclic N than SD and FD. Heterocyclic N compounds were mainly found in pyridine as odorants described as “sour, putrid, fishy, amine, bitter, and roasted”, followed by 1-methyl-1H-pyrrole “smoky, woody, and herbal”, and 3-ethylpyride “tobacco, oak, moss, leather” (15, 16, 41). 3-Ethylpyridine content was not significantly different (p<0.05) in CED, SD, and FD from WP and HP, and was not detected (ND) in DP in all the drying methods. In pyridine compounds, HP with CED, SD, and FD had higher content ranging from 21.45±0.12 to 24.58±2.84%, followed by DP (21.33±0.28 to 22.31±0.86%) and WP (18.81±0.76 to 22.18±1.12%). The high pyridine retention in HP beans was attributed to the extended contact with mucilage, which is rich in sugars that undergo microbial fermentation, and led to increased levels of pyridine-related compounds (44, 46). DP involved drying the whole cherry which underwent minimal intervention, showing slightly lower pyridine levels than HP, while rinsing and removal of mucilage during WP gave the lowest pyridine range due to the reduction of pyridine precursors in the absence of the mucilage layer (45). Pyridine content was not influenced by DP and HP under different drying methods; however, CED-WP showed higher pyridine content compared to SD-WP and FD-WP. This result suggested that CED for WP preserved pyridine levels by maintaining a stable temperature and humidity. This finding aligned with research indicating that CED retained volatile compounds by reducing their degradation, unlike SD and FD, where temperature fluctuations or heat causes pyridine loss. This result concurred with scores from the cupping taste notes. CED-WP was reported as unclean, unbalanced, and with more sour bitterness, reducing the final score compared to SD-WP and FD-WP. For 1-methyl-1H-pyrrole, DP with CED, SD, and FD had the highest range of 8.59±0.25 to 9.44±0.74%, followed by HP (7.68±0.02 to 9.15±0.54%) and WP (5.29±0.08 to 8.91±0.01%). The DP and HP methods did not exhibit significant variation in 1-methyl-1H-pyrrole content across CED, SD, and FD giving stable levels of nitrogen-containing compounds like pyrrole regardless of the drying method (15). WP beans showed a significantly higher 1-methyl-1H-pyrrole content in FD compared to CED and SD because the higher heat exposure in FD drove reactions between amino acids and sugars that increased the pyrrole content (47).

7.3.4.3 Aldehydes

Aldehyde compounds were high in SD-DP (5.88±0.12%) and FD-WP (5.52±0.04%), followed by CED-DP (5.24±0.59), FD-DP (5.31±0.40%), CED-HP (5.10±0.78%), SD-HP (5.02±0.01%), SD-WP (4.80±0.18%), CED-WP (4.05±0.58), and FD-HP (4.00±0.11%). Aldehydes are important compounds in coffee aroma, particularly for their contribution to fresh, fruity, and floral notes which enhance coffee's complexity (44). Aldehydes are formed during roasting through the breakdown of carbohydrates and lipids as well as by Maillard reactions (15, 45, 48). Aldehydes include acetaldehyde, 3-methylbutanal, 2-methylbutanal, and hexanal (15). The main aldehyde found in 3-methylbutanal had an odor description "fruity, malty", followed by hexanal "green, grassy, and fruity", and acetaldehyde "pungent and fruity". In both DP and HP, 3-methylbutanal content remained relatively stable across controlled CED, SD, and FD ranging from 3.29±0.30 to 3.88±0.14% for DP and 3.41±0.52 to 3.87±0.04% for HP. 3-Methylbutanal is a key volatile compound resulting from the Strecker degradation of leucine during roasting but also initiated to a smaller extent during fermentation, especially in DP and HP, where mucilage is either retained or present longer than in WP (45). DP and HP contribute additional substrates and microbial activity, promoting consistent formation of 3-methylbutanal across various drying methods (15). Thus, DP and HP of 3-methylbutanal were not influenced by CED, SD, and HP. However, SD-WP (4.07±1.2%) exhibited a significantly higher 3-methylbutanal level than CED-WP (2.95±0.47%) and CED-FD (2.25±0.06%). The elevated level of 3-methylbutanal in SD-WP was due to the prolonged and variable temperature condition of SD, which enhanced the rate of oxidative reactions and subsequent aldehyde formation compared to the more stable, lower oxygen CED and FD (48). WP involves early removal of the mucilage layer and the beans lack the protective, antioxidant-rich environment found in HP and DP. This makes WP beans more susceptible to lipid and amino acid degradation under fluctuating sun drying conditions, potentially increasing aldehyde levels like 3-methylbutanal (47).

For WP, hexanal was notably higher in FD-WP, with levels reaching 3.07 ± 0.10 compared to CED-WP (0.96±0.11%) and SD-WP (0.73±1.03%). Hexanal, a key aldehyde contributing fresh and green, grassy notes, forms primarily from the oxidation of lipids, particularly unsaturated fats, which are sensitive to heat and oxygen exposure

(15). The high hexanal level in FD-WP beans was attributed to the rapid drying process, which accelerated lipid oxidation and increased hexanal formation. By contrast, slower drying CED and SD allowed a more gradual temperature increase, potentially limiting oxidation rates, resulting in lower hexanal levels (48). In HP, hexanal was highest in SD-HP (1.11±0.54%), followed by CED-HP (0.94±0.75%) and FD-HP (0.45±0.63%). The reduced hexanal content in FD-HP beans compared to SD-HP suggested that HP retained mucilage and sugars and led to an antioxidant-rich environment. This inhibited lipid oxidation and decreased hexanal formation under rapid drying conditions like FD (44). SD exposed the beans to variable temperatures and prolonged oxidation, leading to a moderate increase in hexanal. No significant differences were recorded in DP of CED, SD, and FD ranging from 1.57±0.13 to 1.79±0.02%. DP is conducted with the coffee cherries intact, providing a protective barrier against oxidation and stabilizing hexanal levels. This protective effect contributed to relatively stable lipid oxidation rates in DP compared to WP and HP (47). Acetaldehyde content was highest in DP, ranging from 0.22±0.31 to 0.36±0.05% compared to HP (0.15±0.21-0.31±0.00%) and WP (0.14±0.19-0.20± 0.21%). Acetaldehyde was not detected in SD-WP. As a key aldehyde in coffee, acetaldehyde contributes to fruity and fresh notes and typically occurs through the breakdown of carbohydrates and amino acids during fermentation and drying (45).

7.3.4.4. Ketones

Higher ketone compounds were presented in SD-HP (5.78±0.67%), FD-DP (5.64±1.65%), CED-DP (5.50± 0.05%), and FD-HP (5.07±2.67%) followed by CED-HP (4.75±1.04%), FD-WP (4.67±0.67%), CED-WP (4.66±0.25%), SD-WP (4.14±1.18%), and SD-DP (3.44±2.38%). Ketones were found mainly in 2,3-pentandione, with odor description “buttery, oily, caramel-like”, and in 2,3-butanedion, 3-hydroxy-2-butanone, acetol, 1-hydroxy-2-butanone, furaneol, γ-butyrolactone, and 3-hydroxy-4-5-dimethyl-2-(5H)-furanone, with the main odor related to “buttery, sweet, and caramel-like” (15, 16, 41). Ketones are important compounds in coffee that contribute to its flavor and aroma profile, particularly richness, sweetness, buttery, and caramel-like. The level of 2,3-pentanedione, a diketone known for its buttery and creamy notes, was highest in HP, ranging from 2.09±0.35 to 2.66±0.09%, followed by DP at 1.22±0.04 to 2.38±0.01% and WP at 0.19±0.06 to 2.14±0.02%. The higher

concentration of 2,3-pentanedione in HP was attributed to the retention of mucilage during processing, which fostered an environment conducive to the enzymatic and microbial reactions that led to the formation of this compound (15). The fermentation of sugars present in the mucilage promoted the synthesis of 2,3-pentanedione through various metabolic pathways (48). The wide range of 2,3-pentanedione in DP indicated fluctuation in fermentation conditions, including temperature and microbial activity, that influenced compound formation (47). Conversely, WP exhibited the lowest level of 2,3-pentanedione due to washing which removed the mucilage and significantly reduced the potential for the enzymatic reactions that produced diketone (45). Regarding drying methods, both CED and SD demonstrated superior retention of 2,3-pentanedione compared to FD. The slower drying condition of CED and SD allowed better preservation of volatile compounds by minimizing oxidation degradation and ensuring that the formation of flavor compounds was not disrupted by excessive heat (46). FD techniques, while efficient, expose the coffee beans to high temperatures and more rapid moisture loss, leading to the volatilization and degradation of sensitive compounds like 2,3-pentanedione (15). Thus, the significant presence of 2,3-pentanedione in HP and DP, combined with the effects of drying methods, underscored the importance of processing techniques and environmental conditions in shaping the aromatic profile of coffee. For further insights, studies on the metabolic pathways leading to diketone formation in coffee, as well as the effects of processing and drying on flavor retention would be beneficial.

7.3.4.5. Alcohols

The alcohol compound contents significantly differed across the coffee processing and drying methods, with SD-WP exhibiting the highest alcohol concentration at 1.85±2.61%. By comparison, CED-HP had a lower level (0.24±0.33%) and CED-WP (0.13±0.18%). The remaining processes including SD-DP, FD-DP, FD-WP, and CED-DP recorded alcohol levels of 0.05% or less, while SD-HP and FD-HP contained no detectable alcohol. The predominant alcohol detected in these samples was sis 2-furanmethanol, known for imparting caramel-like, burnt, and smoky notes to coffee (15). The elevated levels of 2-furanmethanol in SD-WP were attributed to the longer fermentation and drying time associated with SD. The extended exposure to heat and oxygen during sun drying promoted the Maillard reaction and caramelization

processes, leading to the development of various volatile compounds including 2-furanmethanol (44). This compound is associated with desirable sensory characteristics that enhance the overall complexity of the coffee's flavor profile. CED-HP and CED-WP indicated lower alcohol contents as 2-furanmethanol compared to SD-WP, related to reduced exposure to oxygen and heat fluctuations (47). These conditions inhibited the Maillard reaction and subsequent caramelization, resulting in diminished alcohol levels. The formation of 2-furanmethanol in small amounts (0.05%) across other processing methods such as SD-DP, FD-DP, FD-WP, and CED-DP reflected the varying degrees of enzymatic and oxidative reactions that occurred during drying and processing. Thus, SD-WP reinforced the idea that the extended duration and exposure of sun drying are key factors in enhancing the synthesis of this compound (46).

7.3.4.6. Esters

Esters were only found in ethyl propanoate compounds. Ester compounds such as ethyl propanoate are crucial contributors to the aroma and flavor profile of coffee, providing sweet, fruity, and juicy notes (15). The highest concentrations of ethyl propanoate were observed in CED-DP at 0.56±0.09% and SD-WP at 0.52±0.07%. Other notable levels were found in SD-DP (0.44±0.01%), FD-DP (0.34±0.04%), CED-WP (0.28±0.38%), SD-HP (0.25±0.13%), CED-HP (0.24±0.34%), and FD-HP (0.12±0.16%). No ester compounds were detected in FD-WP. The absence of ester compounds in FD-WP was attributed to the rapid drying process, which led to the loss of volatile compounds and inhibited the esterification reaction (46). FD typically involves higher temperatures which degrade sensitive compounds before they can stabilize to ester compounds. In CED-DP, the controlled drying conditions preserved volatile compounds, while facilitating enzymatic reactions that produced esters (44). The retention of sugars and organic acids during the DP method enhances the production of esters through the esterification reaction, which occurs more efficiently when precursors are present in higher concentrations (47). SD-WP fermentation moderated ester levels and contributed to the fruity and sweet notes characteristic of wet-processed coffee (48). Esters are characterized by pleasant smells and tastes used as flavors in coffee. They are produced by fats and oils due to the reaction between fatty acids and glycerol and the resulting molecules are called triglyceride esters. Each molecule is formed from the reaction of one molecule of glycerol (trihydric alcohol)

and three molecules of fatty acids. The acid molecules may be similar or different, saturated long-chain or unsaturated short-chain (49).

7.3.4.7. Acetate compounds

The presence of acetate compounds, particularly 2-furanmethanol acetate, plays a significant role in shaping the aroma profile of coffee. This specific acetate is associated with ethereal-floral, herbal, and spicy notes which enhance the overall complexity of coffee's sensory characteristics (15). 2-Furanmethanol acetate was detected in several processing methods, with FD-WP showing the highest concentration at 0.50±0.02%, followed by CED-HP (0.25±0.02%), CED-DP (0.18±0.01%), CED-WP (0.12±0.17%), and SD-HP (0.09± 0.13%). No acetates were found in SD-DP, SD-WP, and FD-HP. FD-WP had high 2-furanmethanol content, with the rapid evaporation of water concentrating the remaining volatile compounds including esters and acetates (44). The rapid drying conditions also enhanced the chemical transformation necessary for acetate formation because the fast removal of moisture promoted esterification reactions (47). CED-HP, CED-DP, and CED-WP had lower levels compared to FD-WP. CED techniques reduced the risk of volatilization and degradation of sensitive compounds but limited the rapid reactions that led to higher acetate production (46).

7.3.4.8. Acid compounds

Acid compounds contributed to propanoic acid which had pungent, acidic, cheesy, and vinegar-like notes (15). Propanoic acid was not present in HP for CED, SD, and FD treatments, suggesting that the conditions typically associated with HP, characterized by the retention of mucilage and natural sugars, inhibited the formation of propanoic acid due to the lower availability of the precursor necessary for its synthesis. The highest propanoic acid contents were observed in SD-DP (0.21±0.09%), CED-WP (0.21±0.25%), and SD-WP (0.19±0.18%) followed by FD-WP (0.07±0.06%), CED-DP (0.06±0.04%), and FD-DP (0.05±0.04%). The varying levels of propanoic acid across the different processing methods highlighted how fermentation and drying conditions influenced the formation of acids in coffee. WP and DP presented higher acidity as sourness than HP.

7.3.4.9. Furan

Furan was only found in 2-methylfuran as pungent and fruity notes (15). Furan compounds are formed in food by the thermal degradation of carbohydrates, ascorbic acid, unsaturated fatty acids, and amino acids during the thermal oxidation of lipids and thiamine degradation during roasting (41, 50). The highest furan concentration was observed in SD-HP at 0.16±0.01%, followed by FD-WP (0.14±0.04%), CED-HP (0.14±0.01%), CED-DP (0.09± 0.08%), FD-HP (0.06±0.08%), and CED-WP (0.05±0.07%). Furan was not found in SD-DP, FD-DP, and SD-WP. The higher concentration of 2-methylfuran in SD-HP supported the formation of volatile compounds from the mucilage natural sugars that provided substrates during drying which promoted the development of furans through the Maillard reaction and other thermal degradation pathways (47). The result was not clear in each processing and drying. However, the 2-methylfuran levels across different processing and drying methods underscored the impact of mucilage presence and drying conditions on flavor compound development in coffee.

The controlled conditions in CED influenced the volatile compound formation by preserving precursor compounds such as reducing sugars, amino acids, and organic acids, which are essential for Maillard reactions and esterification during roasting. In contrast, FD's higher drying temperature accelerated moisture loss and oxidative degradation, reducing the availability of key precursors. Pyrazine formation, primarily driven by the Maillard reaction, benefits from CED's gradual drying, allowing better retention of reactants and a more controlled browning process. Similarly, ester formation is enhanced under CED and SD due to the preservation of organic acids and enzymatic activity, whereas rapid drying in FD leads to volatile loss and limited esterification. These findings align with previous research indicating that slower, controlled drying preserves volatile precursors, improving sensory attributes in coffee (21, 27, 44, 47).

Table 7.3 Twenty-Nine Volatile Compounds Related to Coffee Post-Harvesting and Processing

No.	RT	RI	Volatile compound	Odor descriptors	Chemical group	CED-DP (%)	SD-DP (%)	FD-DP (%)	CED-WP (%)	SD-WP (%)	FD-WP (%)	CED-HP (%)	SD-HP (%)	FD-HP (%)
1	1.395	< 1040	Acetaldehyde	Pungent, fruity	Aldehyde	0.36 ± 0.05^{a}	0.22 ± 0.31^{ab}	0.35 ± 0.06^{a}	0.14 ± 0.19^{b}	ND	0.20 ± 0.21^{b}	0.29 ± 0.04^{ab}	0.31 ± 0.00^{a}	0.15 ± 0.21^{b}
2	1.899	< 1040	2-Methylfuran	Pungent, fruity, malty, cocoa	Furan	0.09 ± 0.08^{ab}	ND	ND	0.05 ± 0.07^{b}	ND	0.14 ± 0.04^{a}	0.14 ± 0.01^{a}	0.16 ± 0.01^{a}	0.06 ± 0.08^{b}
3	2.051	< 1040	3-Methylbutanal	Fruity, malty, cocoa	Aldehyde	3.29 ± 0.30^{ab}	3.88 ± 0.14^{a}	3.40 ± 0.54^{ab}	2.95 ± 0.47^{ab}	4.07 ± 1.20^{a}	2.25 ± 0.06^{b}	3.87 ± 0.04^{a}	3.61 ± 0.54^{ab}	3.41 ± 0.52^{ab}
4	2.525	< 1040	2,3-butanedione	Buttery, oily, fruity, caramel-like, cheesy	Ketone	0.62 ± 0.05^{bc}	0.84 ± 0.29^{b}	1.69 ± 0.03^{a}	0.64 ± 0.05^{bc}	ND	0.66 ± 0.08^{bc}	0.49 ± 0.01^{c}	0.72 ± 0.04^{bc}	0.52 ± 0.03^{c}
5	3.45	1047	2,3-Pentanedione	Buttery, oily, caramel-like	Ketone	2.38 ± 0.01a	1.42 ± 2.02ab	1.22 ± 0.04ab	2.14 ± 0.02a	0.19 ± 0.06b	1.72 ± 0.63ab	2.36 ± 0.12b	2.66 ± 0.09b	2.09 ± 0.35b
6	4.304	1070	Hexanal	Green, grassy, fruity, fatty-green	Aldehyde	1.60 ± 0.30^{ab}	1.79 ± 0.02^{ab}	1.57 ± 0.13^{ab}	0.96 ± 0.11^{b}	0.73 ± 1.03^{b}	3.07 ± 0.10^{a}	0.94 ± 0.75^{b}	1.11 ± 0.54^{ab}	0.45 ± 0.63^{b}
7	5.519	1230	1-Methyl-1H-pyrrole	Smoky, woody, herbal	Heterocyclic N	8.59 ± 0.25^{a}	9.38 ± 1.38^{a}	9.44 ± 0.74^{a}	6.86 ± 0.08^{ab}	5.29 ± 3.39^{b}	8.91 ± 0.01^{a}	7.68 ± 0.02^{ab}	8.53 ± 0.95^{a}	9.15 ± 0.54^{a}
8	6.147	1170	Pyridine	Sour, putrid, fishy, amine, bitter, roasted, bitter, astringent, burnt	Heterocyclic N	21.33 ± 0.28^{ab}	22.31 ± 0.86^{ab}	21.38 ± 1.51^{ab}	22.18 ± 1.12^{ab}	18.50 ± 2.48^{b}	18.81 ± 0.76^{b}	24.58 ± 2.84^{a}	21.45 ± 0.18^{ab}	22.15 ± 2.82^{ab}

Table 7.3 (continued)

No.	RT	RI	Volatile compound	Odor descriptors	Chemical group	CED-DP (%)	SD-DP (%)	FD-DP (%)	CED-WP (%)	SD-WP (%)	FD-WP (%)	CED-HP (%)	SD-HP (%)	FD-HP (%)
9	6.707	1198	Pyrazine	Cooked, spinach, rancid, peanuts, strong	Pyrazine	22.51 ± 0.04^{bc}	20.78 ± 0.12^{c}	23.19 ± 1.44^{b}	23.91 ± 0.49^{ab}	24.51 ± 0.72^{a}	24.87 ± 2.76^{a}	21.79 ± 0.42^{bc}	22.27 ± 0.05^{bc}	23.09 ± 2.23^{b}
10	8.24	1255	2-Methyl-pyrazine	Nutty, roasted, chocolate	Pyrazine	7.80 ± 0.45^{bc}	9.59 ± 2.28^{a}	9.01 ± 0.50^{a}	7.81 ± 1.85^{bc}	6.68 ± 1.16^{c}	6.98 ± 0.68^{c}	7.20 ± 1.93^{bc}	8.19 ± 0.13^{b}	8.72 ± 0.00^{b}
11	8.354	1277	3-Hydroxy-2-butanone	Sweet, Buttery, creamy	Ketone	0.90 ± 0.26^{b}	0.33 ± 0.47^{c}	1.60 ± 1.10^{a}	0.40 ± 0.54^{c}	1.54 ± 0.18^{a}	0.90 ± 0.14^{b}	0.92 ± 0.27^{b}	1.63 ± 0.23^{a}	1.22 ± 1.72^{ab}
12	8.472	1294	Acetol	Sweet, caramellike	Ketone	0.58 ± 0.06^{b}	0.74 ± 0.25^{a}	0.72 ± 0.43^{a}	0.31 ± 0.43^{c}	0.40 ± 0.08^{c}	0.73 ± 0.35^{a}	0.38 ± 0.08^{c}	0.45 ± 0.11^{c}	0.53 ± 0.74^{b}
13	9.765	1310	2,5-Dimethylpyrazine	Nutty, roasted, grassy	Pyrazine	23.04 ± 0.66^{cd}	23.57 ± 1.89^{cd}	22.42 ± 0.37^{d}	26.12 ± 2.24^{a}	24.94 ± 2.02^{b}	24.20 ± 0.76^{c}	25.34 ± 0.25^{b}	24.11 ± 0.39^{c}	22.46 ± 0.32^{d}
14	10.714	1320	2,6-Dimethylpyrazine	Chocolate, cocoa, roasted, nutty, toasted nut, roasted meat	Pyrazine	0.94 ± 0.13^{ab}	0.66 ± 0.10^{b}	0.87 ± 0.04^{ab}	0.85 ± 0.54^{ab}	0.97 ± 0.40^{ab}	1.25 ± 0.13^{a}	0.58 ± 0.06^{b}	0.77 ± 0.06^{ab}	0.66 ± 0.17^{b}
15	10.801	1323	Ethyl pyrazine	Nutty, peanut, butter	Pyrazine	0.64 ± 0.06^{c}	0.23 ± 0.33^{d}	0.54 ± 0.06^{c}	1.52 ± 1.82^{b}	1.08 ± 0.88^{b}	0.63 ± 0.21^{c}	0.24 ± 0.20^{d}	0.23 ± 0.06^{d}	2.99 ± 3.65^{a}
16	10.889	1334	2,3-Dimethylpyrazine	Nutty, roasted, grassy, chocolate	Pyrazine	2.06 ± 1.06^{a}	2.74 ± 0.71^{a}	0.81 ± 0.53^{b}	0.50 ± 0.69^{b}	1.05 ± 0.21^{ab}	2.02 ± 2.07^{a}	1.43 ± 0.04^{ab}	2.14 ± 1.08^{a}	1.33 ± 1.88^{ab}
17	11.007	1363	1-Hydroxy-2-butanone	Sweet, coffee	Ketone	0.29 ± 0.23^{a}	0.04 ± 0.06^{b}	0.10 ± 0.13^{b}	0.03 ± 0.04^{b}	0.06 ± 0.08^{b}	0.48 ± 0.51^{a}	0.15 ± 0.21^{ab}	ND	0.03 ± 0.04^{b}

