Quantitative Analysis of Micro Minerals in Palm Kernel Seed Oil

By

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CERTIFICATION

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DEDICATION

I dedicate this work to God Almighty, my source of strength, inspiration, wisdom, knowledge and understanding and to my lecturers who have taught me up to this point in my academic pursuit, equipping me with knowledge for both self and societal development.

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ABSRTACT

The African oil palm (*Elaeis guineensis*) is a crucial economic crop, widely cultivated for its oil-rich kernels. Palm kernel seed oil (PKSO) is a significant source of essential minerals such as iron (Fe), zinc (Zn), and copper (Cu), but concerns exist regarding potential contamination with toxic heavy metals like cadmium (Cd). This study aims to determine the mineral composition of PKSO and assess its implications for human health and food safety.

Palm kernel samples were obtained from New Benin Market, Benin Metropolis, Edo State, Nigeria. The oil extraction process involved heating, grinding, and pressing the kernels. Mineral analysis was conducted using Atomic Absorption Spectroscopy (AAS) after acid digestion. Quality assurance measures included duplicate analyses and blank sample validation to ensure data reliability.

Results showed that PKSO contained Fe (2.23 ± 0.21 mg/100g), Zn (1.86 ± 0.04 mg/100g), Cu (0.64 ± 0.49 mg/100g), and nitrogen (174.16 ± 4.57 mg/100g). Cadmium (Cd) was undetectable, indicating no toxic heavy metal contamination. These findings suggest that PKSO is safe edible oil with moderate mineral content, contributing to essential dietary micronutrient intake. However, its relatively low Fe and Zn levels necessitate complementary dietary sources. The absence of toxic metals highlights its safety, but ongoing monitoring is recommended to prevent environmental contamination. This study underscores the nutritional value and safety of PKSO, contributing to food quality control and public health awareness.

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

The African oil palm (*Elaeis guineensis*) is a major economic crop in Nigeria, widely cultivated for its oil-rich fruits. Beyond palm oil, the seeds—palm kernels—are highly valued for their nutritional and industrial applications (Akinyele & Osibanjo, 2020). Palm kernel seed oil contains essential micronutrients such as iron (Fe), zinc (Zn), and copper (Cu), which play vital roles in various physiological functions, including oxygen transport, enzymatic activities, and immune system support. However, concerns have been raised about the presence of toxic heavy metals like cadmium (Cd) and mercury (Hg) in food crops due to environmental pollution (Okonkwo et al., 2021).

Environmental contamination from industrial activities, mining, and excessive agrochemical use has been linked to increasing levels of heavy metals in Nigerian farmlands (Eze et al., 2022). These metals can be absorbed by plants from the soil and water, accumulating in edible parts over time. While iron, zinc, and copper are essential micronutrients required in trace amounts, excessive intake can lead to toxicity. In contrast, cadmium and mercury are non-essential and highly toxic, even at low concentrations, with potential health risks including kidney damage, neurological disorders, and metabolic disturbances (Nwankwo et al., 2020).

Despite the widespread consumption and industrial applications of palm kernel seed oil, limited research has focused on its micronutrient composition, particularly regarding potential contamination with toxic metals. Understanding the levels of these elements is essential for ensuring food safety and public health.

1.2 Aim and Objectives of the Study

This study aims to determine the concentrations of micro minerals specifically cadmium, copper, mercury, iron, and zinc in palm kernel seed oil from different locations in Nigeria and compare the findings with European Union (EU) regulatory standards for food safety. Palm kernel seed oil samples will be collected from Benin City, Edo State, Nigeria, and analyzed using reliable scientific methods to assess their mineral content in relation to established EU safety limits.