Table 7.3 (continued)

No.	RT	RI	Volatile compound	Odor descriptors	Chemical group	CED-DP (%)	SD-DP (%)	FD-DP (%)	CED-WP (%)	SD-WP (%)	FD-WP (%)	CED-HP (%)	SD-HP (%)	FD-HP (%)
18	11.109	1370	3-Ethylpyridine (ns)	Tobacco, oak, moss, leather rotten fish, smoky, leather	Heterocyclic N	ND	ND	ND	0.27 ± 0.37	0.02 ± 0.02	0.18 ± 0.26	0.13 ± 0.03	0.17 ± 0.12	0.04 ± 0.06
19	11.463	1372	2-Ethyl-6-methylprazine (ns)	Flowery, fruity, hazelnut, -like	Pyrazine	0.29 ± 0.21	0.02 ± 0.04	0.03 ± 0.04	0.12 ± 0.17	ND	0.32 ± 0.08	0.12 ± 0.01	0.32 ± 0.28	0.06 ± 0.08
20	12.185	1377	2-Ethyl-5-methypyrazine (ns)	Coffee-like	Pyrazine	0.13 ± 0.12	ND	0.07 ± 0.09	0.09 ± 0.13	ND	0.06 ± 0.08	ND	ND	ND
21	12.685	1390	2-Ethyl-3-methylpyrazine	Nutty, peanut, roasted matter	Pyrazine	0.49 ± 0.51^{a}	ND	0.40 ± 0.56^{b}	0.02 ± 0.02^{c}	ND	0.05 ± 0.01^{c}	ND	0.06 ± 0.08^{c}	0.06 ± 0.08^{c}
22	13.245	1425	2,3-Diethylpyrazine	Raw, nutty, green pepper	Pyrazine	0.55 ± 0.65^{ab}	0.69 ± 0.16^{ab}	0.38 ± 0.31^{ab}	0.26 ± 0.03^{b}	0.55 ± 0.05^{ab}	0.73 ± 0.25^{a}	0.20 ± 0.02^{b}	0.48 ± 0.11^{b}	0.04 ± 0.06^{b}
23	15.459	1490	Furaneol	Caramel, sweet	Ketone	ND	ND	ND	0.12 ± 0.17^{c}	1.74 ± 0.52^{a}	0.12 ± 0.17^{c}	0.20 ± 0.28^{c}	0.32 ± 0.18^{c}	0.69 ± 0.18^{b}
24	16.293	1515	Ethyl propanoate	Sweet, fruity, rum, juicy	Ester	0.56 ± 0.09^{a}	0.44 ± 0.01^{ab}	0.34 ± 0.04^{ab}	0.28 ± 0.38^{ab}	0.52 ± 0.07^{a}	ND	0.24 ± 0.34^{b}	0.25 ± 0.13^{b}	0.12 ± 0.16^{b}
25	16.361	1525	2-Furanmethanol acetate	Ethereal-floral, herbal-spicy	Acetate	0.18 ± 0.01^{b}	ND	0.11 ± 0.06^{b}	0.12 ± 0.17^{b}	ND	0.50 ± 0.02^{a}	0.25 ± 0.11^{b}	0.09 ± 0.13^{b}	ND
26	16.506	1530	Propanoic acid	Pungent, acidic, cheesy, vinegar	Acid	0.06 ± 0.04^{b}	0.21 ± 0.09^{a}	0.05 ± 0.04^{b}	0.21 ± 0.25^{a}	0.19 ± 0.18^{a}	0.07 ± 0.06^{b}	ND	ND	ND

Table 7.3 (continued)

No.	RT	RI	Volatile compound	Odor descriptors	Chemical group	CED-DP (%)	SD-DP (%)	FD-DP (%)	CED-WP (%)	SD-WP (%)	FD-WP (%)	CED-HP (%)	SD-HP (%)	FD-HP (%)
27	19.952	1600	γ-Butyrolactone	Creamy, oily, fatty, caramel	Ketone	0.40 ± 0.01^{b}	0.07 ± 0.10^{c}	0.33 ± 0.05^{b}	0.98 ± 1.00^{a}	0.22 ± 0.10^{b}	0.06 ± 0.08^{c}	0.26 ± 0.25^{b}	ND	ND
28	20.259	1654	2-Furanmethanol	Caramel-like, burnt, smoky	Alcohol	0.02 ± 0.02^{c}	0.05 ± 0.08^{c}	0.05 ± 0.06^{c}	0.13 ± 0.18^{b}	1.85 ± 2.61^{a}	0.05 ± 0.03^{c}	0.24 ± 0.33^{b}	ND	ND

Note Data are presented as mean±SD. Different superscripts in the same row indicate significant differences at $p<0.05$. CED, controlled environment drying; SD, sun drying; FD, fast drying; DP, natural processing; WP, washed processing; HP, honey processing. Source: volatile compound names, odor descriptions, and group chemicals: ((15),(16),(40),(41)).

Table 7.4 Main Volatile Groups Related to Coffee Post-Harvesting and Processing

Chemical groups	DP			WP			HP		
	CED	SD	FD	CED	SD	FD	CED	SD	FD
Acetate	0.18 ± 0.01^{Db}	ND	0.11 ± 0.06^{Db}	0.12 ± 0.17^{Db}	ND	0.50 ± 0.02^{Da}	0.25 ± 0.11^{Db}	0.09 ± 0.13^{Db}	ND
Acid	0.06 ± 0.04^{Db}	0.21 ± 0.09^{Da}	0.05 ± 0.04^{Db}	0.21 ± 0.25^{Da}	0.19 ± 0.18^{Da}	0.07 ± 0.06^{Db}	ND	ND	ND
Alcohol	0.02 ± 0.02^{Dc}	0.05 ± 0.08^{Dc}	0.05 ± 0.06^{Dc}	0.13 ± 0.18^{Db}	1.85 ± 2.61^{Da}	0.05 ± 0.03^{Dc}	0.24 ± 0.33^{Db}	ND	ND
Aldehyde	5.24 ± 0.59^{Cab}	5.88 ± 0.12^{Ca}	5.31 ± 0.40^{Cab}	4.05 ± 0.58^{Cb}	4.80 ± 0.18^{Cab}	5.52 ± 0.04^{Ca}	5.10 ± 0.78^{Cab}	5.02 ± 0.01^{Cab}	4.00 ± 0.11^{Cb}
Ester	0.56 ± 0.09^{Da}	0.44 ± 0.01^{Dab}	0.34 ± 0.04^{Dab}	0.28 ± 0.38^{Dab}	0.52 ± 0.07^{Da}	ND	0.24 ± 0.34^{Db}	0.25 ± 0.13^{Db}	0.12 ± 0.16^{Db}
Furan	0.09 ± 0.08^{Dab}	ND	ND	0.05 ± 0.07^{Db}	ND	0.14 ± 0.04^{Da}	0.14 ± 0.01^{Da}	0.16 ± 0.01^{Da}	0.06 ± 0.08^{Db}
Heterocyclic N	29.91 ± 0.54^{Bb}	31.69 ± 0.52^{Ba}	30.82 ± 0.76^{Bab}	29.31 ± 0.68^{Bb}	23.80 ± 2.85^{Bd}	27.91 ± 0.48^{Bc}	32.40 ± 2.89^{Ba}	30.15 ± 1.01^{Bab}	31.34 ± 0.11^{Bab}
Ketone	5.50 ± 0.05^{Ca}	3.44 ± 2.38^{Cc}	5.64 ± 1.65^{Ca}	4.66 ± 0.25^{Cb}	4.14 ± 1.18^{Cb}	4.67 ± 0.67^{Cb}	4.75 ± 1.04^{Cb}	5.78 ± 0.67^{Ca}	5.07 ± 2.67^{Cab}
Pyrazine	58.45 ± 0.52^{Ab}	58.28 ± 2.96^{Ab}	57.69 ± 0.30^{Ac}	61.19 ± 2.84^{Aa}	59.77 ± 2.21^{Ab}	61.13 ± 0.26^{Aa}	56.89 ± 2.01^{Ac}	58.56 ± 0.99^{Ab}	59.42 ± 2.62^{Ab}

Note Data are presented as mean±SD. Capital superscripts indicate significant differences in the same column compared to chemical groups at $p<0.05$. Small superscripts indicate significant differences in the same row compared to post-harvesting and processing at $p<0.05$. CED, controlled environment drying; SD, sun drying; FD, fast drying; DP, dry processing; WP, washed processing; HP, honey processing.

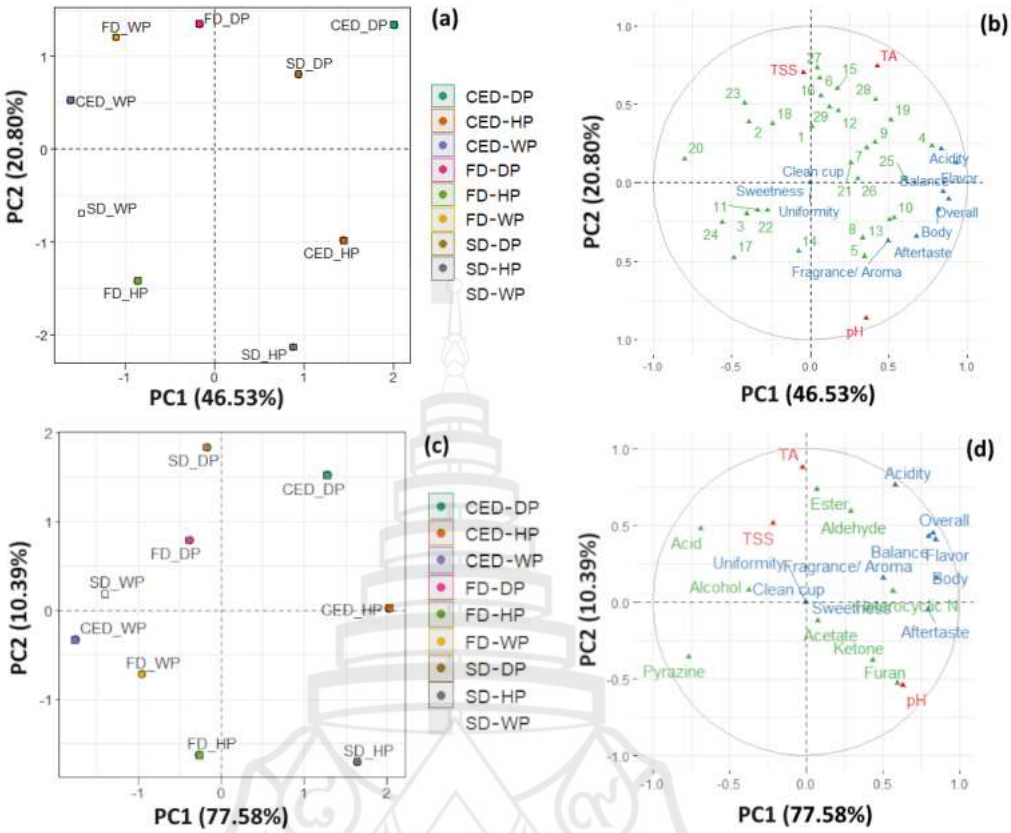
7.3.3 Principal Component Analysis (PCA)

PCA was employed to better understand the relationships between the dying techniques and processing methods on coffee characteristics. The PCA biplot (Figure 7.3 a-b) explains 67.33% of the total variance, with PC1 accounting for 46.53% and PC2 for 20.80%. The DP samples showed correlations to each characteristic related to TA, TSS, acidity, flavor, balance, and volatile compound numbers 6, 9, 12, 15, 16, 19, 27, 28 and 29 (hexanal, 1-methyl-1H-pyrrole, 2,3-butanedione, acetol, 1-hydroxy-2-butanone, 3-hydroxy-4,5-dimethyl-2-(5H)-furanone, 2-ethyl-5-methyprazine, 2-3thyl-3-methypyrazine, and 2,3-diethypyrazine). The increased presence of these volatiles suggested that DP promoted the retention and formation of volatiles that enhanced acidity and body. The extended contact between the beans and pyrazines contributed to nutty, earthy, and slightly bitter notes (48). The association of hexanal and pyrazine derivatives with DP samples aligned with previous studies suggesting that these compounds positively correlated with the enhanced complexity of flavor and aroma in DP coffee (15). WP samples were correlated to volatile compound numbers 2, 3, 11, 18, 20, 23, and 24 (propanoic acid, 2-furanmethanol, 3-ethylpyrdine, γ-butyrolactone, pyrazine, and 2,6-dimethylpyrazine). These compounds contribute to clear, clean cup quality and are typically linked to mild acidity and refined flavor notes. WP, which removes the mucilage before drying, often results in a “cleaner” flavor profile with fewer fermentation notes because removal of the mucilage limits additional microbial activity. Previous studies supported that WP coffee often presented a well-balanced cup with a “clean” acidity due to the reduction in volatiles associated with fermentation such as esters and aldehydes while allowing pyrazines and lactones to enhance nuttiness and sweetness (37, 45). HP samples were mainly correlated to cupping groups including pH, fragrance/aroma, aftertaste, body, overall, balance, and volatile numbers 4, 5, 8 10, 13, 14, and 25 (acetaldehyde, 3-methylbutanal, 2-methylfuran, pyridine, 2,3-pentanedione, and 3-hydroxy-2-butanone). HP retains a portion of the mucilage and offers a balance between the richness of DP and the clarity of WP, leading to a full-bodied profile with fruity and complex notes. The presence of aldehydes like acetaldehyde and furans in HP coffee correlates with increased sweetness, caramel, and fruity flavor because the residual mucilage during drying contributes to the Maillard reaction that produces these compounds (44). HP samples with 2-methylfuran and

pyridine have enhanced complexity, fruity and roasted notes consistent with consumer preferences for sweet and balanced profiles in specialty coffee (46).

The PCA results confirmed that different processing and drying techniques resulted in distinct chemical and sensory profiles in coffee, as documented in the literature. The distribution of volatile compounds and cupping attributes across DP, WP, and HP samples aligned with findings suggesting that specific treatment methods emphasized chemical pathways such as Maillard reactions and microbial activity which impacted the final aroma and flavor (15,48). Figure 7.3c-d shows that PC1 and PC2 accounted for 77.58% and 10.39%, respectively. This PCA was performed on a comprehensive data set of coffee samples with volatile compound groups, chemical properties, and cupping data. The clustering of coffee samples by process type along specific sensory and chemical attributes underscored the influence of processing and drying methods on coffee quality characteristics. CED-DP, SD-DP, and FD-DP were collectively aligned with attributes like acidity, overall, TA, ester, aldehyde, and TSS. This association suggested that DP enhanced characteristics related to acidity and ester formation due to extended contact with natural sugar during fermentation, which promoted esterification reactions and the formation of aldehydes through oxidative pathways (45). By contrast, WP samples were linked to attributes such as uniformity, clean cup, acid, alcohol, and pyrazine. WP effectively removes mucilage, potentially reducing the formation of fermentation-related compounds while emphasizing attributes that contribute to a clean cup. The presence of alcohols and pyrazines in WP samples aligned with findings that WP coffee exhibits heightened clarity and refined acidity because pyrazines contribute to the nutty and earthy aroma found in these samples (48). HP coffee samples were associated with sensory attributes such as sweetness, aftertaste, body, flavor, balance, fragrance/aroma, pH, acetate, ketone, furan, and heterocyclic N. This association suggested that HP enhanced both sensory and chemical complexity. The retention of mucilage in HP favored the development of compounds like acetate, ketones, and heterocyclic N, contributing to richer aromatic notes and greater body in the cup profile (47). These chemical groups impart distinct flavors and aromas and are linked to positive sensory attributes like sweetness, balance, and aftertaste in coffee. These correlations aligned with studies on coffee processing methods that reported variations in volatile compound profiles and sensory attributes

as a function of the processing and drying techniques applied. Previous research studies have shown that chemical transformation in coffee is heavily influenced by environmental conditions during drying, with each process promoting specific flavor and aroma profiles in the final product (46). This analysis reflects how PCA effectively highlighted these complex relationships and supported the importance of processing decisions in determining coffee quality characteristics.



Note 1; 2-furanmethanol acetate, 2; propanoic acid, 3; 2-furanmethanol, 4; acetaldehyde, 5; 3-methylbutanal, 6; hexanal, 7; ethyl propanoate, 8; 2-methylfuran, 9; 1-methyl-1H-pyrrole, 10; pyridine, 11; 3-ethylpyrdine, 12; 2,3-butanedione, 13; 2,3-pentanedione, 14; 3-hydroxy-2-butanone, 15; acetol, 16; 1-hydroxy-2-butanone, 17; furaneol, 18; γ-Butyrolactone, 19; 3-hydroxy-4,5-dimethyl-2-(5H)-furanone, 20; pyrazine; 21; 2-methyl-pyrazine, 22; 2,5-dimethylpyrazine; 23; 2,6-dimethylpyrazine, 24; ethyl pyrazine, 25; 2,3-dimethylpyrazine, 26; 2-ethy-6-methypyrazine, 27; 2-ethyl-5-methyprazine, 28; 2-ethyl-3-methlpyrazine, and 29; 2,3-diethylpyrazine.

Figure 7.3 PCA analysis of the observed volatile compounds (a-b) and the compound classes (c-d)

7.4 Conclusions

Results showed that drying techniques and processing methods significantly impacted the chemical and sensory profiles of roasted coffee beans, influencing key

parameters such as pH, TA, and TSS. CED was the most effective method for enhancing acidity and flavor complexity, particularly in DP and HP coffees, resulting in the highest cupping scores and complex flavor profiles. Conversely, FD resulted in higher pH values and reduced acidity while DP maintained higher TSS levels, indicative of a sweeter profile. CED had a significant concentration of total esters and heterocyclic N, while FD comprised total acetate, and SD included total acids, alcohols, aldehydes, furans, ketones, and pyrazines. Groups of volatile compounds CED-DP, SD-DP, and FD-DP were associated with attributes such as acidity, overall, TA, ester, aldehyde, and TSS. SD-WP, CED-WP, and FD-WP were connected to characteristics such as uniformity, clean cup, acid, alcohol, and pyrazine. FD-HP, SD-HP, and CED-HP were assigned sensory attributes such as sweetness, aftertaste, body, flavor, balance, fragrance/aroma, pH, acetate, ketone, furan, and heterocyclic N. CED-DP, SD-DP, and FD-DP were correlated to characteristics related to TA, TSS, acidity, flavor, balance, and volatile compounds such as hexanal, 1-methyl-1H-pyrrole, 2,3-butanedione, acetol, 1-hydroxy-2-butanone, 3-hydroxy-4,5-dimethyl-2-(5H)-furanone, 2-ethyl-5-methyprazine, 2-3thyl-3-methypyrazine, and 2,3-diethylpyrazine. FD-WP, CED-WP, and SD-WP were associated with volatile compounds including propanoic acid, 2-furanmethanol, 3-ethylpyrdine, γ-butyrolactone, pyrazine, and 2,6-dimethylpyrazine. FD-HP, SD-HP, and CED-HP were correlated with pH, fragrance/aroma, aftertaste, body, overall, balance, and volatiles in acetaldehydes, 3-methylbutanal, 2-methylfuran, pyridine, 2,3-pentanedione, and 3-hydroxy-2-butanone. This research underscored the importance of modifying drying and processing methods to optimize the sensory qualities of specialty coffee. The distinct clustering of coffee samples associated with different processing methods further emphasized the critical role of fermentation and mucilage retention in flavor development. This research contributes to the scientific understanding of coffee processing, offering a basis for future studies to improve specialty coffee production in Thailand and other coffee-growing regions. However, this study was still limited to single coffee-growing site of Doi Change, Chiang Rai, Thailand, single harvesting season, and mixed of Arabica varieties which might influence the outcomes of this study. To validate the findings, the future work should be focused on a single Arabica variety and also expanded to include different coffee-growing regions, different climate, together with different harvesting seasons.

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CHAPTER 8

IMPACT OF ROASTING AND STORAGE CONDITIONS ON THE SHELF STABILITY OF THAI ARABICA COFFEE[5]

Abstract

This research investigated the impact of roasting levels and storage conditions on coffee quality by analyzing moisture content (MC), color, peroxide value (PV), shelf-life, and volatile compounds using solid-phase microextraction-gas chromatography/mass spectrometry (SPME-GCMS). Coffee samples were collected from Doi Chang, Thailand, and processed using natural, washed, and honey methods. The samples were then roasted to light at 205°C, light-medium at 210°C, and medium at 218°C. The roasted coffee beans were packaged in hermetic bags and subjected to accelerated storage conditions for 0, 7, 14, and 21 days at 30, 40, and 50°C with 50% RH. Results showed that roasting level and accelerated storage significantly affected (p<0.05) MC, color, PV, shelf-life, and volatile compound profiles. Eighty-two volatile compounds were identified across the light, light-medium and medium samples. The dominant compound groups were furans (ranging from 35.20±5.85 to 53.55±2.75% d.w.), pyrazines (13.16±1.14 to 32.31±0.76% d.w.), and esters (4.21±0.20 to 16.70±0.93% d.w.), which contribute significantly to coffee aroma. Shelf-life at 30°C was longest for light (10.03±0.11 to 11.68±0.34 days), followed by light-medium (7.28±0.25 to 8.82±0.64 days) and medium (6.33±0.33 to 7.68±0.61 days), compared to storage at 40 and 50°C. The concentrations of volatile compounds including alcohols, aldehydes, esters, furans, furanones, ketones, organic acids, pyrazines, pyridines, pyrroles, sulfides, and terpenes were influenced by roasting level, processing method, and storage conditions, ultimately affecting coffee shelf-life.

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Keywords: Accelerated storage, Lipid oxidation, Shelf-life, Volatile compounds

8.1 Introduction

Coffee is one of the world's most beloved beverages, with the complexities of its flavor, aroma, and character dependent on the roasting process (1). Roasting coffee involves subjecting the beans to heat, which leads to many physical and chemical changes that ultimately influence the flavor and final quality. These changes occur through processes such as Maillard reactions, thermal degradation, pyrolysis, and caramelization (2). The path from raw coffee beans to the aromatic brews that grace countless cups globally is managed by skilled roasters who carefully navigate the multitude of time and temperature variations in the roasting technique.

The Maillard reaction generates hundreds of coffee flavor compounds through chemical reactions between amino acids, peptides or proteins and reducing sugars such as fructose, glucose, galactose, and maltose. These reactions ultimately lead to the production of brown melanoidins, which then interact with other compounds (3). Caramelization is a non-enzymatic complex with sugar as sucrose to glucose and fructose condensation reactions, intermolecular bonding, isomerization, dehydration, fragmentation, polymerization, and degradation which lead to browning reactions that release caramel-like, burned, meaty, sour, and bitter flavors to develop a rich aroma (4). Pyrolysis reactions are longer than Maillard reactions and necessitate greater temperature, with a wide array of organic compounds including alcohols, aldehydes, carboxylic acids, furans, ketones, pyrazines, and pyrroles (4) Several organic compounds including alcohols, aldehydes, acids, amines, dicarbonyls, enoles, esters, furans, furanones, hydrocarbons, imidazoles, indoles, ketones, lactones, oxazoles, phenols, pyrazines, pyridines, pyrroles, quinoxalines, sulfur compounds, terpenes and thiazoles are presented in roasted coffee beans (4-6).

Volatile compound contents depend on coffee seed (7), coffee cherry fermentation process (8), roasting profiles (9), packaging (10-11), and storage (12). Caporaso et al. (6) suggested that the concentration of volatile compounds in coffee is affected by the degree of roasting, with the green coffee composition dictated by the

species of coffee, its geographical origin, the stage of ripening, and pre-harvest and post-harvest processing. Lighter roasted coffee was effectively distinguished from darker roasted coffee, whereas the degree of roasting had a greater impact than the coffee's geographical origin (13). The volatile compounds sourced from roasted coffee defects were examined by Yang et al. (14). They identified indole for light defects, 4-ethyl-2-methoxyphenol for scorched defects, phenol for dark defects, maltol for baked defects, and 2,5-dimethylfuran for underdeveloped defects. By contrast, Nicoli et al. (12) claimed that coffee quality declined during storage due to chemical and physical changes that significantly impacted the ability of the coffee brew including the release of volatiles and CO_2, migration of surface oil, and oxidation reactions. The packaging of roasted coffee is primarily affected by oxygen transmission rate, moisture, and CO_2 which result in a change in flavor, quality loss, and reduced shelf-life (10). The coffee quality must be maintained by using packaging materials that restrict the ingress of oxygen to mitigate the rate of oxidative degradation of the aroma and subsequent loss of freshness inside the packaging (10-11). The Arrhenius model has been used to study how the peroxide value in green coffee beans changes over time to understand the relationship between coffee quality and lipid oxidation and predict the shelf-life of the beans (15-16). The decrease of volatile compounds in coffee beans is related to their oxidation and shelf-life (13, 17).

Changes in coffee color and moisture content occur during roasting due to the generation of higher molecular weight colored melanoidins, which change color from greenish-gray-blue to yellow, orange, brown, dark brown and almost black, influencing the final brew aroma and flavor characteristics (3, 7, 18). The Specialty Coffee Association of America (SCA) has established the following criteria for cupping coffee: 63 Agtro "Gourmet", and 48 Agtro "Commercial" for color and roasting profiles completed within a minimum of 8 min and a maximum of 12 min (19). Fibrianto et al. (9) characterized light roast coffee by fruity and sour tastes, medium roast coffee by a strong mouthfeel, and more complex fragrance and aroma compared to dark roast coffee which exhibited a strong acrid, bitter, burnt, and smoky taste (9). The aroma profiles of coffee become more smoky, earthy, and sulfurous as a result of the transition from light-to-dark roasting (20). Thus, it is necessary to determine the appropriate

coffee roasting profile and the primary focus of coffee quality concentration by choosing between light and medium roasting levels.

To assess the chemical characteristics of coffee, several analytical techniques have been developed such as FTIR (21-23), NIR (24-26), and hyperspectral imaging (27-29). Recent improvements have made these techniques non-destructive and rapid. For the analysis of volatile compounds, GCMS is particularly effective method (30,31), and the SPME-GCMS approach has proven useful in determining coffee properties like adulteration (32), processing (33), and origin (34). The current focus in analytical technique development for coffee is on achieving rapid and non-destructive evaluation. While the coffee industry commonly uses cupping protocols for quality evaluation, integrating analytical parameters with sensory attributes can enhance our understanding of how pre- and post-harvest processing, roasting and storage conditions influence important chemical precursors and their resulting sensorial outcomes (35-37). Therefore, this study investigated the impact of roasting levels on the shelf-life of roasted coffee beans under accelerated storage conditions. Coffee quality was assessed by examining lipid oxidation and changes in volatile compounds using SPME-GCMS. Multivariate analysis was employed to determine the relationship between these analytical parameters and the cupping attributes of the roasted coffee.

8.2 Materials and Methods

8.2.1 Sample Preparation

The coffee cherries (*C. Arabica* cv. Catmor and Caturra) used in this study were harvested from Doi Chang, Chiang Rai, Thailand, during the 2021-22 coffee cherry harvesting at an altitude of 1280 meters. The coffee cherries (30 kg) were divided into three processing batches of 10 kg each as dry, wet, and honey process. The ripe cherries were floated to remove the soil, leaves, damaged sections, and green cherries with low density. The dry process involved drying whole ripe cherries until 9-12% moisture content, milling the outer layer and sorting for the roasting process. Wet process began with de-pulping the cherry, followed by fermentation in water tanks to reach a pH of 4.3, thorough washing, drying, milling, and sorting. The honey process started by de-

pulping with the mucilage left on, followed by drying, milling, and sorting to produce green coffee beans.

A 1,500 g batch of each processed type of green coffee beans was roasted using a 2 kg HB roaster (HB-L2, The Coffee Company Ltd., Hong Kong, China). The roast levels for each type of coffee process were light, light-medium, and medium roasted. The roasting profile was conducted at 205-218 °C for 8-10 min (23). The light, light-medium and medium roast coffee samples are shown in Figure 8.1. Following the roasting process, 250 g of roasted coffee beans were placed in hermetic bags and preserved in a Constant Climate Chamber (HPP750, Memmert GmbH, Schwabach, Germany). The temperature and relative humidity (RH) were regulated at 30, 40, and 50°C and 50%, respectively. Samples were removed from the accelerated storage chamber every seven days (0, 7, 14, and 21 days) for peroxide value and volatile compound analyses.

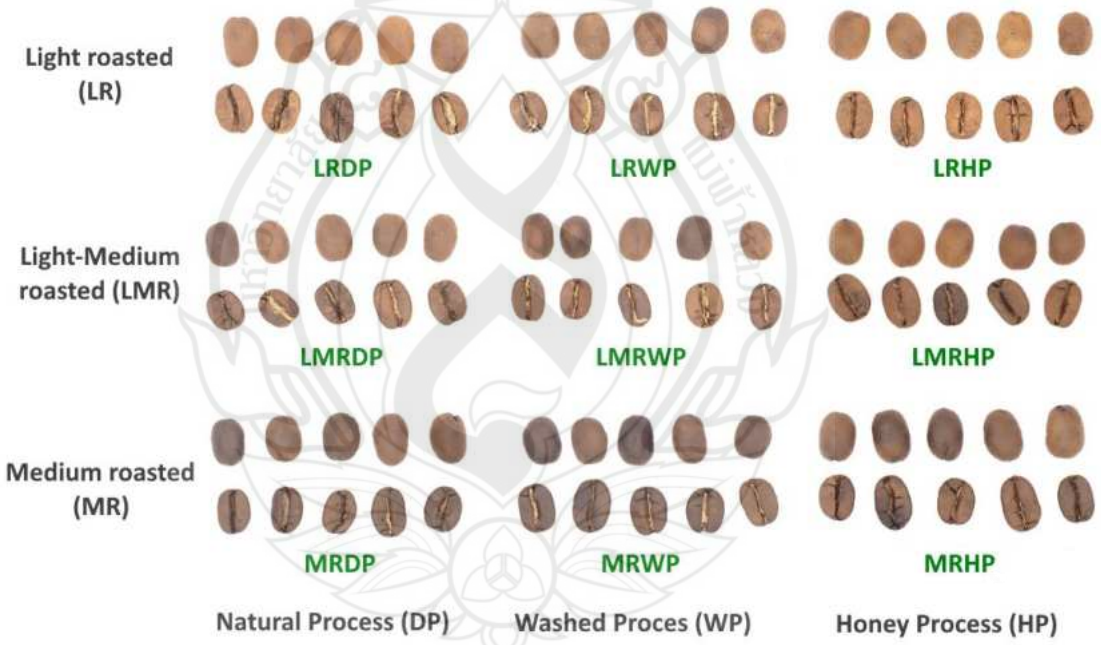


Figure 8.1 The Appearance of RCB after Undergoing the Different Roasting Levels

8.2.2 Moisture Content (MC)

The moisture content was evaluated by drying the sample in a hot air oven at 70±1°C for 16.0±0.5 hours until a consistent weight was attained following the AOAC 2000 method 979.12 (39) and calculated using Eq. (1):

$$\% \text{ Moisture (w.b.)} = (\text{weight loss on drying (g)}/ \text{ weight of samples (g)}) \times 100 \quad (1)$$

8.2.3 Color Determination

The roasted coffee bean color values were quantified using a colorimeter (Color Quest XE, Hunter Associates, Reston, VA, USA) and represented based on the CIE Lab color scale (38). A standard white tile was used to calibrate the colorimeter giving coordinates for the illuminant D65: $L^* = 94.64$, $a^* = -0.80$, and $b^* = 0.07$. L^* measures lightness ($L^* = 100$ means white, $L^* = 0$ means black), a^* indicates the contribution of red or green (redness (+) and greenness (−)), and b^* determines the role of blue or yellow (yellowness (+) and blueness (−)). Total color difference (ΔE) was calculated for each sample using Eq. (2):

$$\Delta E = ((\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2)\ ½ \quad (2)$$

8.2.4 Peroxide Value

The PV was determined in accordance with AOAC Official Method 965.33 (40). As described by Aung Moon et al. (16), 1 g of oil sample (S) and a blank (B) were added to a 250 mL Erlenmeyer flask followed by 30 mL of chloroform-acetic acid (2:3 v/v). Then, 0.5 mL of saturated KI solution was added and the flask was agitated and left to stand in the dark for one min. The reaction was halted by rapidly adding 30 mL of distilled water. The solution was titrated with 0.003 M sodium thiosulfate until the blue hue disappeared. The PV was recorded as milliequivalents of peroxide per kilogram of oil (meq/kg of oil) using Eq. (3):

$$\text{PV (meq/kg samples)} = (2 \times (\text{Samples-Blank}) \text{ (mL)})/(\text{weight of oil (g)}) \quad (3)$$

8.2.5 Shelf-life Prediction

The shelf-life prediction of RCB was computed utilizing kinetic models (15, 38,41). The Arrhenius relationship, which establishes a connection between the rate of temperature change and three temperatures as 30°C, 40°C, and 50°C under accelerated storage condition with 50% RH were utilized to integrate Eqs. (4)-(7).

$$\text{Zero-order model: } PV = k_0 t + PV_0 \quad (4)$$

$$\text{First-order model: } \ln(PV) = kt + \ln(PV_0) \quad (5)$$

$$\text{Arrhenius equation: } \ln(k) = -Ea/RT + \ln(k_0) \quad (6)$$

$$\text{Shelf-life prediction: } SL = (\ln(PV) - \ln(PV_0)) / (k_0 e^{(-Ea/RT)}) \quad (7)$$

where k_0 and k are the reaction rate constants, PV and PV_0 are the PVs at storage time, t is the initial value, k_0 is a pre-exponential factor, Ea is the activation energy (J mol^{-1}), T is the absolute temperature, R is the molar gas content (8.3144 J K^{-2} mol^{-2}), and SL is the shelf-life prediction.

8.2.6 Volatile Compound Analysis

The volatile compounds in coffee were evaluated by solid-phase microextraction-gas chromatography/mass spectroscopy (SPME-GCMS) (6, 42). One hundred milligrams of ground samples were weighed and placed in 5 mL vials. Coffee samples were equilibrated for 10 min at 40°C, followed by 20 min fiber contact and 5 min injection. A 1 cm 50/30 µm DVB/Carboxen/ PDMS StableFlex fiber was used, and 20 µL of 3-heptanone was added as the internal standard in 0.01% methanol solution. The GC conditions were adjusted to match with a 30 m length Zebron ZB-WAX column with 0.25 mm internal diameter and 1 µm film thickness. The GC (Trace Ultra) was coupled to a mass spectrometer (PolarisQ, ThermoElectron, San Jose, CA, USA) with an RTX-5MS column (5% diphenyl, 95% dimethyl polysiloxane) 30 m 0.25 mm I.D. (Restec, Ireland), and helium was used as the carrier gas (1 mL/min). The GC oven program was controlled at 250°C in the splitless mode at a constant flow of 1.6 mL/min. The GC oven program was set as 40°C held for 5 min, followed by an increase to 180°C at a rate of 3°C/min, and then the rate was set at 10°C/min until the temperature reached 250°C which was held for 5 min. The ion source (detector) and interface temperatures were 300°C and 275°C. Mass spectra were developed in the electron impact mode at 70 eV using a m/z range of 50-350 and 2 s scan time. The volatile compounds were

detected by comparing the mass spectra against the NIST database when reference compounds were unavailable. The identification was carried out by relating the linear retention indices (LRI) of the volatiles under the experimental conditions described above to the data from the literature. The results of each compound peak area were presented as a percentage of the total GCMS peak area. Each investigation was conducted in duplicate.

8.2.7 Statistical Analysis

The results from the various treatments for moisture content, peroxide value, shelf-life, and volatile compounds were recorded as mean values with standard deviations (n=3). Analysis of variance (ANOVA) statistical analyses were carried out using SPSS statistical software (version 20, SPSS Inc., Chicago, II, USA). Tukey's test ($p \leq 0.05$) was used to compare mean data to identify significant variations between the treatments. Principal component analysis (PCA) was performed using R Statistical Software (v4.1.2, R Core Team, IN, USA, 2021). All parameters were normalized to exclude dimensional consequences before analysis.

8.3 Results and Discussion

8.3.1 Moisture Content and Color of Roasted Coffee Bean

Table 1 shows the influence of different roasting treatments on coffee bean moisture content (MC) and color parameters. The MC and color parameters were significantly different ($p<0.05$) for the light, light-medium and medium roast. The maximum MC values were found in light of dry, wet and honey processes as 2.11±0.05%, 1.8±0.1%, and 2.13±0.03%, followed by light-medium (1.49±0.03%, 1.4±0.1%, and 1.62±0.02%) and medium (1.6±0.1%, 1.3±0.2%, and 0.9±0.1%), respectively. The decrease in MC was consistent with previous results, regardless of the range of roasting degrees, ranging from 2.57±0.01 to 1.6±0.2% (2) and 3.12±0.01% to 1.10±0.01% (43). Moisture evaporation was related to percentage loss of mass, volume, and density as well as the generation of CO_2 and volatile chemicals from the Maillard and pyrolysis reactions, which contributed to the first crack and caramelization stage (1).

The CIELab values of light ranged from 39.5±0.5 to 39.6±0.4, 4.0±0.2 to 4.3±0.1, and 4.3±0.3 to 4.7±0.1, light-medium (37.8±0.2 to 38.3±0.6, 3.0±0.2 to 4.0±0.1, and 2.6±0.5 to 3.3±0.3), and medium (37.3±0.3 to 37.4±0.2, 2.3±0.1 to 2.5±0.1, and 1.6±0.1 to 1.8±0.1), respectively. Thus, the color changes observed in the roasted coffee beans were significantly influenced by both roasting level and accelerated storage conditions. The CIELab values indicated that as the roasting level increased, the beans darkened, with light roast maintaining the highest brightness (*L** value) and medium roast exhibiting the lowest brightness. This change in color is attributed to the Maillard reaction and oxidation polymerization, which occur during roasting and contribute to the formation of brown pigments (43-46).

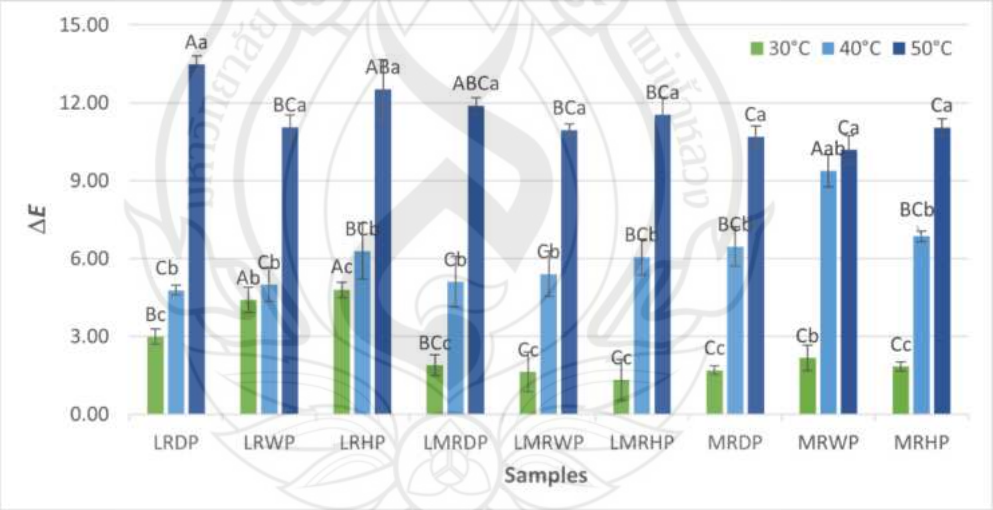
Table 8.1 Initial Moisture Content and Color Parameters of RCB

Roasting level	Process	MC (%)	*L**	*a**	*b**
Light roasted	DP	2.1 ± 0.1^{a}	39.6 ± 0.4^{a}	4.3 ± 0.1^{a}	4.7 ± 0.1^{a}
	WP	1.8 ± 0.1^{b}	39.5 ± 0.5^{a}	4.0 ± 0.1^{a}	4.6 ± 0.4^{a}
	HP	2.13 ± 0.03^{a}	39.4 ± 0.1^{a}	4.0 ± 0.2^{a}	4.3 ± 0.3^{a}
Light-medium roasted	DP	1.49 ± 0.03^{c}	38.2 ± 0.2^{b}	3.3 ± 0.2^{bc}	2.9 ± 0.2^{b}
	WP	1.4 ± 0.1^{c}	37.8 ± 0.2^{b}	3.0 ± 0.2^{c}	2.6 ± 0.5^{b}
	HP	1.6 ± 0.02^{bc}	38.3 ± 0.6^{b}	3.5 ± 0.1^{b}	3.3 ± 0.3^{b}
Medium roasted	DP	1.58 ± 0.1^{bc}	37.4 ± 0.2^{c}	2.3 ± 0.1^{d}	1.6 ± 0.1^{c}
	WP	1.3 ± 0.23^{d}	37.3 ± 0.4^{c}	2.5 ± 0.1^{d}	1.8 ± 0.1^{c}
	HP	0.9 ± 0.1^{d}	37.3 ± 0.3^{c}	2.5 ± 0.1^{d}	1.8 ± 0.1^{c}

Note Data are presented as mean ± SD ($n = 3$), Means with different letters in columns indicate significant differences at ($p < 0.05$). DP = Natural/ Dry process; WP = Washed/ Wet process; HP = Honey process; MC = moisture content.

The ΔE values were calculated after storage for 21 days to establish a relationship with the color change phase of roasted coffee bean, as shown in Fig. 2. Significant differences ($p<0.05$) in ΔE values were induced by the roasting level and accelerated storage conditions. Results showed that the ΔE of 30°C ranged from 1.3±0.8

to 4.8±0.3, 40°C ranged from 4.8±0.2 to 9.4±0.6, and 50°C ranged from 10.2±0.6 to 13.5±0.3. Thus, storage at higher temperatures resulted in greater autoxidation than at lower temperatures. Light roasted exhibited the greatest change in color from light brown to medium brown during storage at 40 and 50°C, caused by increased melanoidins during storage. The melanoidins produced by a non-enzymatic reaction transformed the color value of the coffee beans from bright to brown, and pyrolysis caused the beans to darken when subjected to heat treatment (1). This melanoidin compound, which is responsible for the brown hue, is associated with the acid flavor or taste-forming compounds tannins, acetic acid, and several volatile compounds such as aldehydes, furfural, ketones, alcohols, esters, formic acid, and acetic acid which react with amino acids causing sugar reduction (9, 44). Thus, this result underscores the importance of controlling both roasting levels and storage temperature to maintain the desired color and flavor attributes of roasted coffee beans. The significant color changes observed at higher temperature might have implications for the shelf-life and quality of coffee during storage, particularly regarding its visual appeal and flavor characteristics.



Note Means with different capital letters indicate significant differences in roasting levels at $p<0.05$: different lower-case letters indicate significant differences among storage temperatures at $p<0.05$: LR = Light roasted; LMR = Light-medium roasted; MR = Medium roasted; DP = Natural/ Dry process; WP = Washed/ Wet process; HP = Honey process.

Figure 8.2 Total color difference (ΔE) of RCB after undergoing accelerated storage at 30, 40, and 50°C for 21 days

8.3.2 Effect of Accelerated Storage Conditions on the Lipid Oxidation of Roasted Coffee Bean

Peroxide values (PV) were utilized to determine the extent of lipid oxidation at different roasted coffee levels. Accelerated storage time and temperature significantly impacted the PV of roasted coffee bean (p<0.05), as shown in Table 2. The initial PVs for light were 0.6±0.1, 0.73±0.02, and 0.9±0.2 meq/kg of oil for dry, wet and honey, respectively. Light-medium were 1.6±0.4, 1.3±0.5, and 1.7±0.2 meq/kg of oil for dry, wet and honey, respectively while MR were 1.9±0.2, 1.9±0.2, and 1.9±0.1 meq/kg of oil for dry, wet, and honey, respectively. The PV increased on days 7 and 14 and then decreased on day 21. These findings were consistent with Getachew and Chun (47). They reported that the initial PV of encapsulated oil and bulk coffee was 1.03 and 1.03 meq peroxide/kg of oil, respectively and that after 12 weeks of storage at 45°C, these increased to 4.56 and 7.21 meq peroxide/kg. Accelerated storage at a low temperature of 30°C resulted in the lowest PV compared to storage at 40°C and 50°C. The PV of medium increased faster at high temperatures than light-medium and light roasted. Tadros et al. (48) found that the PV of roasted coffee oil decreased after 14 days of storage, which they attributed to the decomposition of short-chain aldehydes and carboxylic acids. The stability of coffee quality and the concentration of volatile compounds including esters, carbohydrates, amino acids, and lipids, as well as the autoxidation of aldehydes and ketones during the roasting process, are factors that influence the PV of roasted coffee bean (49).