CHAPTER TWO

LITERATURE REVIEW

2.1 *Elaeis guineensis*

Palm kernel (*Elaeis guineensis*) is a species of palm commonly called African oil palm and is the principal sources of palm oil. It is native to west and southeast Africa, specifically within the areas of Angola, Gambia and Nigeria (south-east). The nut is the edible seed of the oil palm tree which is gotten when a palm kernel's hard shell is broken. The palm tree belongs to the Arecaceae family, in order of Arecales. In addition, Palm kernel nuts are commonly planted in four tropical regions which include Africa, Southeast Asia, Latin America and South Pacific (Okonkwo *et al*., 2015). The fruit yields two oils, palm oil and kernel oil each exhibiting differences in composition, properties and applications. Moreover, palm kernel oil has also been reported to be rich in important food properties compared to some other oil seeds and nuts as well as a good source of amino acids for children and adults (Akinniyi and Waziri, 2011). Additionally, Palm kernel nuts as shown in figure 1 constitute some components of the diet of many Nigerians especially in the rural areas, some people take it raw while others prefer to boil it before consuming.

Elaeis guineensis is the primary source of both palm oil and palm kernel oil. The species has significant agronomic, industrial, and economic value, particularly in the tropics. Historically, oil palm cultivation was limited to West and Central Africa, but its commercial expansion has led to large-scale plantations in Asia and South America (Obahiagbon, 2021).

One of the unique aspects of *E. guineensis* is its high oil productivity compared to other oilseed crops such as soybean and sunflower. This high yield is attributed to its long productive life span and efficient use of solar energy for biomass accumulation (Akpan and Udoh, 2020). In addition to its oil production, the kernel of the fruit contains essential minerals, making it a valuable resource for nutritional and industrial applications (Oghale *et al*., 2019).

Palm kernel seeds have gained attention due to their mineral composition, which includes essential trace elements like iron, zinc, and copper. However, environmental factors, such as soil composition, agricultural practices, and industrial contamination, can introduce toxic heavy metals like cadmium and mercury into the seeds, raising food safety concerns (Oluwatosin *et al*., 2018).

Figure 1: Image of *Elaeis guineensis* nut (Ezieshi 2017)

2.1.1 Geographical Distribution

Elaeis guineensis is indigenous to West and Central Africa, thriving in tropical rainforests with high rainfall and temperatures between 24–32°C. The largest natural populations are found in

Nigeria, Ghana, Cameroon, and the Democratic Republic of the Congo (Ekwueme and Nduka, 2020).

Due to its economic importance, oil palm plantations have expanded beyond Africa to Southeast Asia (Malaysia and Indonesia), which now dominate global palm oil production (Ibe and Eke, 2022). In Nigeria, the crop is cultivated extensively in Edo, Delta, Akwa Ibom, Cross River, Ondo, and Imo states, where soil and climatic conditions favor its growth (Uzo et al., 2019).

Table 2.1 summarizes the major oil palm-producing regions and their estimated contribution to global production.

Table 2.1: Major Oil Palm-Producing Regions and Their Contribution to Global Production

Region	Major countries	Estimated global share (%)
West & Central Africa	Nigeria, Ghana, Cameroon	5-8%
Southeast Asia	Indonesia, Malaysia	85%
South America	Colombia, Brazil	3- 5%

(*Source*: Ibe and Eke, 2022)

2.1.2 Botanical Description

Elaeis guineensis is a monocotyledonous perennial plant with a single, unbranched stem reaching heights of 20–30 meters. The leaves are long, pinnate, and arranged in a spiral form, while the flowers are borne in clusters, with both male and female inflorescences present on the same plant (Oluwatosin *et al*., 2020).

The fruit, known as a drupe, has three distinct layers:

1. Exocarp (outer skin) – smooth and thin

2. Mesocarp (pulp) – oil-rich, orange in color

3. Endocarp (shell) – encloses the kernel, which contains oil and essential minerals

The palm kernel is of particular interest due to its mineral content, which is influenced by environmental and soil factors (Adetunji and Uche, 2018).