Among the coffee roasting processes, the light-medium as wet process gave the highest PV in comparison to dry and honey processes, while at light-medium, the PV of honey was higher than dry and wet processes. At medium roasted, dry showed the lowest PV during the 21-day accelerated storage period in comparison to wet and honey processes. Peroxide and hydroperoxide are the principal by-products of autooxidation; a greater PV signifies reduced oxidation rancidity, which in turn impacts the shelf-life of green coffee bean (15, 22). The hydrogen peroxide of coffee silver skin provides the best quality for optimizing shelf-life, and sensory and visual qualities (50).

Table 8.2 Peroxide Values of Roasted Coffee Bean (RCB) after Undergoing Accelerated Storage Conditions

Roasting level	Process	Control	Peroxide value (PV)								
			30°C			40°C			50°C		
			Day 7	Day 14	Day 21	Day 7	Day 14	Day 21	Day 7	Day 14	Day 21
Light roasted	DP	0.6 ± 0.1^{Cc}	1.2 ± 0.3^{Bbc}	1.7 ± 0.2^{Bbc}	0.6 ± 0.1^{Bc}	1.4 ± 0.3^{CDbc}	2.3 ± 0.2^{ABCab}	0.7 ± 0.2^{Cc}	1.1 ± 0.2^{Dbc}	3 ± 1^{Ca}	1.0 ± 0.1^{Dc}
	WP	0.73 ± 0.02^{Cd}	1.0 ± 0.3^{Bcd}	1.7 ± 0.4^{Bbc}	0.7 ± 0.1^{Bd}	1.2 ± 0.1^{Dbcd}	1.9 ± 0.2^{BCb}	0.9 ± 0.3^{BCd}	1.4 ± 0.3^{CDbcd}	3.1 ± 0.4^{Ca}	1.1 ± 0.1^{CDcd}
	HP	0.9 ± 0.2^{BCcde}	1.8 ± 0.9^{ABbc}	1.93 ± 0.04^{ABb}	0.50 ± 0.15^{Be}	1.5 ± 0.2^{BCDbcd}	1.7 ± 0.2^{Cbc}	0.7 ± 0.1^{Cde}	1.7 ± 0.1^{BCDbc}	3.2 ± 0.1^{Ca}	1.0 ± 0.3^{CDbcde}
Light-medium roasted	DP	1.6 ± 0.4^{ABbcd}	1.9 ± 0.2^{ABbc}	2 ± 1^{ABbc}	0.6 ± 0.3^{Bd}	2.2 ± 0.3^{ABbc}	2.7 ± 0.4^{ABb}	1.1 ± 0.4^{ABCcd}	2.3 ± 0.5^{ABCbc}	4.3 ± 0.5^{ABCa}	1.3 ± 0.2^{CDcd}
	WP	1.3 ± 0.5^{ABCcde}	2 ± 1^{ABcde}	2.3 ± 0.2^{ABbc}	0.9 ± 0.1^{ABe}	2.3 ± 0.1^{Abc}	2.8 ± 0.3^{ABb}	1.1 ± 0.1^{ABCcd}	2.1 ± 0.4^{ABCbcd}	4.1 ± 0.4^{ABCa}	1.4 ± 0.1^{CDcde}
	HP	1.7 ± 0.2^{Abcd}	2.13 ± 0.01^{Abc}	2.4 ± 0.2^{ABb}	0.73 ± 0.01^{ABe}	2.13 ± 0.01^{ABCbc}	2.6 ± 0.5^{ABCb}	1.2 ± 0.3^{ABCde}	2.1 ± 0.5^{ABCbc}	4.0 ± 0.3^{BCa}	1.5 ± 0.1^{Ccde}
Medium roasted	DP	1.9 ± 0.2^{Abcd}	2.1 ± 0.6^{Abc}	2.53 ± 0.01^{Ab}	1.1 ± 0.1^{Ad}	2.8 ± 0.1^{Ab}	2.7 ± 0.2^{ABb}	1.4 ± 0.1^{ABcd}	2.5 ± 0.2^{ABb}	5.1 ± 0.2^{Aa}	2.2 ± 0.1^{Bbc}
	WP	1.9 ± 0.2^{Abcd}	2.5 ± 0.1^{Abc}	2.6 ± 0.2^{Abc}	1.1 ± 0.4^{Ad}	2.5 ± 0.4^{Abc}	2.8 ± 0.3^{ABb}	1.5 ± 0.5^{Acd}	2.9 ± 0.2^{Ab}	5.5 ± 0.8^{Aa}	2.5 ± 0.2^{Abc}
	HP	1.9 ± 0.1^{Ade}	2.6 ± 0.1^{Acde}	2.5 ± 0.2^{Abcd}	1.1 ± 0.4^{Af}	2.9 ± 0.4^{Ab}	2.9 ± 0.2^{Ab}	1.4 ± 0.1^{ABef}	3.0 ± 0.3^{Ab}	5.6 ± 0.4^{Aa}	2.7 ± 0.1^{Abc}

Note Data are presented as mean ± SD (n = 3), Means with different capital letters in the same columns indicate significant differences in roasting levels at p<0.05: different lower-case letters in the same row indicate significant differences among storage temperatures and times at p<0.05. DP; natural process, WP; washed process, and HP; honey process.

8.3.3 Shelf-life of Roasted Coffee Beans

The shelf-life of roasted coffee bean was determined using kinetic models and Arrhenius equation approaches based on peroxide value. The different roasting levels and accelerated storage conditions gave significantly different (p<0.05) results for roasted coffee bean shelf-life, as shown in Table 3. An increase in storage temperature was associated with a decrease in shelf-life. Thus, storage of green coffee bean at a lower temperature of 30°C was preferable compared to 40°C and 50°C. (15, 22). An increase in temperature leads to a drop in the partial pressure of O_2, which in turn reduces sensory properties and shelf-life (31). light had an extended shelf-life in comparison to light-medium and medium roasted. The shelf-life of roasted coffee bean is determined by the relationship between their oxidation processes and physicochemical features, which leads to the development of various volatile chemicals and sensory characteristics similar as shelf life of food product and food package mitigated on their physiological and biochemical changes (52). This relationship is influenced by the level of roasting and storage conditions.

Table 8.3 Shelf-Life of RCB after Undergoing Accelerated Storage Conditions

Roasting level	Process	Storage conditions					
		30°C		40°C		50°C	
		Shelf-life (days)	R^2	Shelf-life (days)	R^2	Shelf-life (days)	R^2
Light roasted	DP	10.0 ± 0.1^{ABa}	0.87	8.4 ± 0.4^{Ab}	0.97	7.4 ± 0.6^{Ab}	0.88
	WP	11.7 ± 0.3^{Aa}	0.98	10.1 ± 0.6^{Ab}	0.95	7.6 ± 0.1^{Ac}	0.93
	HP	11.1 ± 0.4^{ABa}	0.91	9.3 ± 0.6^{ABb}	0.89	6.9 ± 0.5^{ABc}	0.95
Light-medium	DP	7.5 ± 0.1^{CDa}	0.99	5.5 ± 0.3^{CDb}	0.97	4.1 ± 0.9^{Cb}	0.90
roasted	WP	8.8 ± 0.6^{BCa}	0.87	6.6 ± 0.7^{BCb}	0.94	5 ± 1^{BCb}	0.91
	HP	7.3 ± 0.3^{CDa}	0.87	5.0 ± 0.2^{CDb}	0.94	4.3 ± 0.8^{Cb}	0.90
Medium	DP	6.3 ± 0.3^{Da}	0.89	4.6 ± 0.6^{Db}	0.96	4.2 ± 0.7^{Cb}	0.88
roasted	WP	$7.7 \pm 0.6C^{Da}$	0.86	4.5 ± 0.3^{Db}	0.87	3.5 ± 0.2^{Cb}	0.93
	HP	$6.7 \pm 0.5C^{Da}$	0.87	4 ± 1^{Db}	0.85	3.4 ± 0.3^{Cb}	0.94

Note Data are presented as mean ± SD (n = 3). Means with different capital letters in the same columns indicate significant differences in roasting level at p<0.05: different lower-case letters in the same row indicate significant differences among storage temperatures at p<0.05. DP; natural process, WP; washed process, and HP; honey process.

8.3.4 Effect of Roasting Level on Volatile Compounds in Roasted Coffee Beans

Eighty-two volatile compounds, belonging to thirteen chemical groups, were identified (Table 8.5). Volatile alcohols, aldehydes, esters, furans, furanones, ketones, organic acids, pyrazines, pyridines, pyrroles, sulfides, and terpenes are commonly found in roasted coffee bean (3-5, 8, 13, 39). From these, twenty-six representative compounds were selected for further analysis across different roast levels (Table 8.4). Most of these volatile compounds showed significant differences (p<0.05) across the roasting levels, while propanal, hexanal, and 2,3-pentanedione concentrations did not differ significantly (p>0.05).

Alcoholic components, such as maltol (caramel-like) and 1-hexanol (fruity and alcoholic), have been identified in coffee (5, 14). Both maltol and 1-hexanol concentrations increased with higher roasting levels. The medium beans, roasted at a higher temperature and longer duration than light-medium and light roast, exhibited more complex flavors and aromas including caramel-like and fruity notes. For processing methods, wet yielded the highest concentrations of both maltol and 1-hexanol. Higher alcohol content, along with amino acid precursors, may be directly related to ester compound production, which is heavily dependent on a nitrogen source (5). The prolonged fermentation period in tanks during the wet results in a more refined flavor profile and complex acidity, potentially contributing to alcoholic compound formation. Alcoholic compounds are generated during fermentation (8), while roasting influences the production of biologically derived alcohols through the breakdown of linalool and lipids (7). Therefore, both post-harvest processing and roasting levels influenced alcoholic compound development. In the aldehyde group, propanal is described as ethereal, pungent, earthy, alcoholic, and almond-like, while hexanal is characterized as green, grassy, and fruity (6, 53). Neither propanal nor hexanal showed significant differences (p>0.05) across roasting levels or processing methods. Aldehydes are formed via the Maillard reaction, Strecker degradation, and through the interaction of amino acids and polyphenols in the presence of polyphenol oxidase at normal temperatures (13).

Ethyl acetate, an ester, is associated with fruity and grape-like notes, while methyl salicylate is characterized by wintergreen and mint-like aromas (5). Ester

concentrations decreased with increasing roast levels (9), suggesting that light coffees exhibit higher concentrations of esters, contributing to acidic and fruity notes, while medium coffees have a more intense mouthfeel, and dark roasts are predominantly bitter. Coffee processing appeared to have minimal impact on ethyl acetate levels. However, dry and honey process coffees exhibited higher concentrations of other esters including methyl salicylate, ethyl propanoate, ethyl-3-methylbutyrate, and methyl acetate. These compounds contribute to a range of aroma descriptors such as fruity, winey, sweet, juicy, rum, wintergreen, and mint-like (5-6, 8). Esters significantly influence the final coffee beverage by contributing to floral and fruity sensory profiles (5). Ester hydrolysis and non-enzymatic browning are likely primary causes of coffee deterioration, leading to a sour taste and reduced shelf-life during storage (12).

Furan compounds contribute significantly to the coffee aroma. 2-Furancarboxaldehyde is characterized by sweet, bready, and caramel-like notes (3), while 5-methylfuran and furfuryl alcohol are known for their sweet, caramel-like, and brown aromas (5). Furfuryl alcohol concentrations were highest in medium (15.9±0.4 to 16.4±0.4 % d.w.), followed by light-medium (15.22±0.02 to 16.4±0.1 % d.w.) and light (14.3±0.2 to 16.3±0.4 % d.w.). These compounds likely arise from carbohydrates, which undergo hydrolysis during roasting, generating furans that create sweet, caramel, and burnt notes to the coffee (8). Furan derivatives are primarily formed through Maillard and pyrolysis reactions, as well as thermal oxidative degradation of polyunsaturated fatty acids, thiamine, and nucleoside breakdown during roasting (4-13). The longer roasting time in medium led to higher breakdown of sugars compared to light-medium and light roasted. Conversely, 2-furancarboxaldehyde-5-methyl concentrations were higher in light (11.3±0.4 to 13.1±0.6% d.w.) and decreased in light-medium (11.4±0.1 to 13.20±0.03% d.w.) and medium (10.8±0.3 to 12.18±0.01% d.w.). Dry and wet coffees exhibited higher concentrations of these furan compounds than honey coffees. These differences may be related to the higher levels of total furans and non-volatile compounds in dry and wet, which are associated with the degradation of chlorogenic acid into phenols and lactones, a process that becomes more pronounced during more vigorous roasting (6).

Furanone compounds were also detected in the coffee samples. 3-Hydroxy-4,5-dimethyl-2(5H)-furanone, characterized by clover and curry-like aromas, was found at

concentrations ranging from 0.0571±0.0001 to 0.23±0.02% d.w. 4-Methyl-5-ethyl-3-hydroxy-2(5H)-furanone, described as buttery and seasoning-like (5), was present at concentrations between 0.1±0.1 and 0.3±0.1 % d.w. Both furanones were found at higher concentrations in light-medium than light and were not detected in medium roast. Higher furanone concentrations are associated with lower roasting degrees (8). Furanones are formed through the degradation of Amadori compounds, which are products of the Maillard reaction between pentose carbohydrates and glycine or alanine (20). Coffee processing did not impact furanone concentrations.

Ketone compounds, such as 2,3-pentanedione (described as buttery, oily, and caramel-like) and dihydro-2-methyl-3-furanone (identified as sweet and roasted), have been found in coffee (5, 14). 2,3-Pentanedione concentrations showed no significant difference (p>0.05) across roasting or processing. This lack of significant difference may be attributed to the coffee beans not being roasted to the second crack, which would have resulted in a darker, more alkaline roast characterized by burnt or oily surface beans (9). Dihydro-2-methyl-3-furanone concentrations were higher in light-medium (0.83±0.02 to 1.602±0.001% d.w.) compared to light (0.64±0.03 to 1.06±0.04% d.w.) and medium (0.68±0.01 to 1.10±0.06% d.w.). Honey samples exhibited lower dihydro-2-methyl-3-furanone content than dry and wet samples. Ketones are formed through Maillard and pyrolysis reactions between amino compounds and reducing sugars, or between peptides, proteins, and ammonia (4). High sugar content can lead to the reduction and formation of other compounds such as aldehydes and ketones that are often associated with buttery and caramel flavors (3). Ketone formation in raw coffee seeds can also occur through the oxidation of fatty acids, leading to increased hydroperoxide concentrations and subsequent auto-oxidation (13).

Organic acids, such as propanoic acid anhydride (described as pungent, acidic, cheesy, and vinegary) and butyric acid (defined as acidic, sour, and cheesy), are important flavor compounds in coffee (5, 8). Both propanoic and butyric acid concentrations were highest in the light range (0.94±0.03 to 1.18±0.01% d.w. and 0.08±0.01 to 0.15±0.03% d.w., respectively) and decreased in light-medium (0.92±0.01 to 1.05±0.03% d.w. and 0.065±0.003 to 0.08±0.01% d.w., respectively) and medium (0.78±0.01 to 0.85±0.03% d.w. and 0.085±0.003 to 0.093±0.002% d.w., respectively). During roasting, sucrose is converted to glucose and fructose through caramelization

and the Maillard reaction, which transforms a range of organic acids. Carbohydrates, including oligosaccharides and polysaccharides, are also converted to organic acids, contributing to acidity. These acids are partially incorporated into melanoidins (contributing to color) and partially solubilized (3). Thus, lighter roasts are associated with higher levels of organic acids. With increasing roast intensity, these acids are lost, while Maillard and lipid breakdown lead to the formation of other compounds (14). The wet exhibited higher concentrations of propanoic acid anhydride, and butyric acid, contributing to a more complex acidity described as sour and fermented compared to dry and honey.

Phenolic compounds, such as 4-vinyl guaiacol, contribute to cloy, smoky, bacon, phenolic, and spicy notes (4-5, 8), while 4-ethyl-2-methoxy-phenol is associated with smoky and spicy characteristics (13-14). Higher roasting temperatures and longer roasting times resulted in increased levels of both 4-vinyl guaiacol and 4-ethyl-2-methoxy-phenol in medium coffee (2.32±0.01 to 2.93±0.02% and 1.03±0.02 to 1.04±0.03% d.w., respectively) compared to light-medium (2.07±0.02 to 2.83±0.02% and 0.108±0.005 to 0.17±0.02% d.w., respectively) and light (1.57±0.02 to 2.2±0.1% and 0.08±0.01 to 0.19±0.01% d.w., respectively). Lower concentrations of these phenolic compounds in light and light-medium likely contributed to reduced astringency, whereas medium roast exhibited both smoky and astringent notes (4-5). Chlorogenic acid degradation during roasting yields lactones and phenolic derivatives, including caffeic acid, which influence coffee aroma and flavor through hydrolysis or isomerization, affecting bitterness and astringency (3, 4, 6). In medium coffee, guaiacol and phenol compounds were associated with phenolic, burnt, plastic, rubber, and smoky aroma notes (5). Higher phenolic compound concentrations can lead to hydrolysis and oxidation, resulting in melanoidin formation from ferulic acid during storage and roasting (3, 6). During coffee processing, honey and wet coffees contained higher concentrations of 4-vinyl guaiacol and 4-ethyl-2-methoxy-phenol than dry coffee, suggesting that dry processing may help to maintain coffee quality by minimizing the development of phenolic content during processing and roasting.

Pyrazines, such as methyl- and ethyl-pyrazines, contribute to nutty and roasted flavors (13). These pyrazines were found in lower concentrations in medium coffee (4.57±0.02 to 4.64±0.02% and 2.37±0.02 to 2.59±0.01% d.w., respectively) compared

to light-medium (4.97±0.02 to 5.57±0.02% and 2.36±0.02 to 2.603±0.002% d.w., respectively) and light (5.53±0.02 to 5.98±0.01% and 2.52±0.01 to 2.74±0.03% d.w., respectively). While pyrazines are generally formed through the Maillard reaction between reducing sugars and amino acids during roasting (13-14), high temperatures during later roasting stages can cause the breakdown of the major pyrazine components (7), explaining the lower concentrations in medium roast. Coffee processing appeared to have no significant effect on pyrazine compound concentrations.

Pyridine compounds, such as pyridine and 2-acetylpyridine, contribute to distinct flavor and aroma characteristics. Pyridine is associated with fishy and sour notes, while 2-acetylpyridine imparts corny and nutty aromas (5). 2-Acetylpyridine concentrations were lower in medium coffee (0.902±0.001 to 1.11±0.01% d.w.) compared light-medium (0.97±0.02 to 1.196±0.002% d.w.) and light (1.006±0.003 to 1.24±0.02% d.w.). Pyridine formation is linked to extended roasting times, likely through the Maillard reaction and trigonelline decomposition (14). Some studies suggested a positive correlation between pyridine compounds and roasting time, with higher concentrations in the initial roasting stages and a decrease with longer durations (6); however, this study found the opposite trend, with pyridine concentrations highest in medium coffee (3.68±0.01 to 4.62±0.01% d.w.) compared to light-medium (2.01±0.02 to 3.17±0.02% d.w.) and light (1.093±0.004 to 1.791±0.005% d.w.). Hill and Borem (3) suggested that pyridine concentrations influence sensory perception, with low concentrations contributing to coffee and chocolate notes and high concentrations to fishy and putrid odors. Dry coffee exhibited the highest pyridine concentration compared to wet and honey process coffees. This difference could be attributed to the long drying times in the post-harvest process for dry coffee, which may contribute to the development of sour notes.

2-Formyl pyrrole contributes musty, beef-like, and coffee-like notes, while 1-methyl pyrrole is associated with woody and herbal scents (5). Both 2-formyl pyrrole and 1-methyl pyrrole were found in higher concentrations in medium coffee (0.92±0.01 to 1.07±0.02% and 0.595±0.003 to 0.98±0.01% d.w., respectively) compared to light-medium (0.83±0.02 to 0.87±0.02% and 0.83±0.02 to 0.97±0.02% d.w., respectively) and light (0.57±0.02 to 0.63±0.02% and 0.43±0.02 to 0.66±0.03% d.w., respectively). The higher concentrations of pyrroles in medium coffee result from the thermal

degradation of Amadori intermediates, the reaction of aldoses with alkylamines, and other processes like caramelization, pyrolysis, and trigonelline degradation, all of which contribute to roasted, nutty, and cocoa flavors (13). Pyridinium derivative production and trigonelline degradation account for approximately 3% of pyrrole formation (3). Dry coffee was characterized by a greater abundance of pyrrole compounds with herbaceous, hay-like, and nutty notes compared to honey and wet coffees (14), while honey coffee exhibited a higher concentration of 1H-pyrrole, described as sweet, warm, and nutty (5), than dry and wet coffees.

Sulfur compounds, such as 3-methylthiophene described as ashy (14) and dimethyl sulfide associated with sulfur and cabbage notes (8) were quantified. 3-Methylthiophene concentrations were similar in medium (0.75±0.03 to 0.82±0.01% d.w.) and light-medium (0.84±0.02 to 0.97±0.02% d.w.) and higher than in light (0.39±0.01 to 0.93±0.02% d.w.). Dimethyl sulfide followed a similar trend, with medium (0.12±0.01 to 0.16±0.02% d.w.) and light-medium (0.12±0.02 to 0.17±0.02% d.w.) having higher concentrations than light (0.09±0.01 to 0.13±0.02% d.w.). These results suggested a lower sulfur compound content in light roast coffee. Sulfur compound production during roasting occurs through heat reactions and Strecker degradation (5). Although present in low concentrations, sulfur-containing molecules like thiols, sulfides, and thiophenes significantly impact coffee aroma. Wet coffee exhibited higher 3-methylthiophene concentrations than honey and dry process coffees, possibly due to variations in the environment and the water used during tank fermentation. Sulfur compounds were found in the lowest amounts in roasted coffee bean compared to the other compound groups.