2.1.3 Taxonomical classification

Taxonomical classification refers to the system of naming and organizing organisms into groups based on their similarities and differences. Taxonomy is the branch of biology that deals with this classification, and it is used to help scientists understand the relationships between different organisms. In taxonomy, organisms are classified into groups based on shared characteristics, such as their physical features, genetic makeup, or evolutionary history.

For example, all organisms in the same genus share a common ancestor.

Table 2.2 gives the taxonomical classification of *Elaeis guineensis* which is a very specific classification.

Table 2.2: Scientific Classification of *Elaeis guineensis*

Taxonomic Rank	Classification
Kingdom	Plantae
Phylum	Tracheophyta
Class	Liliopsida
Order	Arecales
Family	Arecaceae
Genus	Elaeis
Species	Elaeis guineensis

(*Source:* Okwu and Ukanwa, 2019)

2.2 Palm Kernel Seed Oil

African palm kernel seed oil, derived from the kernels of the African oil palm (*Elaeis guineensis*), is distinctive edible oil obtained from the seed rather than the mesocarp. This oil exhibits a high level of saturation, primarily due to its abundant medium-chain fatty acids, with lauric acid being particularly prominent. The elevated lauric acid content not only contributes to the oil's semi-solid consistency at ambient temperatures but also enhances its oxidative stability and imparts antimicrobial properties, making it valuable for both culinary and industrial applications (Imoisi et al., 2018).

Recent research has provided a comprehensive profile of the fatty acids present in African palm kernel seed oil. Studies indicate that the oil comprises significant proportions of lauric, myristic, palmitic, oleic, and linoleic acids. This unique composition is responsible for the oil's resilience to oxidation and thermal degradation—properties that are critically important in food processing, where high temperature stability is required. Moreover, the saponification characteristics of the oil, largely driven by its medium-chain fatty acids, make it an ideal candidate for producing soaps, detergents, and various personal care products (Imo and Ijagem, 2021).

From a nutritional perspective, the high saturation level of African palm kernel seed oil is a subject of ongoing debate. Diets rich in saturated fats have been traditionally associated with elevated levels of low-density lipoprotein cholesterol (LDL-C), a known risk factor for cardiovascular disease. However, it is noteworthy that the oil is free of cholesterol and trans fats, which distinguishes it from many animal-based fats and may lessen some of the associated health risks. The complex interplay between its antimicrobial benefits and the potential cardiovascular implications of its saturated fat content is a focal point for current interdisciplinary research.

Environmental sustainability is another critical dimension of African palm kernel seed oil production. The expansion of oil palm cultivation in Africa, while offering significant economic benefits, has raised environmental concerns such as deforestation, biodiversity loss, and increased carbon emissions. Researchers and industry stakeholders are actively investigating sustainable agricultural practices that can improve yield and oil quality while simultaneously mitigating adverse ecological impacts. This dual focus on enhancing industrial utility and promoting environmental stewardship highlights the broader significance of African palm kernel seed oil in both scientific research and practical applications.

African palm kernel seed oil stands out due to its unique fatty acid profile, which provides both functional and nutritional benefits. Its resistance to oxidation and suitability for industrial processing are balanced by important considerations regarding cardiovascular health and environmental sustainability. Ongoing studies are essential to fully elucidate these aspects and to develop sustainable production practices that optimize both the economic and ecological outcomes associated with this valuable oil.

2.3 Chemical Composition of Palm Kernel Seed Oil

Recent investigations into the African palm kernel seed oil reveals that its composition is multifaceted, encompassing major lipid constituents, a range of bioactive phytochemicals, vitamins, and a spectrum of minerals. This comprehensive chemical profile not only determines its physical and oxidative properties but also underpins its nutritional value and industrial applications.

2.3.1 Fatty Acids

Palm kernel seed oil, derived from the kernel of the oil palm (*Elaeis guineensis*), is a tropical oil widely used in food, cosmetics, and industrial applications due to its unique fatty acid composition. Unlike palm oil, which is extracted from the fruit's mesocarp, palm kernel oil is obtained from the seed and exhibits a distinct profile dominated by saturated fatty acids, particularly medium-chain fatty acids (MCFAs).

The primary fatty acid in palm kernel oil is lauric acid (C12:0), which typically constitutes approximately 45–55% of the total fatty acid content. Lauric acid is a medium-chain saturated fatty acid known for its antimicrobial properties and rapid metabolism in the human body (Dayrit, 2015). Following lauric acid, myristic acid (C14:0) is the second most abundant, accounting for 14–18%, while palmitic acid (C16:0) ranges from 7–10%. Oleic acid (C18:1), a monounsaturated fatty acid, is present in smaller amounts, typically 12–19%, contributing to the oil's semi-solid consistency at room temperature (Pantzaris and Basiron, 2017). Other minor components include capric acid (C10:0) and caprylic acid (C8:0), each contributing 3–7%, and stearic acid (C18:0) at around 2–4% (Sundram *et al.,* 2019).

This high saturation level, with saturated fatty acids comprising about 80–85% of the total, distinguishes palm kernel oil from many other vegetable oils and aligns its properties with coconut oil, another lauric oil. The predominance of MCFAs enhances its stability against oxidation, making it suitable for frying and long-shelf-life products (Gunstone, 2020). However, its high saturated fat content has raised concerns regarding cardiovascular health, though recent studies suggest that lauric acid may have a neutral or less detrimental effect compared to longer-chain saturated fats (Eyres *et al.,* 2016).

2.3.2 Phytochemicals

Palm kernel seed oil is predominantly recognized for its high content of saturated fatty acids, such as lauric acid. However, its phytochemical content—non-nutritive plant compounds with potential health benefits—is less prominent compared to oils like olive or palm fruit oil. Phytochemicals in palm kernel oil are present in small quantities, and their levels are heavily influenced by the extraction and refining processes, which often diminish these compounds.

Among the phytochemicals identified in crude palm kernel oil are phenolic compounds, tocopherols, and sterols. Phenolic compounds, which possess antioxidant properties, are found in trace amounts in unrefined oil. These compounds, including phenolic acids, contribute to oxidative stability but are largely removed during refining to produce the neutral, shelf-stable oil used commercially (Tan *et al.,* 2017). Tocopherols, a form of vitamin E, are natural antioxidants present in crude palm kernel oil at levels of approximately 20–50mg/kg, though these are significantly lower than in palm fruit oil (Sundram *et al.,* 2019). The refining process, including bleaching and deodorization, reduces tocopherol content, limiting their presence in the final product (Gunstone, 2020).

Phytosterols, such as beta-sitosterol, stigmasterol, and campesterol, are also detected in crude palm kernel oil, with concentrations ranging from 50–100 mg/kg (Pantzaris and Basiron, 2017). These compounds are known for their cholesterol-lowering potential, but their levels in palm kernel oil are modest compared to other vegetable oils like soybean or corn oil. Additionally, trace amounts of carotenoids may be present in unrefined oil, contributing a slight yellowish hue, though these are typically eliminated during processing (Ofori-Boateng and Lee, 2016).

The low phytochemical content in refined palm kernel oil reflects its primary use as a stable fat source rather than a functional food. In contrast, the residual palm kernel meal retains more phytochemicals, such as flavonoids and tannins, which are of interest in animal nutrition and pharmaceutical research (Abdullah *et al.,* 2021). Overall, while crude palm kernel oil contains some beneficial phytochemicals, their concentrations are minimal, and refining further reduces their significance.

2.3.3 Phenolic Compounds

Palm kernel seed oil, derived from the kernel of the oil palm (Elaeis guineensis), is primarily known for its high saturated fatty acid content, such as lauric acid, but it also contains minor bioactive constituents, including phenolic compounds. These naturally occurring phytochemicals, though present in small amounts, contribute to the oil's antioxidant properties and potential health benefits, distinguishing crude palm kernel oil from its refined counterpart.