Terpene compounds, such as linalool associated with citrus, orange and lemon notes and α-terpineol described as citrus, woody, and lemon (5) were analyzed. Linalool and α-terpineol concentrations were higher in light (0.198±0.001 to 0.36±0.02% d.w. and 0.031±0.001 to 0.130±0.002% d.w., respectively) and light-medium (0.08±0.01 to 0.13±0.02% d.w. and 0.06±0.02 to 0.27±0.02% d.w., respectively) than in medium (0.022±0.001 to 0.05±0.03% d.w. and 0.09±0.01 to 0.104±0.002% d.w., respectively). Similarly, dry and honey coffees contained higher levels of linalool and α-terpineol than wet process coffee. The highest terpene content was observed in light coffee and in dry and honey processing methods, suggesting a potential association with citrus

notes like lemon and orange. Terpene production during coffee mucilage removal is linked to the malonic acid pathway. Certain yeast species (e.g., *Saccharomyces cerevisiae*, *Torulaspora delbrueckii*, and *Hanseniaspora uvarum*) present during coffee fermentation can convert glycoside precursors to terpenes (5).

Table 8.4 The Main Volatile Compounds of Roasted Coffee Beans at Different Roasting Levels

Volatile compound	Description	Group	Samples (% d.w.)								
			Light roasted			Light-medium roasted			Medium roasted		
			DP	WP	HP	DP	WP	HP	DP	WP	HP
Maltol	Caramel	Alcoholic	1.0± 0.1^{d}	1.7± 0.3^{c}	0.8± 0.1^{d}	2.114± 0.004^{b}	2.1± 0.1^{b}	2.24± 0.02^{ab}	2.5± 0.2^{ab}	2.8± 0.3^{a}	2.6± 0.3^{a}
1-Hexanol	Fruity and alcoholic	Alcoholic	0.3± 0.1^{c}	0.4± 0.1^{abc}	0.4± 0.1^{c}	0.6± 0.1^{abc}	0.6± 0.2^{ac}	0.4± 0.1^{bc}	0.7± 0.3^{a}	0.7± 0.3^{a}	0.6± 0.2^{ab}
Propanal^{ns}	Ethereal, pungent, earthy, alcoholic	Aldehyde	0.17± 0.01	0.171± 0.003	0.1± 0.2	0.1± 0.1	0.17± 0.03	0.19± 0.03	0.3± 0.1	0.3± 0.1	0.23± 0.02
Hexanal^{ns}	Green, grassy, fruity	Aldehyde	0.18± 0.01	0.176± 0.003	0.5± 0.2	0.2± 0.1	0.22± 0.03	0.3± 0.6	0.2± 0.1	0.2± 0.1	0.20± 0.02
Ethyl acetate	Fruity, grape	Ester	6.7± 0.4^{b}	7.5± 0.4^{a}	6.26± 0.04^{bcd}	6.8± 0.1^{b}	6.8± 0.3^{b}	5.9± 0.5^{d}	6.15± 0.04^{cd}	6.0± 0.2^{cd}	5.5± 0.2^{e}
Methyl salicylate	Wintergreen, mint-like	Ester	1.0± 0.2^{a}	0.8± 0.3^{ab}	1.2± 0.2^{a}	0.6± 0.1^{bc}	0.2± 0.1^{cd}	0.04± 0.02^{d}	0.08± 0.02^{d}	0.6± 0.2^{cd}	0.07± 0.01^{d}
2-Furancarbox aldehyde, 5-methyl-	Sweet, caramel, bready, brown, coffee	Furan	11.3± 0.4^{c}	13.1± 0.6^{a}	11.69± 0.03^{bc}	13.20± 0.03^{a}	12.3± 0.4^{b}	11.4± 0.1^{c}	12.18± 0.01^{b}	10.8± 0.3^{d}	10.97± 0.03^{d}
Furfuryl alcohol	Sweet, caramellic, brown	Furan	16.3± 0.4^{a}	16.06± 0.01^{b}	14.3± 0.2^{d}	15.22± 0.02^{c}	15.4± 0.4^{c}	16.4± 0.1^{a}	15.9± 0.4^{bc}	16.4± 0.1^{a}	16.0± 0.1^{b}
3-Hydroxy-4,5-dimethyl-2(5H) furanone	Fenugreek, curry	Furanone	0.0571± 0.0001^{b}	0.1131± 0.0001^{ab}	0.2± 0.1^{a}	0.18± 0.01^{a}	0.23± 0.02^{a}	0.2± 0.1^{a}	ND	ND	ND

Table 8.4 (continued)

Volatile compound	Description	Group	Samples (% d.w.)								
			Light roasted			Light-medium roasted			Medium roasted		
			DP	WP	HP	DP	WP	HP	DP	WP	HP
4-Methyl-5-ethyl-3-hydroxy-2(5H) furanone	Buttery, seasoning-like	Furanone	ND	ND	0.3± 0.1[a]	0.16± 0.01[ab]	0.18± 0.02[ab]	0.1± 0.1[b]	ND	ND	ND
2,3-Pentanedione[ns]	Buttery, oily, caramel-like	Ketone	1.3± 0.1	1.28± 0.04	1.32± 0.01	1.3± 0.1	1.3± 0.1	1.6± 0.2	1.1± 0.1	1.23± 0.02	1.28± 0.04
Dihydro-2-methyl-3-furanone	Sweet, roasted	Ketone	0.64± 0.03[e]	1.06± 0.04[c]	0.78± 0.01[d]	1.602± 0.001[a]	1.52± 0.01[b]	0.83± 0.02[d]	0.68± 0.01[e]	1.1± 0.1[c]	0.76± 0.02[d]
Propanoic acid, anhydride	Pungent, acidic, cheesy, vinegar	Organic Acid	0.94± 0.03[c]	1.18± 0.01[a]	0.97± 0.02[c]	0.94± 0.03[c]	1.05± 0.03[b]	0.92± 0.01[c]	0.85± 0.03[d]	0.8005 ±0.0003[d]	0.78± 0.01[d]
Butyric acid	Acidic, sour, cheesy	Organic Acid	0.08± 0.01[c]	0.13± 0.02[b]	0.15± 0.03[a]	0.08± 0.01[c]	0.065± 0.003[c]	0.076± 0.002[c]	0.093± 0.002[bc]	0.085± 0.003[c]	0.088± 0.001[bc]
4-vinyl guaiacol	Clove, smoky, bacon, phenolic, spicy	Phenolic	1.57± 0.02[d]	2.2± 0.1[c]	2± 0[c]	2.93± 0.02[a]	2.495± 0.003[b]	2.07± 0.02[c]	2.88± 0.01[a]	3± 0[a]	2.32± 0.01[b]
Phenol, 4-ethyl-2-methoxy-	Smoky, spicy	Phenolic	0.103± 0.002[c]	0.19± 0.01[b]	0.08± 0.01[c]	0.108± 0.005[c]	0.17± 0.02[b]	0.13± 0.02[b]	1.04± 0.03[a]	1.03± 0.02[a]	1.03± 0.02[a]
Pyrazine, methyl-	Nutty, cocoa, roasted	Pyrazine	5.53± 0.02[ab]	5.98± 0.01[a]	5.74± 0.02[a]	4.97± 0.02[b]	5.57± 0.02[ab]	5.38± 0.01[a]	4.64± 0.02[c]	4.62± 0.01[c]	4.57± 0.02[c]
Pyrazine, ethyl-	Nutty, cocoa, roasted	Pyrazine	2.55± 0.03[b]	2.74± 0.03[a]	2.52± 0.01[b]	2.36± 0.02[c]	2.603± 0.002[b]	2.47± 0.02[c]	2.43± 0.02[c]	2.37± 0.02[c]	2.59± 0.01[b]

Table 8.4 (continued)

Volatile compound	Description	Group	Samples (% d.w.)								
			Light roasted			Light-medium roasted			Medium roasted		
			DP	WP	HP	DP	WP	HP	DP	WP	HP
Pyridine	Sour, Fishy	Pyridines	1.791± 0.005^{e}	1.66± 0.02^{e}	1.093± 0.004^{f}	2.16± 0.02^{d}	3.17± 0.02^{c}	2.01± 0.02^{d}	3.68± 0.01^{c}	4.62± 0.01^{a}	4.13± 0.08^{b}
2-Acetylpyridine	Corn, nutty	Pyridines	1.202± 0.001^{ab}	1.24± 0.02^{a}	1.006± 0.003^{b}	1.17± 0.02^{b}	1.196± 0.002^{ab}	0.97± 0.02^{c}	1.11± 0.01^{b}	0.902± 0.001^{c}	0.92± 0.01^{c}
2-Formyl pyrrole	Musty, beef, coffee-like	Pyrroles	0.601± 0.001^{d}	0.57± 0.02^{d}	0.63± 0.02^{d}	0.87± 0.02^{b}	0.86± 0.02^{b}	0.83± 0.02^{c}	1.07 ±0.02^{a}	0.93± 0.02^{b}	0.92± 0.01^{b}
1-Methyl pyrrole	Woody, herbal	Pyrroles	0.43± 0.02^{d}	0.6001± 0.0001^{c}	0.66± 0.03^{cd}	0.83± 0.02^{b}	0.97± 0.02^{a}	0.907± 0.004^{a}	0.595± 0.003^{cd}	0.98± 0.01^{a}	0.68± 0.01^{c}
3-Methylthiophene	Ash	Sulfur	0.72± 0.01^{d}	0.93± 0.02^{b}	0.39± 0.01^{e}	0.84± 0.02^{c}	0.97± 0.02^{a}	0.88± 0.01^{b}	0.82± 0.01^{c}	0.84± 0.02^{c}	0.75± 0.03^{d}
Dimethyl sulfide	Sulfur, cabbage	Sulfur	0.09± 0.01^{b}	0.12± 0.01^{b}	0.13± 0.02^{b}	0.17± 0.02^{a}	0.17± 0.02^{a}	0.12± 0.02^{b}	0.13± 0.02^{b}	0.12± 0.01^{b}	0.16± 0.02^{a}
Linalool	Citrus, orange, lemon	Terpenes	0.36± 0.02^{a}	0.198± 0.001^{b}	0.34± 0.02^{a}	0.08± 0.01^{c}	0.09± 0.01^{c}	0.13± 0.02^{c}	0.022± 0.001^{d}	0.05± 0.03^{d}	0.043± 0.002^{d}
α-terpeniol	Citrus, woody, lemon	Terpenes	0.103± 0.002^{b}	0.07± 0.02^{c}	0.031± 0.001^{d}	0.06± 0.02^{c}	0.08± 0.01^{bc}	0.27± 0.02^{a}	0.09± 0.01^{bc}	0.104± 0.002^{b}	0.09± 0.01^{bc}

Note Data are presented as mean ± SD (n = 3). Means with different superscripts in the same row indicate significantly different roasting levels p<0.05: DP = natural/ dry process; WP = washed/ wet process; HP = honey process; RT = retention time – d.w. = dry weight; ns = not significant; ND = not-detected.

8.3.5 Changes in the Main Volatile Compound Groups after Undergoing Accelerated Storage

After 21 days of accelerated storage at 30, 40, and 50°C, the volatile component structure of coffee changed significantly (p<0.05), as shown in Fig. 3. Most volatile groups including aldehydes, sulfides, alcohols, pyridines, pyrroles, ketones, esters, and furans experienced reduced levels, while organic acids, phenolics, and pyrazines increased. Furanones and terpenes maintained their stability. The increase in organic acids, phenolics, and pyrazines during accelerated storage may be attributed to oxidation, oxygen permeation, and CO_2 release affecting coffee's flavor, quality, and shelf-life (10). The oxidation of lipids and thermal degradation of carbohydrates and amino acids result in the increase of organic acids including formic and acetic acid (3, 5, 8). The oxidation of chlorogenic acid and the degradation of lignin result in the formation of smaller phenolic derivatives, which cause an increase in phenolic compounds (3-4). Pyrazines, which are responsible for the nutty and roasted aromas, increased during Maillard reactions, notably during high-temperature storage (3, 6). The production of pyrazines and phenolic compounds is accelerated by elevated storage temperatures, which enhance the earthy and savory flavors (5, 8). Thus, the color and physicochemical properties of roasted coffee beans were influenced by the thermal oxidation of polyphenols (44), which resulted in volatile release, surface oil migration and oxidation, leading to off-flavors (12). The increase of this volatile compound could influence by storage conditions, affecting color, moisture, water activity, and sensory traits, while also microbial activity, mold growth and decay (40).

The reduction in aldehydes, sulfides, alcohols, pyridines, pyrroles, ketones, esters, and furans during accelerated storage was ascribed to chemical degradation, evaporation, and oxidation reactions. Strecker degradation further diminishes the concentration of aldehydes, including furfural and 5-hydroxymethylfurfural, which undergo oxidation to form acids and alcohols (13). The sulfur compound dimethyl sulfide either dissipates rapidly or oxidizes into less volatile derivatives (5, 8). Oxidation of alcohol into aldehydes and acids or esterification into esters might result in their decline and degradation at high temperature and prolonged storage (7, 13). Pyridines and pyrroles are vulnerable to oxidation and Maillard reactions, which may result in their degradation into less volatile nitrogenous compounds (3, 13). The

presence of the ketone diacetyl diminished by oxidation and secondary reactions (13). The hydrolysis of esters under heat results in the reduction of fruity and floral fragrances, while furans degrade through oxidation and polymerization, causing the formation of less volatile compounds (5, 12). These losses are further accelerated by storage conditions such as temperature, oxygen exposure, and packaging which affect the quality and aroma of the coffee (10, 12, 54). The most substantial decreases were observed at 50°C, with the reduction of compounds associated with fruity, floral, roasty, and nutty fragrances which reduced the freshness and sensory attributes of the coffee.

By contrast, furanones were not detected in the control samples of MR-DP, MR-WP, and MR-HP. Furanones, such as hydroxymaltol, are relatively stable under thermal conditions due to their cyclic structure (6). Their degradable rates are lower than other furans, leading to a relatively unchanged concentration during storage. Terpenes, such as linalool and limonene, exhibit high thermal stability due to their structural resilience (5-6), with their concentration decreasing during long-term storage due to slow oxidation and volatilization. Thus, the changes in volatile compounds during accelerated storage at 30, 40, and 50°C over 21 days were driven by oxidation, Maillard reactions, Strecker degradation, and thermal degradation all impact coffee's chemical composition and sensory properties (3-4, 6, 38). Organic acids, phenolics, and pyrazines increase, while aldehydes, sulfides, alcohols, and ketones decrease due to oxidation and volatilization. These insights are critical for optimizing storage conditions to preserve the quality of coffee.

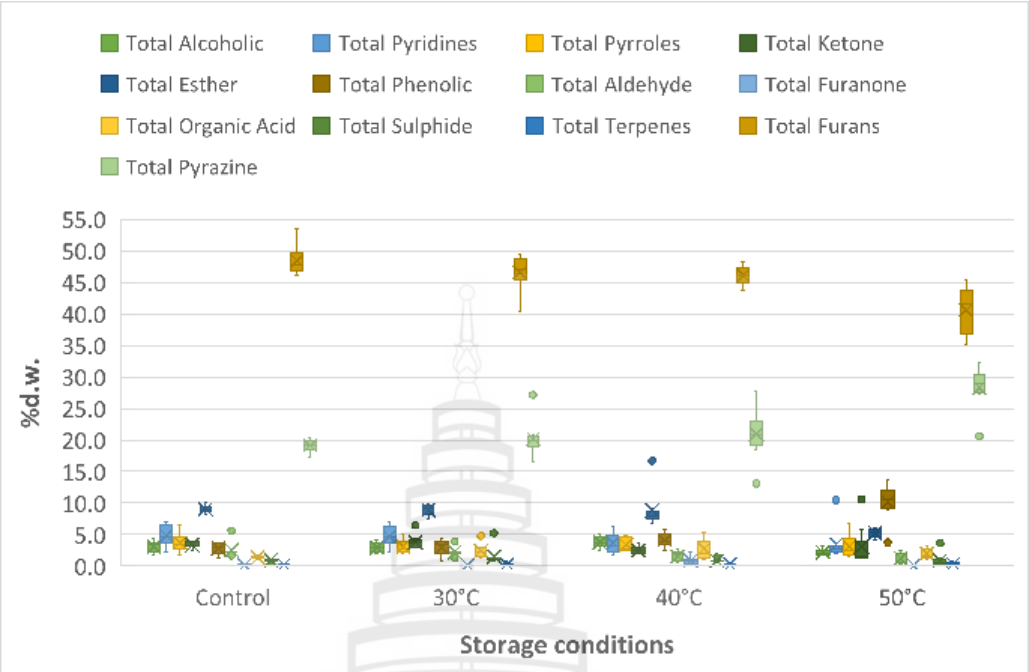


Figure 8.3 Changes in Roasted Coffee Bean Volatile Compound Groups after Undergoing Accelerated Storage for 21 Days

8.3.6 Principal Component Analysis (PCA)

Principal component analysis (PCA) was conducted to characterize the impact of different levels of roasting (light, light-medium and medium under dry, wet and honey processes) on several factors including moisture content (MC), color *L* a* b**, peroxide value (PV), shelf-life (SL), and total volatile compound groups (alcohols, aldehydes, esters, furans, furanones, ketones, organic acids, phenolics, pyrazines, pyridines, pyrroles, sulfides, and terpenes). The data matrix consisted of 9 rows, each representing the treatment group, and 19 columns corresponding to the analysis parameters. The analysis was conducted during accelerated storage at 30, 40, and 50°C, for 21 days. Based on the PCA data presented in Fig. 4(a), the control samples accounted for 78.74% of the explained variance. The variables LMR-DP, LMR-WP, and LMR-HP were clustered in positive PC1, accounting for 65.66% of the explained variance and related to variable totals of organic acids, phenolics, ketones, esters, pyrazines, aldehydes, alcohols, and peroxide values indicating complex compositions. This finding aligns with previous studies indicating that medium to high roasting levels as light-medium roast tend to produce a broader range of volatile compounds due to

Maillard reactions and caramelization processes (6). The control samples in PC2 corresponded to 16.08% with LR-DP, LR-WP, and LR-HP connected with positive PC2 in terms of total pyrroles, terpenes, MC, *L**, *a**, and *b**. This suggests that lighter roasting levels retain more favorable shelf-life characteristic, such as higher MC and certain volatile compound like terpenes, which are known to contribute to the desirable aromatic profile of coffee (55). MR-DP, MR-WP, and MR-HP were found in negative PC2 with total pyridine and furan compounds. This suggests that medium roasted retain some desirable volatile compounds but also accumulate higher levels of pyridine and furans, which can reduce aroma quality and increase bitterness (30).

On the other hand, after accelerated storage at 30, 40, and 50°C for 0, 7, 14, and 21 days the shelf-life was estimated by the increase in the peroxide value and collecting the volatile chemical groups indicated in Fig. 4(b-d). The total variances at 30, 40, and 50°C from roasted coffee beans were 68.05, 68.66, and 65.02 %, respectively. The reduced shelf-life at higher storage temperatures was reflected by the negative association of MR-DP, MR-WP, and MR-HP with longer shelf-life, especially in the presence of increased PV and the volatility of compounds like aldehydes and furans. These results are consistent with findings from other studies, which showed that higher storage temperatures accelerated the degradation of volatile compounds and affect coffee flavor quality (56). In Fig. 4(b) at 30°C, the first two PCs explained 50.21 and 17.84%. LR-WP and LR-HP, had a high shelf-life as these substances were related to MC, total ketones, organic acids, terpenes, and ester content whereas higher roasting levels of LMR-DP, LMR-WP, LMR-HP, MR-WP, and MR-DP were related in negative PC2 because these contained PV, *L**, *a**, and total furans, pyridines, furanones and alcohols. LR-DP showed a positive association with PC2 and total sulfides, pyrroles, and *b** values; however, MR-HP exhibited a negative correlation with total aldehydes, furans, and phenolics compounds. These results suggest that roasting at higher levels accelerates the degradation of volatile compounds like aldehydes and alcohols, which have been identified as contributors to less desirable coffee flavors (6).

At 40°C (Fig. 4(c)), PC1 and PC2 were retained as two principal components accounting for 38.69 and 29.97%, respectively. Positive PC2 in LR-DP, LR-WP, and LR-HP was associated with shelf-life as well as *L**, *a**, *b**, MC, and total terpenes, ketones, organic acids, and pyrazines. LMR-DP, MR-DP, MR-WP, and MR-HP had

negative PC2 values and were connected to total aldehydes, alcohols, furans, pyridines, phenolics, sulfides, and PV. LMR-WP was positive in PC1 with pyrroles and negative in LMR-HP. Fig. 4(d) shows the accelerated storage at 50°C, with PC1 and PC2 accounting for 43.63% and 21.39%. Shelf-life was linked with the variance of LMR-WP, LMR-DP, LR-WP, LR-DP, LMR-HP, MR-WP, and MR-DP, with reduction of PV, *L**, *a**, *b**, total furans, alcohols, pyrazines, furanone, terpenes, organic acids, esters, pyridines, ketones, aldehydes and pyrroles. LR-HP was linked to positive PC1, which showed total sulfides. MR-HP was associated with negative PC2 levels in total ketones. These results highlight the vulnerability of certain volatile compounds to degradation at elevated temperatures, validating finding form other studies that suggest accelerated deterioration of coffee aroma under harsher storage conditions (56).Thus, accelerated storage at the highest temperature of 50°C resulted in the largest reduction in shelf-life and decrease in numerous volatile compounds compared to 40 and 30°C. Different roasting levels varied depending on the storage conditions and the transformation of volatile chemicals. Light roast had the highest shelf-life among total ketones, organic acids, terpenes, esters, and pyrazines, while light-medium and medium interacted with aldehydes, alcohols, furans, furanones, pyridines, phenolics, and sulfide compounds.

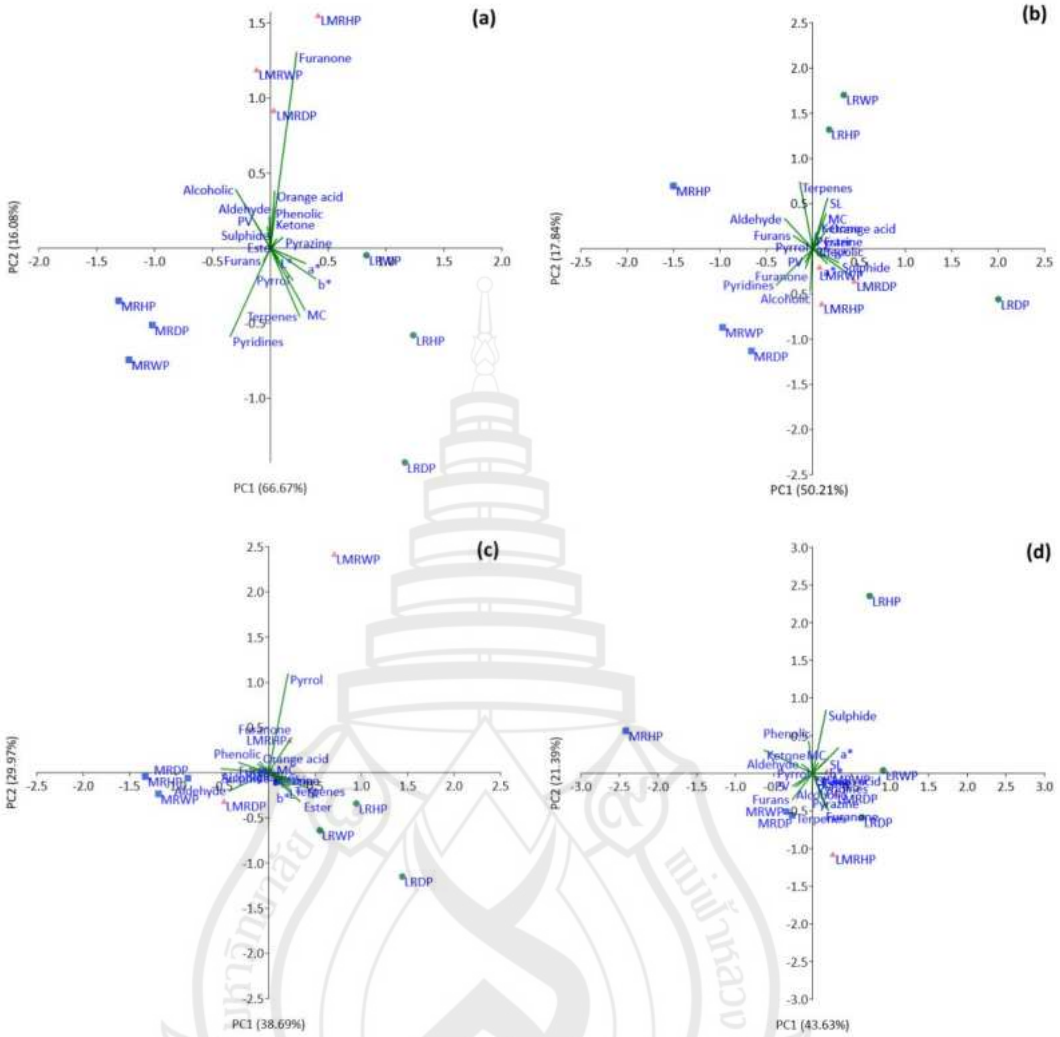


Figure 8.4 Biplots of Roasted Coffee Beans after Undergoing Accelerated Storage Conditions. (a) Control, (b) 30°C (c) 40°C, and (d) 50°C. LR = Light roasted; LMR = Light-medium roasted; MR = Medium roasted; DP = Natural/ Dry process; WP = Washed/ Wet process; HP = Honey process.

8.4 Conclusions

This study demonstrates that roasting level and accelerated storage conditions significantly affected (p<0.05) coffee quality, shelf-life, and volatile compound profiles. Lighter roasts retained more favorable volatile compounds such as terpenes and pyrazine and exhibited longer shelf-life. Light-medium roasts showed a broader range of volatile compounds, including organic acids, phenolics, and aldehydes, nevertheless had a shorter shelf-life compared to light roast, due to increased oxidation. Medium roasts showed greater oxidation and degradation of volatile compounds, including aldehydes, alcohol and furans. Higher storage temperature (40°C and 50°C) accelerated quality loss, with 50°C inducing the most substantial reduction in volatile compound due to thermal degradation. These findings emphasize the importance of optimizing roasting and storage conditions to preserve coffee quality. Future research should further investigate the effects of environmental factors and long-term storage on stability of specific volatile compounds.

8.5 Supplementary

Table 8.5 Identification of Volatile Compounds in Light, Light-medium and Medium Roasted of Arabica Coffee Beans

No.	RT	Volatile Compound name	Description	Group	LRDP (%)	LRW P (%)	LRHP (%)	LMRD P (%)	LMRW P (%)	LMRH P (%)	MRD P (%)	MRW P (%)	MRHP (%)
1	2.09	Propanol	Ethereal, pungent, earthy, alcoholic	Aldehyde	0.17 ±0.07^{b}	0.17 ±0.07^{b}	0.06 ±0.05^{c}	0.11 ±0.08^{b}	0.17 ±0.07^{b}	0.19 ±0.10^{ab}	0.26 ±0.12^{a}	0.29 ±0.12^{a}	0.23 ±0.10^{a}
2	2.33	2-Methylbutanal	Green, malty	Aldehyde	0.06 ±0.03^{b}	0.05 ±0.03^{b}	5.48 ±3.15^{a}	0.02 ±0.01^{b}	0.03 ±0.01^{b}	0.02 ±0.01^{b}	0.03 ±0.02^{b}	0.02 ±0.01^{b}	0.02 0.01^{b}
3	2.72	2,5-Dimethylfuran	Ethereal	Furan	4.18 ±0.51^{a}	3.79 ±0.56^{ab}	2.88 ±1.76^{c}	3.61 ±0.45^{ab}	3.13 ±0.38^{b}	4.48 ±0.55^{a}	3.47 ±0.10^{b}	3.46 ±0.06^{b}	3.53 ±0.52^{ab}
4	3.06	2,3-Butanedione	Buttery, creamy, caramel like	Ketone	0.10 ±0.06^{b}	0.03 ±0.07^{c}	1.23 ±0.51^{a}	0.12 ±0.06^{b}	0.11 ±0.06^{b}	0.29 ±0.07^{b}	0.11 ±0.06^{b}	0.15 ±0.09^{b}	0.19 ±0.08^{b}
5	3.15	2,3-Pentanedione	Buttery, oily, caramel-like	Ketone	1.29 ±0.54^{b}	1.28 ±0.53^{b}	1.32 ±0.60^{b}	1.29 ±0.35^{b}	1.32 ±0.31^{b}	1.58 ±0.38^{a}	1.11 ±0.40^{b}	1.23 ±0.37^{b}	1.28 ±0.41^{b}
6	3.53	Propanoic acid, anhydride	Pungent, acidic, cheesy, vinegar	Organic Acid	0.94 ±0.32^{b}	1.18 ±0.37^{a}	0.97 ±0.27^{b}	0.94 ±0.27^{b}	1.05 ±0.27^{a}	0.92 ±0.21^{b}	0.85 ±0.20^{bc}	0.80 ±0.13^{bc}	0.78 0.16^{c}
7	3.73	2-Methylthiol propanol	Soy sauce	Aldehyde	0.02 ±0.04^{b}	0.13 ±0.06^{a}	0.08 ±003^{b}	0.08 ±0.04^{b}	0.13 ±0.06^{a}	0.09 ±0.03^{b}	0.11 ±0.06^{a}	0.12 ±0.04^{a}	0.15 ±0.05^{a}
8	3.96	2-Vinylfuran	Ethereal, rum, cocoa note	Furan	0.04 ±0.02^{b}	0.05 ±0.03^{b}	0.18 ±0.09^{a}	0.05 ±0.01^{b}	0.05 ±0.03^{b}	0.04 ±0.02^{b}	0.07 ±0.04^{b}	0.06 ±0.02^{b}	0.05 ±0.03^{b}
9	4.11	Pyrazine	Cooked spinach, rancid peanuts, strong	Pyrazine	0.32 ±0.13^{b}	0.34 ±0.05^{b}	0.19 ±0.09^{d}	0.38 ±0.11^{b}	0.46 ±0.10^{a}	0.35 ±0.09^{b}	0.28 ±0.17^{c}	0.41 ±0.13^{a}	0.30 ±0.09^{b}
10	4.27	1H-Pyrrole	Sweet, warm, nutty	Pyrroles	0.05 ±0.71^{d}	0.03 ±0.06^{d}	0.79 ±0.45^{b}	0.03 ±0.03^{d}	0.14 ±0.07^{cd}	2.76 ±1.56^{a}	0.03 ±0.13^{d}	0.28 ±0.14^{c}	0.05 ±0.04^{d}
11	4.33	Pyridine	Sour, Fishy	Pyridines	1.79 ±0.72^{d}	1.66 ±0.27^{d}	1.09 ±0.11^{e}	2.16 ±0.34^{c}	3.17 ±1.02^{b}	2.01 ±1.29^{c}	3.68 ±1.07^{b}	4.62 ±1.23^{a}	4.13 ±1.21^{a}

Table 8.5 (continued)

No.	RT	Volatile Compound name	Description	Group	LRDP (%)	LRW P (%)	LRHP (%)	LMRD P (%)	LMRW P (%)	LMRH P (%)	MRD P (%)	MRW P (%)	MRHP (%)
12	4.73	Propanoic acid	Pungent, acidic, cheesy, vinegar	Organic Acid	0.29 ±0.15[a]	0.39 ±0.07[a]	0.17 ±0.11[b]	0.31 ±0.03[a]	0.32 ±0.03[a]	0.33 ±0.03[a]	0.26 ±0.06[a]	0.16 ±0.03[b]	0.23 ±0.04[b]
13	4.87	2,3-Pendadione	Oily, buttery	Ketone	ND	ND	ND	ND	0.02 ±0.01[b]	0.02 ±0.02[b]	0.13 ±0.0[4a]	0.18 ±0.03[a]	0.10 0.06[a]
14	5.06	Dimethyl disulfide[ns]	Onion, cabbage-like, sulfur	Sulfur	ND	0.03 ±0.02	0.09 ±0.04	0.02 ±0.00	0.03 ±0.01	0.02 ±0.02	0.04 ±0.01	0.04 ±0.01	0.04 ±0.01
15	5.42	Hexanal	Green, grassy, fruity	Aldehyde	0.18 ±0.33[c]	0.18 ±0.09[c]	0.45 ±0.18[a]	0.20 ±0.09[b]	0.22 ±0.04[b]	0.25 ±0.08[b]	0.17 ±0.03[c]	0.21 ±0.07[b]	0.20 ±0.06[b]
16	5.57	3-Methylthiophene	Ash	Sulfur	0.72 ±2.47[c]	0.93 ±0.28[a]	0.39 ±0.26[d]	0.84 ±0.36[b]	0.97 ±0.27[a]	0.88 ±0.28[b]	0.82 ±0.21[b]	0.84 ±0.23[b]	0.75 ±0.20[c]
17	5.83	3-Pyridinamine	White to yellow-brown crystals, unpleasant odor	Pyridines	ND	ND	ND	ND	0.02 ±0.01[a]	0.02 ±0.01[a]	0.02 ±0.01[a]	0.02 ±0.01[a]	0.03 ±0.01[a]
18	5.93	Pyrazine, methyl-	Nutty, cocoa, roasted	Pyrazine	5.53 ±1.36[a]	5.98 ±1.39[a]	5.74 ±1.61[a]	4.97 ±1.38[ab]	5.57 ±1.17[a]	5.38 ±1.28[a]	4.64 ±1.05[b]	4.62 ±1.01[b]	4.57 ±1.11[b]
19	6.18	Furfural	Almond-like, woody, bready	Furan	11.97 ±2.99[a]	12.08 ±2.60[a]	11.65 ±2.95[a]	9.26 ±1.58[b]	8.97 ±1.01[b]	9.54 ±1.97[b]	7.17 ±1.41[c]	6.24 ±1.27[d]	5.92 ±1.13[d]
20	6.62	5-methyl-furfural	Sweet, caramellike, coffee-like	Furan	0.20 ±0.15[a]	0.08 ±0.15[b]	0.22 ±0.12[a]	0.12 ±0.12[b]	0.28 ±0.09[a]	0.25 ±0.07[a]	0.15 ±0.08[b]	0.20 ±0.04[a]	0.27 ±0.01[a]
21	6.80	Furfuryl alcohol	Sweet, caramellike, brown	Furan	16.33 ±1.29[a]	16.06 ±0.32[a]	14.32 ±0.85[c]	15.22 ±0.73[b]	15.37 ±0.40[b]	16.35 ±0.78[a]	15.89 ±0.45[ab]	16.37 ±0.42[a]	16.04 ±0.84[a]
22	7.12	2-Methyl-pyrazine	Nutty	Pyrazine	1.52 ±0.73[a]	0.97 ±0.05[c]	1.38 ±0.27[a b]	1.35 ±0.23[a]	1.56 ±0.32[a]	1.47 ±0.18[ab]	1.44 ±0.16[ab]	1.51 ±0.35[a]	1.34 ±0.11[ab]

Table 8.5 (continued)

No.	RT	Volatile Compound name	Description	Group	LRDP (%)	LRW P (%)	LRHP (%)	LMRD P (%)	LMRW P (%)	LMRH P (%)	MRD P (%)	MRW P (%)	MRHP (%)
23	7.49	2,3-Hexandione[ns]	Buttery, cheesy, sweet, creamy	Ketone	0.07 ±0.11	0.10 ±0.10	0.06 ±0.11	0.05 ±0.08	0.04 ±0.12	0.03 ±0.11	0.03 ±0.07	0.02 ±0.09	0.02 ±0.08
24	7.80	Butyric acid[ns]	Acidic, sour, cheesy	Organic Acid	0.08 ±0.32	0.13 ±0.21	0.15 ±0.09	0.08 ±0.04	0.06 ±0.27	0.08 ±0.29	0.09 ±0.17	0.08 ±0.19	0.09 ±0.18
25	8.12	Furfuryl formate	Ethereal	Furan	0.58 ±2.03^{d}	0.77 ±2.64^{c}	0.63 ±0.15^{d}	0.77 ±0.14^{c}	0.95 ±2.54^{b}	0.89 ±2.28^{b}	1.07 ±2.17^{a}	1.18 ±2.13^{a}	1.14 ±2.16^{a}
26	8.26	Ethyl acetate	Fruity, grape	Ester	6.68 ±2.73^{b}	7.50 ±2.88^{a}	6.26 ±1.00^{b}	6.76 ±0.73^{b}	6.82 ±2.60^{b}	5.89 ±2.34^{bc}	6.15 ±2.41^{b}	6.00 ±2.46^{b}	5.46 ±2.19^{c}
27	8.36	Pyrazine, ethyl-[ns]	Nutty, cocoa, roasted	Pyrazine	2.55 ±1.11	2.74 ±1.12	2.52 ±0.43	2.36 ±0.37	2.60 ±1.04	2.47 ±1.07	2.43 ±1.19	2.37 ±1.12	2.59 ±1.31
28	8.47	2,3-dimethyl-Pyrazine[ns]	Sweet, Coffee	Pyrazine	0.81 ±0.44	0.81 ±0.42	0.79 ±0.17	0.68 ±0.12	0.77 ±0.40	0.79 ±0.40	0.68 ±0.44	0.67 ±0.38	0.81 ±0.57
29	8.63	2-Methyl-pyrazine	Nutty	Pyrazine	0.13 ±0.06^{a}	0.03 ±0.10^{b}	0.05 ±0.01^{b}	0.04 ±0.01^{b}	0.04 ±0.10^{b}	0.06 ±0.07^{b}	0.05 ±0.07^{b}	0.05 ±0.08^{b}	0.06 ±0.42^{b}
30	8.77	Ethyl-3-methylbutyrate	Fruity	Ester	0.33 ±0.14^{a}	0.34 ±0.13^{a}	0.25 ±0.06^{b}	0.28 ±0.04^{b}	0.33 ±0.14^{a}	0.28 ±0.11^{ab}	0.29 ±0.17^{ab}	0.32 ±0.17^{a}	0.25 ±0.13^{b}
31	9.11	3-Hydroxy-2-butanone [ns]	Sweet, buttery, creamy	Ketone	0.07 ±0.04	0.01 ±0.01	0.09 ±0.05	0.02 ±0.01	0.08 ±0.04	0.02 ±0.01	0.08 ±0.05	0.08 ±0.05	0.09 ±0.05
32	9.69	Acetol	Nutty, roasted, grassy	Ketone	0.13 ±0.04^{a}	0.08 ±0.04^{b}	0.10 ±0.02^{a}	0.17 ±0.06^{a}	0.06 ±0.02^{b}	0.07 0.02^{b}	0.15 ±0.07^{a}	0.07 ±0.07^{b}	0.05 ±0.11^{b}
33	9.79	2-Furancarboxaldehyde, 5-methyl-	Sweet, caramel, bready, brown, coffee	Furan	11.25 ±1.32^{c}	13.08 ±1.03^{a}	11.69 ±0.96^{bc}	13.20 ±0.93^{a}	12.25 ±0.63^{b}	11.37 ±0.61^{c}	12.18 ±0.57^{b}	10.81 ±0.04^{c}	10.97 ±0.67^{c}
34	10.19	3-Methylbutanal [ns]	Malty, cocoa	Aldehyde	0.07 ±0.00	0.10 ±0.00	0.07 ±0.02	0.09 ±0.03	0.05 ±0.03	0.03 ±0.06	0.09 ±0.03	0.06 ±0.02	0.06 ±0.06

Table 8.5 (continued)

No.	RT	Volatile Compound name	Description	Group	LRDP (%)	LRW P (%)	LRHP (%)	LMRD P (%)	LMRW P (%)	LMRH P (%)	MRD P (%)	MRW P (%)	MRHP (%)
35	10.73	2-Furanmethanol, acetate	Onion, garlic, sulfurous, pungent, horseradish	Furan	5.99 ±2.02^{b}	2.82 ±1.19^{d}	3.73 ±0.56^{d}	3.47 ±0.31^{d}	3.71 ±0.65^{d}	4.91 ±0.28^{c}	5.51 ±0.49^{b}	5.68 ±0.80^{b}	7.06 ±3.92^{a}
36	10.81	2,6-Dimethyl pyrazine	Nutty, roasted, cocoa, coffee-like	Pyrazine	1.81 ±0.57^{b}	1.88 ±0.25^{b}	1.66 ±2.04^{bc}	2.07 ±1.59^{a}	1.72 ±0.28^{bc}	1.93 ±0.14^{b}	2.06 ±0.88^{a}	1.86 ±0.92^{b}	1.25 ±3.37^{c}
37	10.97	2-ethyl-3-methyl-Pyrazine	Nutty, peanut, butter	Pyrazine	1.78 ±0.49^{b}	1.86 ±0.64^{b}	1.70 ±0.34^{b}	2.08 ±0.41^{a}	1.23 ±0.24^{c}	1.46 ±0.50^{c}	1.56 ±0.13^{c}	1.42 ±0.20^{c}	1.34 ±0.21^{c}
38	11.16	1-Methyl pyrrole	Woody, herbal	Pyrroles	0.43 ±0.15^{c}	0.60 ±0.33^{b}	0.66 ±0.11^{b}	0.83 ±0.15^{ab}	0.97 ±0.45^{a}	0.91 ±0.45^{a}	0.59 ±0.18^{c}	0.98 ±0.03^{a}	0.68 ±0.39^{b}
39	11.34	Pyrazine, 2-ethenyl-6-methyl- ^{ns}	Cooked spinach, rancid peanuts, strong	Pyrazine	0.21 ±0.47	0.24 ±0.54	0.17 ±0.03	0.22 ±0.01	0.24 ±0.53	0.16 ±0.49	0.24 ±0.29	0.20 ±0.05	0.20 ±0.47
40	11.46	2-Acetylpyridine	Corn, nutty	Pyridines	1.20 ±0.60^{a}	1.24 ±0.68^{a}	1.01 ±0.58^{a}	1.17 ±0.68^{a}	1.20 ±0.67^{a}	0.97 ±0.59^{b}	1.11 ±0.69^{a}	0.90 ±0.14^{b}	0.92 ±0.43^{b}
41	11.68	1-Hydroxy-2-butanone	Tobacco, oak, moss, leather	Ketone	0.16 ±0.08b	0.35 ±0.08a	0.33 ±0.07a	0.40 ±0.08a	0.41 ±0.08a	0.22 ±0.07b	0.35 ±0.07a	0.20 ±0.06b	0.21 ±0.16b
42	12.05	1-Hexanol	Fruity and alcoholic	Alcoholic	0.31 ±0.08^{b}	0.44 ±0.15^{b}	0.35 ±0.06^{b}	0.55 ±0.05^{a}	0.62 ±0.22^{a}	0.37 ±0.12^{b}	0.69 ±0.07^{a}	0.68 ±0.05^{a}	0.56 ±0.27^{a}
43	12.28	2-Heptanone ^{ns}	Fresh, lemon grass, herbal	Alcoholic	0.20 ±0.42	0.20 ±0.03	0.19 ±0.04	0.30 ±0.08	0.24 ±0.05	0.22 ±0.05	0.20 ±0.02	0.25 ±0.06	0.19 ±0.09
44	12.74	Dihydro-2-methyl-3-furanone	Sweet, roasted	Ketone	0.64 ±0.31^{b}	1.06 ±0.13^{ab}	0.78 ±0.36^{b}	1.60 ±0.60^{a}	1.52 ±0.38^{a}	0.83 ±0.44^{b}	0.68 ±0.27^{b}	1.10 ±0.49^{ab}	0.76 0.33^{b}
45	13.02	Pyrazine, isopropenyl-	Caramel like nutty roasted aroma	Pyrazine	0.50 ±0.36^{b}	0.31 ±0.61^{c}	0.44 ±0.03^{c}	0.44 ±0.09^{c}	0.37 ±0.51^{c}	0.51 ±0.37^{b}	0.41 ±0.09^{c}	0.43 ±0.09^{c}	0.84 ±0.30^{a}
46	13.25	2,6-diethyl-Pyrazine	Nutty, roasted	Pyrazine	2.21 ±0.83^{a}	2.22 ±0.60^{a}	1.52 ±0.23^{b}	2.05 ±0.11^{a}	2.06 ±0.52^{a}	1.34 ±0.42^{b}	1.65 ±0.06^{b}	1.48 ±0.26^{b}	1.28 ±0.14^{b}

Table 8.5 (continued)