Phenolic compounds in palm kernel oil are a diverse group of molecules characterized by one or more hydroxyl groups attached to an aromatic ring. In crude palm kernel oil, these include phenolic acids such as p-hydroxybenzoic acid, ferulic acid, and caffeic acid, albeit in trace quantities—typically ranging from 1–10 mg/kg (Tan *et al.,* 2017). These compounds are more abundant in the unrefined oil, as refining processes like neutralization and deodorization significantly reduce their presence, often to negligible levels (Gunstone, 2020). The phenolic content is notably lower than in palm fruit oil, which is richer in phenolics due to its mesocarp origin, but it still imparts some oxidative stability to palm kernel oil.

The antioxidant activity of phenolic compounds in palm kernel oil helps protect its lipids from peroxidation, a process that degrades oils under heat or light exposure. This stability is valuable in food applications, such as frying, where oxidative resistance extends shelf life (Pantzaris and Basiron, 2017). Beyond industrial benefits, phenolics may offer health advantages when consumed in unrefined oil, including anti-inflammatory and free radical-scavenging effects, which could mitigate oxidative stress linked to chronic diseases (Sundram *et al.,* 2019). However, their low concentration limits their impact compared to oils like olive oil, a phenolic-rich benchmark.

Extraction methods influence phenolic retention. Cold-pressed or mechanically extracted palm kernel oil preserves more phenolics than solvent-extracted or fully refined versions (Ofori-Boateng and Lee, 2016). Meanwhile, the palm kernel meal byproduct retains higher phenolic levels, including flavonoids and tannins, suggesting that most phenolics remain in the solid residue post-extraction (Abdullah *et al.,* 2021). Thus, while phenolic compounds in palm kernel oil are sparse, their presence in crude forms underscores the oil's potential beyond mere fat content.

2.3.4 Tocopherols and Tocotrienols

Palm kernel seed oil, extracted from the kernel of the oil palm fruit (*Elaeis guineensis*), is a tropical oil valued for its high saturated fatty acid content, notably lauric acid, which constitutes about 45–55% of its composition (Pantzaris and Basiron, 2017). Beyond its lipid profile, the oil contains tocopherols, a group of vitamin E compounds recognized for their antioxidant capabilities. These phytochemicals help safeguard the oil's lipids from oxidative deterioration, which can lead to rancidity and reduced shelf life during storage or processing.

The predominant tocopherol in palm kernel oil is alpha-tocopherol, with trace amounts of gamma-tocopherol also present. The total tocopherol content is relatively low, typically ranging from 20 to 40 parts per million (ppm) (Sundram *et al.,* 2019). This contrasts sharply with palm oil from the fruit's mesocarp, which contains 600–1000 ppm of vitamin E, mostly as tocotrienols (Gunstone, 2020), or soybean oil, with 1000–1500 ppm of tocopherols (Tan *et al.,* 2017). Despite their modest levels, tocopherols in palm kernel oil enhance its oxidative stability, complementing the oil's high saturated fat content, which inherently resists oxidation due to fewer unsaturated bonds (Pantzaris and Basiron, 2017).

Tocopherols serve a practical role in applications like frying or producing margarine and shortenings, where they mitigate lipid peroxidation by neutralizing free radicals, preserving the oil's quality and safety (Ofori-Boateng and Lee, 2016). Nutritionally, they contribute a minor amount of vitamin E, though their low concentration limits their dietary significance compared to richer sources like sunflower oil (Sundram *et al.,* 2019). Refining processes, including bleaching and deodorization, often reduce tocopherol levels in the final product, with crude oil retaining slightly higher amounts (Gunstone, 2020). Unlike palm oil, which is rich in tocotrienols, palm kernel oil contains only negligible traces of these unsaturated vitamin E variants (Tan *et al*., 2017).

Tocopherols, mainly alpha-tocopherol, are present in palm kernel seed oil at 20–40 ppm. Though less abundant than in other oils, they bolster its stability against oxidation, supporting its use in food production while offering minimal nutritional benefits.