No.	RT	Volatile Compound name	Description	Group	LRDP (%)	LRW P (%)	LRHP (%)	LMRD P (%)	LMRW P (%)	LMRH P (%)	MRD P (%)	MRW P (%)	MRHP (%)
47	13.42	2,3-diethyl-5-methylpyrazine	Toasted, nutty, cocoa	Pyrazine	0.81 ±0.28^{c}	1.20 ±0.32^{a}	0.93 ±0.37^{b}	1.17 ±0.21^{a}	0.97 ±0.18^{b}	0.86 ±0.16^{c}	0.79 ±0.10^{c}	0.88 ±0.09^{c}	0.56 ±0.36^{d}
48	13.66	2,5-Dimethylpyrzaine	Nutty, roasted	Pyrazine	0.19 ±0.18^{c}	0.40 ±0.22^{b}	0.23 ±0.13^{c}	0.36 ±0.19^{b}	0.38 ±0.23^{b}	0.30 ±0.18^{b}	0.51 ±0.28^{a}	0.67 ±0.38^{a}	0.50 ±0.28^{a}
49	13.86	Linalool	Citrus, orange, lemon	Terpenes	0.36 ±0.13^{a}	0.20 ±0.14^{a}	0.34 ±0.11^{a}	0.08 ±0.04^{c}	0.09 ±0.06^{c}	0.13 ±0.09^{b}	0.02 ±0.03^{c}	0.05 ±0.08^{c}	0.04 ±0.26^{c}
50	13.94	1,2-Propanediol	Sweet	Alcoholic	0.11 ±0.68^{c}	0.28 ±0.20^{a}	0.29 ±0.26^{a}	0.11 ±0.09^{c}	0.16 ±0.11^{b}	0.20 ±0.17^{b}	0.20 ±0.10^{b}	0.33 ±0.02^{a}	0.14 ±0.09^{c}
51	14.08	2-accetylpyrrole	Musty, nutty, coumarin-like	Pyrroles	0.26 ±0.58^{c}	0.25 ±0.81^{c}	1.25 ±1.01^{a}	0.39 ±0.15^{c}	0.27 ±0.78^{c}	0.37 ±1.36^{c}	0.52 ±0.06^{b}	0.64 ±0.25^{b}	0.57 ±0.26^{b}
52	14.24	Maltol	Caramel	Alcoholic	1.01 ±0.23^{b}	1.70 ±0.30^{b}	0.78 ±0.50^{c}	2.11 ±0.35^{a}	2.06 ±0.61^{a}	2.24 ±0.23^{a}	2.46 ±0.72^{a}	2.82 ±0.23^{a}	2.62 ±1.19^{a}
53	14.43	2-ethyl pyrazine ^{ns}	Nutty, roasted	Pyrazine	1.21 ±0.55	1.70 ±0.11	1.50 ±0.61	1.77 ±0.24	1.61 ±0.20	1.52 ±0.31	1.49 ±0.02	1.52 ±0.02	1.48 ±0.97
54	14.90	Acetoxy acetone ^{ns}	Fruity, buttery dairy	Ketone	0.05 ±0.04	0.09 ±0.20	0.05 ±0.26	0.12 ±0.01	0.07 ±0.20	0.07 ±0.31	0.07 ±0.02	0.10 ±0.02	0.07 ±0.01
55	15.07	Propyl acetate	Sweet and fruity	Ester	ND	0.35 ±0.35^{c}	0.38 ±0.26^{c}	0.39 ±0.04^{c}	0.64 ±0.28^{a}	0.80 ±0.17^{a}	0.59 ±0.43^{b}	0.02 ±0.34^{d}	0.63 ±0.36^{b}
56	15.16	Methyl salicylate	Wintergreen, mint-like	Ester	1.03 ±0.45^{a}	0.79 ±0.56^{b}	1.19 ±0.57^{a}	0.62 ±0.06^{b}	0.24 ±0.24^{c}	0.04 ±0.01^{c}	0.08 ±0.04^{c}	0.59 ±0.32^{b}	0.07 ±0.27^{c}
57	15.68	3,5-diethyl-2-methyl-Pyrazine	Earthy, roasted	Pyrazine	0.24 ±0.06^{c}	0.24 ±0.07^{c}	0.34 ±0.06^{b}	0.35 ±0.05^{b}	0.30 ±0.10^{b}	0.29 ±0.08^{b}	0.49 ±0.04^{b}	0.73 ±0.08^{a}	0.33 ±0.15^{b}
58	15.92	2-Methyllfuran	Pungent, fruity	Furan	0.05 ±0.03^{c}	0.16 ±0.09^{ab}	0.12 ±0.07^{b}	0.11 ±0.07^{b}	0.12 ±0.07^{b}	0.18 ±0.10^{a}	0.19 ±0.11^{a}	0.20 ±0.12^{a}	0.15 ±0.09^{a}
59	16.13	2-Acetyfuran ^{ns}	Sweet, balsam, almond, cocoa	Furan	0.04 ±0.14	0.04 ±0.04	0.10 ±0.02	0.09 ±0.02	0.06 ±0.03	0.05 ±0.02	0.07 ±0.05	0.08 ±0.05	0.06 ±0.09

Table 8.5 (continued)

No.	RT	Volatile Compound name	Description	Group	LRDP (%)	LRW P (%)	LRHP (%)	LMRD P (%)	LMRW P (%)	LMRH P (%)	MRD P (%)	MRW P (%)	MRHP (%)
60	16.29	2-Formyl pyrrole	Musty, beef, coffee-like	Pyrroles	0.60 ±0.29^{c}	0.57 ±0.10^{c}	0.63 ±0.03^{c}	0.87 ±0.27^{b}	0.86 ±0.18^{b}	0.83 ±0.02^{b}	1.07 ±0.43^{a}	0.93 ±0.42^{a}	0.92 ±0.47^{a}
61	16.44	4-Methyl-5-ethyl-3-hydroxy-2(5H)-furanone	Buttery, seasoning-like	Furanone	ND	ND	0.26 ±0.44^{a}	0.16 ±0.09^{a}	0.18 ±0.38^{a}	0.08 ±0.47^{a}	ND	ND	ND
62	16.74	Ethyl propanoate	Sweet, fruity, rum, juicy	Ester	0.37 ±0.15^{b}	0.27 ±0.14^{bc}	0.53 ±0.12^{b}	0.38 ±0.10^{b}	0.38 ±0.09^{b}	0.71 ±0.26^{a}	0.40 ±0.12^{b}	0.23 ±0.11^{c}	0.53 ±0.07^{b}
63	16.91	2-Methoxypyridine	Green, fermented, tea	Pyridines	0.07 ±0.13^{c}	0.17 ±0.01^{a}	0.11 ±0.05^{b}	0.15 ±0.07^{ab}	0.16 ±0.03^{a}	0.13 ±0.03^{b}	0.17 ±0.08^{a}	0.23 ±0.01^{a}	0.19 ±0.05^{a}
64	17.33	Dimethyl sulfide	Sulfur, cabbage	Sulfur	0.09 ±0.07^{c}	0.12 ±0.01^{b}	0.13 ±0.02^{b}	0.17 ±0.01^{a}	0.17 ±0.04^{a}	0.12 ±0.03^{b}	0.13 ±0.05^{b}	0.12 ±0.02^{b}	0.16 ±0.01^{a}
65	17.66	2-Ethyl-6-methylpyrazine ^{ns}	Roasted, hazelnut-like	Pyrazine	0.09 ±0.07	0.13 ±0.01	0.22 ±0.08	0.24 ±0.05	0.15 ±0.08	0.06 ±0.06	0.07 ±0.04	0.17 ±0.11	0.10 ±0.12
66	18.11	2,3-Butanediol ^{ns}	Fruity, caramel, buttery	Alcoholic	0.04 ±0.49	0.06 ±0.01	0.06 ±0.13	0.05 ±0.01	0.06 ±0.00	0.05 ±0.03	0.08 ±0.02	0.08 ±0.01	0.10 ±0.05
67	18.38	Methyl acetate ^{ns}	Fruity, winey	Ester	0.05 ±0.02	0.06 ±0.11	0.07 ±0.13	0.08 ±0.01	0.08 ±0.09	0.11 ±0.18	0.14 ±0.05	0.20 ±0.02	0.15 ±0.22
65	17.66	2-Ethyl-6-methylpyrazine ^{ns}	Roasted, hazelnut-like	Pyrazine	0.09 ±0.07	0.13 ±0.01	0.22 ±0.08	0.24 ±0.05	0.15 ±0.08	0.06 ±0.06	0.07 ±0.04	0.17 ±0.11	0.10 ±0.12
69	18.65	.alpha.Terpeniol ^{ns}	Citrus, woody, lemon	Terpenes	0.10 ±0.05	0.07 ±0.02	0.03 ±0.03	0.06 ±0.14	0.08 ±0.03	0.27 ±0.12	0.09 ±0.04	0.10 ±0.03	0.09 ±0.09
70	18.87	2-((Methylthio)methyl) furan	Smoky, roast, onion, garlic, sulfurous, horseradish, vegetable, pungent	Furan	0.11 ±0.04^{d}	0.26 ±0.07^{c}	0.12 ±0.07^{d}	0.26 ±0.07^{c}	0.35 ±0.12^{c}	0.40 ±0.03^{c}	0.62 ±0.09^{b}	0.95 ±0.16^{a}	0.74 ±0.27^{b}
71	19.04	Phenol, 4-ethyl-2-methoxy-	Smoky, spicy	Phenolic	0.10 ±0.32^{b}	0.19 ±0.06^{b}	0.08 ±0.06^{c}	0.11 ±0.16^{b}	0.17 ±0.05^{b}	0.13 ±0.05^{b}	1.04 ±0.46^{a}	1.03 ±0.47^{a}	1.03 ±0.53^{a}

Table 8.5 (continued)

No.	RT	Volatile Compound name	Description	Group	LRDP (%)	LRW P (%)	LRHP (%)	LMRD P (%)	LMRW P (%)	LMRH P (%)	MRD P (%)	MRW P (%)	MRHP (%)
72	19.38	5-furfural	almond, woody, sweet	Furan	0.06 ±0.03[b]	0.20 ±0.09[a]	0.18 ±0.10[a]	0.26 ±0.15[a]	0.29 ±0.16[a]	0.26 ±0.04[a]	0.38 ±0.15[a]	0.20 ±0.08[a]	0.28 ±0.06[a]
73	19.44	γ-Butyrolactone	Creamy, oily, fatty, caramel	Ketone	0.05 ±0.88[c]	0.10 ±0.01[bc]	0.08 ±0.04[c]	0.16 ±0.03[b]	0.19 ±0.06[b]	0.17 ±0.09[b]	0.43 ±0.11[a]	0.21 ±0.10[b]	0.33 ±0.12[a]
74	19.74	5-methyl-Furfural	Sweet, caramellike, coffee-like	Furan	0.05 ±0.41[c]	0.17 ±0.7[3b]	0.18 ±0.02[b]	0.23 ±0.05[b]	0.12 ±0.73[b]	0.10 ±1.01[bc]	0.11 ±0.06[bc]	0.39 ±0.67[a]	0.04 ±0.07[c]
75	19.94	4-vinyl guaiacol	Clove, smoky, bacon, phenolic, spicy	Phenolic	1.57 ±0.65[c]	2.23 ±0.51[b]	2.00 ±0.32[b]	2.83 ±0.33[a]	2.49 ±0.41[ab]	2.07 ±0.72[b]	2.88 ±0.98[a]	2.90 ±1.68[a]	2.32 ±1.85[a]
76	20.45	Furfuryl propionate	Sweet, fruity, green	Furan	2.32 ±1.25[a]	0.16 ±0.09[c]	0.18 ±1.02[c]	0.17 ±0.18[c]	0.16 ±0.05[c]	0.18 ±0.04[c]	0.16 ±0.62[c]	1.04 ±0.38[b]	0.17 ±0.84[c]
78	21.37	3-Methyl-butanoic acid[ns]	Cheesy, dairy, creamy, fermented	Organic Acid	0.04 ±0.04	0.05 ±0.01	0.06 ±0.04	0.08 ±0.03	0.09 ±0.03	0.10 ±0.04	0.07 ±0.08	0.12 ±0.02	0.05 ±0.05
79	22.41	3-Hydroxy-4,5-dimethyl-2(5H) furanone	Fenugreek, curry	Furanone	0.06 ±0.03[b]	0.11 ±0.02[a]	0.15 ±0.03[a]	0.18 ±0.03[a]	0.23 ±0.10[a]	0.21 ±0.06[a]	ND	ND	ND
80	24.39	Pyrrole	Nutty, hay-like, herbaceous	Pyrroles	1.22 ±0.70a	0.20 ±0.11b	0.16 ±0.08 b	0.13 ±0.07b	0.15 ±0.08b	0.02 ±0.03c	0.03 ±0.02c	0.06 ±0.03c	ND
81	25.11	Guaiacol	Phenolic, burnt, smoky	Phenolic	ND	ND	ND	ND	ND	0.17 ±0.15[a]	0.16 ±0.09[a]	0.08 ±0.05[a]	0.03 ±0.47[a]
82	25.24	Phenol	Phenolic, plastic, rubber, smoky	Phenolic	ND	ND	ND	ND	ND	ND	ND	0.27 ±0.16[a]	0.10 ±0.05[a]

Note Data are presented as mean ± SD (n=3). Means with different in the same row indicate significant difference roasting level $p < 0.05$. LR; light roast, LMR; light-medium roast, MR; medium roast, DP; natural/ dry process, WP; washed/ wet process, HP; honey process, RT; retention time, and d.w; dry weight, ND; non-detected, and ns; non-significant.

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CHAPTER 9

CONCLUSIONS

This research presents an integrated and innovative approach to enhancing specialty coffee quality through advancements in drying, storage, packaging, roasting, and analytical techniques that showed in overall conclusion as Figure 9.1. The application of controlled environment drying (CED) was shown to significantly improve the physicochemical and sensory attributes of coffee, particularly in dry and honey-processed beans. Accelerated shelf-life testing, combined with advanced lipid oxidation markers, provided a clearer understanding of how temperature, packaging, and processing influence green and roasted coffee stability. The use of ATR-FTIR spectroscopy as a non-destructive tool for real-time monitoring of lipid oxidation represents a novel method for predicting shelf-life and quality deterioration. Furthermore, the study established the impact of roasting profiles on shelf-life and volatile compound retention, offering practical insights for optimizing post-harvest and roasting practices. Concurrently, these innovations contribute to a holistic strategy for improving flavor, consistency, and storage stability in specialty coffee supporting producers, roasters, and quality control systems in Thailand and beyond.

In first experiment, studying about how post-harvest processing and drying methods impact the physicochemical, biochemical, and sugar compositions of green (GCB) and roasted coffee beans (RCB). Controlled environment drying (CED) improved GCB quality, enhancing physicochemical and biochemical properties and sugar content more effectively than sun drying (SD) and fast drying (FD). RCB quality depended on the initial GCB condition; roasting reduced moisture content, water activity, color, density, and compounds such as caffeine, trigonelline, chlorogenic acid, caffeic acid, sucrose, and fructose, while developing aroma and flavor. Among post-harvest methods, dry processing (DP) preserved the highest levels of caffeine, trigonelline, chlorogenic and caffeic acids, all associated with cup quality. Honey processing (HP) resulted in higher sucrose and fructose, which enhanced flavor upon

roasting. Washed processing (WP) removed some beneficial compounds during processing.

This second experiment studied the effects of accelerated storage and various packaging types on the physical and chemical properties of GCB. Lipid oxidation levels varied with temperature and storage duration, with higher temperatures and prolonged storage accelerating oxidation and quality degradation. Key indicators such as peroxide value (PV), acid value (AV), ρ-anisidine value (PAV), total oxidation (TOTOX), thiobarbituric acid reactive substances (TBARS), free fatty acids (FFA), and saturated fatty acids (SFA) increased over time, while moisture content, a_w, and unsaturated fatty acids (USFA) decreased. Principal component analysis and hierarchical cluster analysis highlighted the impact of storage conditions and packaging on GCB quality, with hermetic (GrainPro®) packaging proving most effective in preserving GCB quality and delaying oxidation-related changes.

In this third experiment, the shelf-life of GCB stored in GrainPro® bags was assessed through lipid oxidation indicators, specifically peroxide and TBARS levels. Results showed that at 30 °C, honey-processed beans had a longer shelf-life than naturally processed beans, with cooler storage temperatures extending overall bean longevity compared to storage at 40 °C and 50 °C. ATR-FTIR spectroscopy and lipid oxidation metrics proved effective for monitoring GCB quality. Partial least squares models yielded accurate predictions for TBARS levels, and variable importance projection (VIP) identified key ATR-FTIR wavenumber ranges (3000–2825, 2154–2150, 1780–1712, 1487–2483, 1186–1126, 1107–1097, and 1012–949 cm^{-1}) associated with lipid oxidation. This correlation between oxidation and ATR-FTIR analysis underscores the influence of processing methods on GCB shelf-life, highlighting ATR-FTIR's potential as a non-destructive tool for coffee quality monitoring.

In the fourth experiment, roasting level and accelerated storage significantly influenced (p<0.05) moisture content, color, PV, shelf-life, and volatile compound profiles. PV was used as an oxidation indicator, with medium roast (MR) exhibiting the shortest shelf-life. Among processing methods, WP demonstrated better long-term preservation compared to HP and DP. At 30°C storage, light roast (LR) had the longest shelf-life (10.03±0.11 to 11.68±0.34 days), followed by light-medium roast (LMR) (7.28±0.25 to 8.82±0.64 days) and MR (6.33±0.33 to 7.68±0.61 days), with further

reductions observed at higher temperatures (40°C and 50°C). The predominant volatile compound groups were furans (35.20±5.85 to 53.55±2.75% d.w.), pyrazines (13.16±1.14 to 32.31±0.76% d.w.), and esters (4.21±0.20 to 16.70±0.93% d.w.), all of which decreased after accelerated storage. As expected, storage at 50°C caused the greatest degradation due to thermal effects. However, organic acids, phenolics, and pyrazines increased as a result of thermal oxidation. These findings provide valuable insights for coffee roasters and buyers in selecting optimal storage conditions to extend shelf-life while preserving quality.

In the fifth experiment, this study demonstrates that drying techniques and processing methods significantly influence the chemical and sensory profiles of roasted coffee beans, affecting key parameters such as pH, TA, and TSS. CED was the most effective in enhancing acidity and flavor complexity, particularly in DP and HP coffees, resulting in the highest cupping scores. In contrast, FD increased pH and reduced acidity, while DP maintained higher TSS levels, indicating a sweeter profile. CED had high concentrations of esters and heterocyclic nitrogen, while FD had more acetate, and SD included a variety of acids, alcohols, aldehydes, furans, ketones, and pyrazines. Each processing method showed distinct volatile compound profiles linked to specific sensory attributes like acidity, body, aftertaste, and aroma. These findings highlight the importance of refining drying and processing techniques to optimize coffee quality. Thus, these findings highlight the importance of refining drying, processing, storage techniques and roasting profiles to optimize coffee quality. The study emphasizes the role of fermentation, mucilage retention and lipid oxidation reactions in flavor development, offering valuable insights for improving specialty coffee production in Thailand and globally.

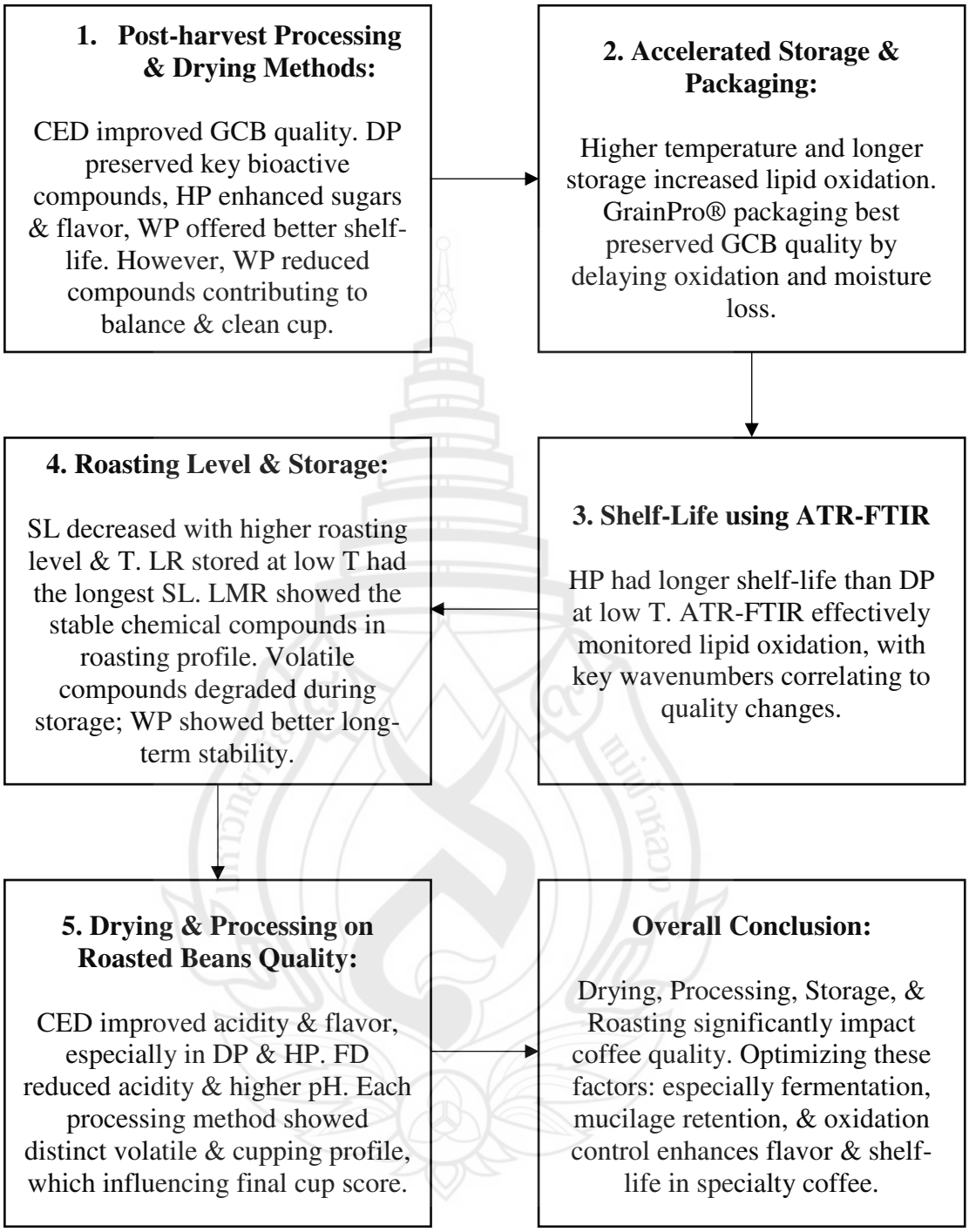

Figure 9.1 Overall Conclusion

CHAPTER 10

SUGGESTION

The findings of this research offer valuable insights into the impact of post-harvest processing, drying methods, and storage conditions on the quality and shelf-life of both green and roasted coffee beans. However, there are several key areas that warrant further investigation. One significant avenue for future research is the application of controlled environment drying (CED), which has shown potential in enhancing the physicochemical, biochemical, and sensory attributes of coffee. CED could be particularly beneficial in improving the quality of Thai coffee and meeting both commercial and specialty-grade standards. By applying this technique, Thai coffee producers can address challenges posed by climate change and the use of mixed coffee varieties. To further improve quality, it would be valuable to explore the application of CED to single-origin varieties, as this could create unique flavor profiles that enhance the overall quality of the coffee.

Additionally, fermentation and mucilage retention were found to influence flavor development in coffee. Future studies should focus on the specific biochemical processes during these stages, particularly for natural, honey, and washed processing methods. Understanding how fermentation variables affect volatile compound formation will be crucial for optimizing flavor profiles and aligning them with market preferences. For mixed-variety plantations, experimenting with alternative fermentation methods, such as anaerobic or natural yeast fermentation, could offer valuable insights into the creation of distinct volatile compounds that enhance the cupping experience.

The research on accelerated storage conditions also highlighted the importance of packaging materials in preserving the quality of green coffee beans. Future studies should explore the mechanisms of lipid oxidation further and investigate innovative packaging solutions to extend the shelf-life of coffee. Advanced packaging techniques, such as vacuum-sealed or modified atmosphere packaging (MAP), should be explored to reduce oxidation and maintain the integrity of the coffee's flavor over extended

storage periods. An interesting avenue for research could involve comparing the long-term storage quality of hulled vs. un-hulled beans, potentially studying the effects over a one or two-year period. In addition to packaging, non-destructive techniques like FTIR, NIR, image analysis, and electronic noses should be refined for better quality control during both pre- and post-harvest stages. These methods could significantly improve the monitoring and management of coffee quality, ensuring consistency across different stages of production.

Finally, aligning post-harvest processing, drying techniques and roasting profiles with Thai coffee quality standards will be crucial as coffee consumption in Thailand continues to grow. Establishing clear, standardized methods for assessing and certifying coffee quality will help Thai coffee producers gain recognition in the global specialty coffee market. Future research should focus on developing these guidelines, with particular attention to key parameters such as acidity, sweetness, body, and aroma. The development of a certification system based on these standards will help to elevate the quality and competitiveness of Thai coffee on the world stage. Incorporating these suggestions for further study will not only optimize coffee production techniques but also contribute to the sustainability and global recognition of the Thai coffee industry.

APPENDIX

RESEARCH PAPER

AgriEngineering

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Article

Influence of Post-Harvest Processing and Drying Techniques on Physicochemical Properties of Thai Arabica Coffee

Sai Aung Moon [1,2], Sirirung Wongsakul [1,2,3], Hiroaki Kitazawa [4] and Rattapon Saengrayap [1,2,3,*]

[1] School of Agro-Industry, Mae Fah Luang University, Chiang Rai 57100, Thailand; 6471401001@lamduan.mfu.ac.th (S.A.M.); sirirung@mfu.ac.th (S.W.)
[2] Coffee Quality Research Group, Mae Fah Luang University, Chiang Rai 57100, Thailand
[3] Integrated AriTech Ecosystems Research Group, Mae Fah Luang University, Chiang Rai 57100, Thailand
[4] Department of Food and Nutrition, Faculty of Human Sciences and Design, Japan Women's University, 2-8-1 Mejirodai, Bunkyo-ku 112-8681, Japan; kitazawah@fc.jwu.ac.jp
* Correspondence: rattapon.sae@mfu.ac.th; Tel.: +66-53917186; Fax: +66-53916737

Abstract: Coffee post-processing drying eliminates moisture content, reduces fungal and microbe growth, and develops unique aroma and flavor compounds. Thai coffee producers use controlled-environment drying (CED) techniques to improve the quality and cupping scores of the coffee. This research investigated how different drying methods, including sun drying (SD), controlled-environment drying at 20–30 °C, 50–55% RH, and fast drying (FD) at 30–45 °C influenced the physicochemical characteristics of coffee undergoing dry (DP), washed (WP), and honey (HP) processing. Results showed that true density, moisture content, water activity, color, caffeine, trigonelline, chlorogenic acid, caffeic acid, sucrose, and fructose in green coffee beans were significantly affected ($p < 0.05$) by both drying technique and post-harvest processing. Drying techniques and processing directly impacted the characteristics of green (GCB) and roasted coffee beans (RCB). Findings suggested a correlation between CED, SD, and FD based on the physicochemical and biochemical properties and sugar contents of both green and roasted coffee beans.

Keywords: controlled-environment drying; drying characteristic; LTLH; quality

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1. Introduction

Thailand first introduced coffee farming in 1849. The most common coffee varieties are Arabica, which is mainly found in Northern Thailand, and Robusta, which is primarily grown in the southern region [1–3]. Arabica varieties, including Catimor, Caturra, Typica, Bourbon, Catuai, and Mundo Novo, are mainly cultivated in Chiang Rai, Chiang Mai, Nan, Lampang, and Tak Provinces [1–3]. Many coffee plantations now commonly grow mixed *Caffea arabica* seeds as it costs more to separate beans during post-harvesting. Climate change also negatively impacts rising temperatures and water scarcity [4]. Thus, several Thai coffee farmers focus on the drying stage to reduce the moisture from 55–60% to 9–12% as a safe range for storage before roasting while also enhancing the organoleptic qualities of green coffee beans.

The drying stage is a critical post-harvest procedure that contributes significantly to the development of the distinctive color, flavor, and taste of a coffee beverage [5]. Sun drying is a common technique utilized by coffee producers in Thailand. The taste of the coffee is significantly affected by the sun-drying process, which depends on climatic conditions [5]. Several researchers investigated mechanical drying techniques in industrial settings to reduce drying time [6,7]. Shofinita et al. [6] reported that a high temperature during the drying process could lead to reduced storage time and structural damage; therefore, methods of coffee drying and the operating conditions should be carefully considered. Both sun and machine drying are essential to achieving homogeneity, ensuring the desired color, and controlling pests to enhance the longevity of storage [7]. However, many parameters

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Lipid Oxidation Changes of Arabica Green Coffee Beans during Accelerated Storage with Different Packaging Types

Sai Aung Moon [1,2], Sirirung Wongsakul [1,2,3], Hiroaki Kitazawa [4] and Rattapon Saengrayap [1,2,3,5,*]

1 School of Agro-Industry, Mae Fah Luang University, Chiang Rai 57100, Thailand
2 Coffee Quality Research Group, Mae Fah Luang University, Chiang Rai 57100, Thailand
3 Tea and Coffee Institute, Mae Fah Luang University, Chiang Rai 57100, Thailand
4 Institute of Food Research, National Agriculture and Food Research Organization (NARO), 2-1-12 Kannondai, Tsukuba 305-8642, Ibaraki, Japan
5 Integrated AriTech Ecosystems Research Group, Mae Fah Luang University, Chiang Rai 57100, Thailand
* Correspondence: rattapon.sae@mfu.ac.th; Tel.: +66-53917186; Fax: +66-53916737

Abstract: The storage conditions of green coffee beans (GCBs) are indispensable in preserving their commercial value. In Thailand, coffee farmers and roasters typically store GCBs for six months to a year before roasting. However, the beans undergo oxidation during storage, influencing both quality and taste. This study investigated changes in GCB lipid oxidation under different accelerated storage conditions (30 °C, 40 °C and 50 °C with 50% RH) and packaging, i.e., plastic woven (PW), low-density polyethylene (LDPE) and hermetic/GrainPro® (GP) bags. Samples were collected every five days (0, 5, 10, 15 and 20 days) and analyzed for lipid oxidation parameters including acid value (AV), free fatty acids (FFA), peroxide value (PV), *p*-anisidine value (PAV), total oxidation value (TOTOX), thiobarbituric acid reactive substances (TBARS), moisture content (MC), water activity (a_w) and color. Primary oxidation was observed, with AV, FFA and PAV gradually changing during storage from 1.49 ± 0.32 to 3.7 ± 0.83 mg KOH/g oil, 3.82 ± 0.83 to 9.51 ± 1.09 mg KOH/g oil and 0.99 ± 0.03 to 1.79 ± 0.14, respectively. Secondary oxidation changes as PV and TBARS were reported at 0.86 ± 0.12 to 3.63 ± 0.10 meq/kg oil and 6.76 ± 2.27 to 35.26 ± 0.37 MDA/kg oil, respectively, affecting the flavor and odor of GCBs. Higher storage temperature significantly influenced a lower GCB quality. GP bags maintained higher GCB quality than LDPE and PW bags. Results provided scientific evidence of the packaging impact on oxidation for GCB under accelerated storage.

Keywords: green coffee beans; packaging; quality; rancidity; shelf life

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1. Introduction

Coffee is now one of the most popular drinks and is widely consumed daily. Arabica varieties are the most productive, have the highest quality, and are grown at high elevations above 1000 m worldwide [1,2]. In 1849, Arabica coffee (*Coffea arabica*) was introduced to Thailand as Catimor, Caturra, Typica, Bourbon, Catuai, Mundo Novo and others [3,4]. The Chiang Rai region of Northern Thailand including Doi Chang, Pang Khon, Mae Chang Tai, Doi Tung and Chiang Mai produces Arabica coffee, with 19,900 ha of farming land mainly located in the highlands [5]. Thai coffee has spread to countries including the United States, Canada, the United Kingdom, South Korea, Singapore, Malaysia, Cambodia and Laos. Thai Arabica coffee has a unique profile of intense fruity-floral aroma, acidity, clean-cup, full profile and flavors depending on the processing method [6,7].

However, farmers have faced unstable coffee bean prices, with a lack of market access and the high production costs of hired labor and chemical fertilizers. Sustainable farming practices are required to support local communities and improve farmers' living standards [7]. Chuqian [8] also suggested the utilization of advanced processing techniques and equipment to develop a qualified, precise, commercialized industry on a large scale, improve product quality, and conduct more comprehensive investigations and research

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Application of ATR-FTIR for Green Arabica Bean Shelf-Life Determination in Accelerated Storage

Sai Aung Moon [1], Sirirung Wongsakul [1,2,3], Hiroaki Kitazawa [4], Sila Kittiwachana [5] and Rattapon Saengrayap [1,2,3,*]

[1] School of Agro-Industry, Mae Fah Luang University, Chiang Rai 57100, Thailand; 6471401016@lamduan.mfu.ac.th (S.A.M.); sirirung@mfu.ac.th (S.W.)
[2] Coffee Quality Research Group, Mae Fah Luang University, Chiang Rai 57100, Thailand
[3] Integrated AgriTech Ecosystems Research Group, Mae Fah Luang University, Chiang Rai 57100, Thailand
[4] Department of Food and Nutrition, Faculty of Human Sciences and Design, Japan Women's University, 2-8-1 Mejirodai, Bunkyo-ku, Tokyo 112-8681, Japan; kitazawah@fc.jwu.ac.jp
[5] Department of Chemistry, Faculty of Science, Chiang Mai University, Chiang Mai 50200, Thailand; sila.k@cmu.ac.th
* Correspondence: rattapon.sae@mfu.ac.th; Tel.: +66-5391-7186

Abstract: Coffee bean oxidation is associated with enzymatic and non-enzymatic browning, the degradation of desirable aromatic compounds, the development of undesirable flavors, increased susceptibility to microbial spoilage, and volatile compound losses. This study investigated natural dry process (DP) and honey process (HP) green coffee beans stored in GrainPro® bags for 0, 5, 10, and 20 days under accelerated storage conditions at 30 °C, 40 °C, and 50 °C with relative humidity of 50%. A kinetic model was used to estimate the shelf life of the green coffee beans. DP recorded durability of 45.67, 29.9, and 24.92 days at 30 °C, 40 °C, and 50 °C, respectively, with HP 60.34, 38.07, and 19.22 days. Partial least squares (PLS) analysis was performed to build the models in order to predict the shelf life of coffee based on peroxide (PV) and thiobarbituric acid reactive substances (TBARS) values. In terms of prediction with leave-one-out cross-validation (LOOCV), PLS provided a higher accuracy for TBARS (R^2 = 0.801), while PV was lower (R^2 = 0.469). However, the auto-prediction showed good agreement among the observed and predicted values in both PV (R^2 = 0.802) and TBARS (R^2 = 0.932). Based on the variable importance of projection (VIP) scores, the ATR-FTIR peaks as 3000–2825, 2154–2150, 1780–1712, 1487–2483, 1186–1126, 1107–1097, and 1012–949 cm^{-1} were identified to be the most related to PV and TBARS on green coffee beans shelf life. ATR-FTIR showed potential as a fast and accurate technique to evaluate the oxidation reaction that related to the loss of coffee quality during storage.

Keywords: infrared spectroscopy; multivariate analysis; oxidation; rancidity

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1. Introduction

The global production and consumption of coffee are supported by a comprehensive market analysis, appreciated for its rich flavor, aroma, and stimulating properties [1]. Arabica has fallen 7.1% to 94 million bags, while Robusta is set to rise 5.1% to 73 million bags [2]. Several factors influence the final quality of coffee, including climate change [3], post-harvest [4], coffee processing [5–7], and storage [8–10], which negatively impact coffee quality assessment and the sensory characteristics of coffee, as well as the obtaining of optimal and market prices [11]. Additionally, maintaining the quality of coffee throughout its shelf life presents a significant challenge for Thai coffee producers, distributors, and consumers.

As coffee ages, it undergoes chemical changes that degrade its sensory attributes, leading to a loss flavor, aroma, and overall appeal [8–11]. Also, the quality of the coffee could change while it is being stored, causing mold to grow and harmful compounds to

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Comparative analysis of post-harvest processing and drying techniques on the cupping quality of Thai Arabica coffee

Sai Aung Moon [a,b], Sirirung Wongsakul [a,b,c,d], Hiroaki Kitazawa [e], Rattapon Saengrayap [a,b,c,d,*]

[a] School of Agro-Industry, Mae Fah Luang University, Chiang Rai, 57100, Thailand
[b] Coffee Quality Research Group, Mae Fah Luang University, Chiang Rai, 57100, Thailand
[c] Integrated ArtTech Ecosystems Research Group, Mae Fah Luang University, Chiang Rai, 57100, Thailand
[d] Tea and Coffee Institute, Mae Fah Luang University, Chiang Rai, 57100, Thailand
[e] Department of Food and Nutrition, Faculty of Human Sciences and Design, Japan Women's University 2-8-1, Mejirodai, Bunkyo-ku, Tokyo, 112-8681, Japan

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ABSTRACT

Climate variability poses significant challenges to Thai Arabica coffee. Unstable weather has negatively impacted the quality of Northern Thai Arabica, leading to issues with quality consistency and reduced market competitiveness for Thai coffee growers. Enhancing refining postharvest processing methods is crucial for improving the overall quality of Thai coffee. This study investigates the impact of drying techniques, i.e., controlled environment drying (CED), sun drying (SD), and fast drying (FD), alongside processing methods. i.e., dry process (DP), washed process (WP), and honey processes (HP), on the pH, total titratable acidity (TA), total soluble solids (TSS), volatile compounds, and cupping scores of roasted coffee beans. Results showed significant differences ($p < 0.05$) among the drying methods and processing techniques regarding the pH, TA, TSS, volatile compounds, and cupping scores of the roasted beans. CED-DP and CED-HP obtained the highest cupping scores of 83.17 ± 1.26 and 83.33 ± 0.58, respectively. CED gave high levels of total ester and heterocyclic N, FD gave high total acetate, and SD gave high total acid, alcohol, aldehyde, furan, ketone, and pyrazine which link to the sensory attributes. Principal component analysis (PCA) of the chemical compound groups explained 87.97 % of the cumulative variance, revealing distinct associations between processing methods and sensory attributes. DP samples were aligned with acidity, overall, TA, TSS, and total esters and aldehydes, while WP samples were aligned with characteristics such as uniformity, clean cup, acid, alcohol, and pyrazine and HP samples were linked to the sensory characteristics of sweetness, aftertaste, body, flavor, balance, fragrance/aroma, pH, acetate, ketone, furan, and heterocyclic N. These findings offer actionable insights for Thai coffee producers to improve coffee quality by selecting the proper postharvest processing for desired characteristics, despite climatic challenges.

1. Introduction

In Northern Thailand, Chiang Rai is a region of major Thai Arabica coffee production. For a decade, Thai coffee farms grow diverse varieties including Catimor, Caturra, and Typica. A mix-variety coffee produces complex cupping characteristics that created the uniqueness of Chiang Rai coffee. Since climate change with rising temperatures and water scarcity now impacts product quality, Thai Arabica production region also faced with these changes which affected directly to Thai coffee industry [1–4]. To address these issues, farmers are prioritizing post-harvest processing and drying of coffee cherries to reduce moisture levels from 55 to 60 % to a more stable 9–12 % for storage. Previous research indicated that drying methods such as controlled environment drying, sun drying, and fast drying combined with processing styles (natural/dry, washed, and honey processing) significantly influenced the coffee's moisture content, density, chemical composition, and sensory attributes [5]. Traditional sun drying, while economical, is time-intensive and climate-dependent, often leading producers to choose mechanical drying for greater consistency [6]. Optimizing these drying and processing techniques is essential for maintaining Thai coffee

* Corresponding author. School of Agro-Industry, Mae Fah Luang University, Chiang Rai, 57100, Thailand.
E-mail address: rattapon.sae@mfu.ac.th (R. Saengrayap).

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Impact of roasting and storage conditions on the shelf stability of Thai Arabica coffee

Sai Aung Moon [a,b], Sirirung Wongsakul [a,b,c,d], Hiroaki Kitazawa [e], Rattapon Saengrayap [a,b,c,d,*]

[a] School of Agro-Industry, Mae Fah Luang University, Chiang Rai, 57100, Thailand
[b] Coffee Quality Research Group, Mae Fah Luang University, Chiang Rai, 57100, Thailand
[c] Integrated ArtTech Ecosystems Research Group, Mae Fah Luang University, Chiang Rai, 57100, Thailand
[d] Tea and Coffee Institute, Mae Fah Luang University, Chiang Rai, 57100, Thailand
[e] Department of Food and Nutrition, Faculty of Human Science and Design, Japan Women's University, 2-8-1, Mejirodai, Bunkyo-ku, Tokyo, 112-8681, Japan

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ABSTRACT

This research investigated the impact of roasting levels and storage conditions on coffee quality by analyzing moisture content (MC), color, peroxide value (PV), shelf-life, and volatile compounds using solid-phase micro-extraction-gas chromatography/mass spectrometry (SPME-GCMS). Coffee samples were collected from Doi Chang, Thailand, and processed using natural/dry, washed/wet, and honey methods. The samples were then roasted to light at 205 °C, light-medium at 210 °C, and medium at 218 °C. The roasted coffee beans were packaged in hermetic bags and subjected to accelerated storage conditions for 0, 7, 14, and 21 days at 30, 40, and 50 °C with 50 % RH. Results showed that roasting level and accelerated storage significantly affected ($p < 0.05$) MC, color, PV, shelf-life, and volatile compound profiles. Eighty-two volatile compounds were identified across the light, light-medium and medium samples. The dominant compound groups were furans (ranging from 35 ± 6 to 54 ± 3 % d.w.) pyrazines (13 ± 1 to 32.3 ± 0.8 % d.w.), and esters (4.2 ± 0.2 to 16.7 ± 0.9 % d.w.), which contribute significantly to coffee aroma. Shelf-life at 30 °C was longest for light (10.0 ± 0.1 to 11.7 ± 0.3 days), followed by light-medium (7.3 ± 0.3 to 8.8 ± 0.6 days) and medium (6.3 ± 0.3 to 7.7 ± 0.6 days), compared to storage at 40 and 50 °C. The concentrations of volatile compounds including alcohols, aldehydes, esters, furans, furanones, ketones, organic acids, pyrazines, pyridines, pyrroles, sulfides, and terpenes were influenced by roasting level, processing method, and storage conditions, ultimately affecting coffee shelf-life.

1. Introductions

Coffee is one of the world's most beloved beverages, with the complexities of its flavor, aroma, and character dependent on the roasting process [1]. Roasting coffee involves subjecting the beans to heat, which leads to many physical and chemical changes that ultimately influence the flavor and final quality. These changes occur through processes such as Maillard reactions, thermal degradation, pyrolysis, and caramelization [2]. The path from raw coffee beans to the aromatic brews that grace countless cups globally is managed by skilled roasters who carefully navigate the multitude of time and temperature variations in the roasting technique.

The Maillard reaction generates hundreds of coffee flavor compounds through chemical reactions between amino acids, peptides or proteins and reducing sugars such as fructose, glucose, galactose, and maltose. These reactions ultimately lead to the production of brown melanoidins, which then interact with other compounds [3]. Caramelization is a non-enzymatic complex with sugar as sucrose to glucose and fructose condensation reactions, intermolecular bonding, isomerization, dehydration, fragmentation, polymerization, and degradation which lead to browning reactions that release caramel-like, burned, meaty, sour, and bitter flavors to develop a rich aroma [4]. Pyrolysis reactions are longer than Maillard reactions and necessitate greater temperature, with a wide array of organic compounds including alcohols, aldehydes, carboxylic acids, furans, ketones, pyrazines, and pyrroles [4] Several organic compounds including alcohols, aldehydes, acids, amines, dicarbonyls, enoles, esters, furans, furanones, hydrocarbons, imidazoles, indoles, ketones, lactones, oxazoles, phenols, pyrazines, pyridines,

* Corresponding author. School of Agro-Industry, Mae Fah Luang University, Chiang Rai, 57100, Thailand.
E-mail address: rattapon.sae@mfu.ac.th (R. Saengrayap).

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CURRICULUM VITAE

NAME Sai Aung Moon

EDUCATIONAL BACKGROUND

2014 Bachelor of Science
Physics
Lashio University, Myanmar

2020 Master of Science
Food Science and Technology
Mae Fah Luang University, Thailand

WORK EXPERIENCE

2015-2017 Community Workers
KawDai Organization, Shan State, Myanmar

SCHOLARSHIP

2021 Grad MFU scholarship

PUBLICATION

Aung Moon S, Wongsakul S, Kitazawa H, Saengrayap R. Impact of roasting and storage conditions on the shelf stability of Thai Arabica coffee. Journal of Agriculture and Food Research 2025 May 26: 101102060.

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