Tocotrienols are a subgroup of vitamin E compounds, structurally related to tocopherols, but distinguished by their unsaturated isoprenoid side chains containing three double bonds, as opposed to the saturated side chains of tocopherols. Like tocopherols, tocotrienols are fat-soluble antioxidants naturally occurring in certain plant oils, seeds, and grains, and they play a significant role in protecting lipids from oxidative damage. They exist in four isoforms—alpha, beta, gamma, and delta—based on the number and position of methyl groups on their chromanol ring, each with slightly varying biological activities.

In the context of palm kernel seed oil, tocotrienols are present only in trace amounts, unlike palm oil extracted from the fruit's mesocarp, which is one of the richest natural sources of tocotrienols, containing 600–1000 mg/kg, with gamma-tocotrienol and alpha-tocotrienol predominating (Sundram *et al.,* 2019). Palm kernel oil, by contrast, has a tocotrienol content typically below detectable limits or less than 10 mg/kg, as its vitamin E profile is dominated by tocopherols, particularly alpha-tocopherol (Pantzaris and Basiron, 2017). This disparity arises because tocotrienols are concentrated in the oil palm's fleshy mesocarp, while the kernel prioritizes saturated fats and other compounds.

Tocotrienols exhibit unique properties compared to tocopherols due to their unsaturated tails, which enhance their mobility and penetration into cell membranes. This structural advantage allows them to offer superior antioxidant protection, particularly against lipid peroxidation in biological systems (Gunstone, 2020). Research highlights their potential health benefits beyond basic antioxidant activity, including cholesterol-lowering effects by inhibiting HMG-CoA reductase (a key enzyme in cholesterol synthesis), anti-inflammatory properties, and neuroprotection. Studies suggest tocotrienols may reduce the risk of cardiovascular diseases and certain cancers, with gamma- and delta-tocotrienols showing particular promise in preclinical models (Tan *et al.,* 2017).

Their scarcity in palm kernel oil limits its relevance as a tocotrienol source, but in palm oil, they contribute significantly to its nutritional value. Refining processes can diminish tocotrienol levels, though less severely than tocopherols, due to their relative heat stability (Ofori-Boateng and Lee, 2016). Overall, tocotrienols represent a potent, albeit minor, component of the vitamin E family, with distinct advantages over tocopherols in specific contexts.

2.3.5 Carotenoids

Carotenoids are a class of naturally occurring pigments synthesized by plants, algae, and some microorganisms, known for their vibrant yellow, orange, and red hues. Chemically, they are tetraterpenoids with a 40-carbon backbone, often containing conjugated double bonds that contribute to their color and antioxidant properties. In the context of oils derived from the oil palm (*Elaeis guineensis*), carotenoids are far more prominent in palm oil from the fruit's mesocarp than in palm kernel seed oil, which is extracted from the kernel.

In palm kernel seed oil, carotenoids are present in negligible amounts, typically ranging from 10 to 30 parts per million (ppm) in crude forms, rendering the oil pale or nearly colorless (Pantzaris and Basiron, 2017). This contrasts sharply with crude palm oil, which boasts 500–700 ppm of carotenoids, primarily beta-carotene, alpha-carotene, and traces of others like lycopene, giving it a deep orange-red appearance (Sundram et al., 2019). The low carotenoid content in palm kernel oil reflects the kernel's composition, which prioritizes saturated fatty acids like lauric acid over pigments concentrated in the fruit's fleshy mesocarp.

Carotenoids serve as potent antioxidants, quenching singlet oxygen and neutralizing free radicals that can oxidize lipids, thus protecting oils from rancidity (Gunstone, 2020). In palm oil, this contributes to oxidative stability and nutritional value, as beta-carotene is a provitamin A precursor, supporting vision, immune function, and skin health. In palm kernel oil, however, their minimal presence offers little antioxidant benefit or nutritional significance. Refining processes—such as bleaching, deodorization, and neutralization—further reduce carotenoids in palm kernel oil to undetectable levels, as these steps aim to remove pigments for a neutral, colorless product suited for food and cosmetic applications (Ofori-Boateng and Lee, 2016).

The stark difference in carotenoid content between palm kernel oil and palm oil underscores their distinct roles. While palm oil's carotenoids are valued in unrefined "red palm oil" for both culinary and health purposes, palm kernel oil's lack thereof aligns with its use as a stable, high-saturated-fat ingredient in products like margarine, shortenings, and confectionery (Tan *et al.,* 2017). Any residual carotenoids in crude palm kernel oil are incidental and largely lost during processing, leaving the oil devoid of the vibrant pigmentation and associated benefits seen in its mesocarp-derived counterpart.

2.3.6 Phytosterols

Phytosterols, also known as plant sterols, are naturally occurring compounds found in plant cell membranes, structurally similar to cholesterol but with additional alkyl groups on their side chains. These bioactive lipids are present in various vegetable oils and are valued for their ability to reduce cholesterol absorption in the human gut, offering potential cardiovascular health benefits. In palm kernel seed oil, extracted from the kernel of the oil palm (*Elaeis guineensis*), phytosterols are present, though in relatively modest amounts compared to other plant oils.

The phytosterol content in crude palm kernel oil typically ranges from 50 to 100 mg/kg (Pantzaris and Basiron, 2017). The primary phytosterols identified include beta-sitosterol, which dominates the profile, alongside smaller quantities of campesterol and stigmasterol (Sundram *et al.,* 2019). This is significantly lower than in palm oil from the fruit's mesocarp, which contains 300–620 mg/kg, or oils like soybean (up to 3000 mg/kg) and corn oil (up to 9700 mg/kg) (Gunstone, 2020). The lower concentration in palm kernel oil reflects the kernel's focus on saturated fatty acids, such as lauric acid, rather than sterol-rich components found in the fruit's fleshy parts.

Phytosterols contribute to the oil's stability by acting as minor antioxidants, though their effect is less pronounced than that of tocopherols or phenolic compounds due to their limited presence (Tan *et al.,* 2017). Their primary health benefit lies in their cholesterol-lowering potential. By competing with dietary and biliary cholesterol for absorption in the intestines, phytosterols can reduce low-density lipoprotein (LDL) cholesterol levels, a risk factor for heart disease (Ofori-

Boateng and Lee, 2016). However, the low phytosterol content in palm kernel oil means its contribution to this effect is minimal unless consumed in large quantities, which is unlikely given its typical use in processed foods.

Refining processes, including bleaching and deodorization, can reduce phytosterol levels in palm kernel oil by 20–50%, depending on the intensity of treatment (Gunstone, 2020). Crude or minimally processed oil retains more phytosterols, but even then, their concentration remains modest. In contrast, the palm kernel meal byproduct contains negligible phytosterols, as these lipophilic compounds partition into the oil during extraction (Abdullah *et al*., 2021). Thus, while phytosterols in palm kernel oil offer a slight nutritional advantage, their low levels limit their practical impact compared to oils richer in these compounds.

2.4 Pharmacological and Medicinal Use of Palm Kernel Seed Oil

Palm kernel seed oil is renowned for its high saturated fatty acid content, particularly lauric acid (45–55%), alongside smaller amounts of myristic, palmitic, and oleic acids (Pantzaris and Basiron, 2017). Beyond its widespread use in food, cosmetics, and industrial applications, palm kernel oil has garnered attention for its pharmacological and medicinal properties, rooted in its fatty acid profile, phytochemicals (e.g., tocopherols, phytosterols), and traditional uses in various cultures. While scientific research on its therapeutic potential is still emerging, evidence suggests applications in antimicrobial activity, skin health, cardiovascular support, and anti-inflammatory effects, among others. This discussion explores these uses, emphasizing the mechanisms, evidence, and limitations of palm kernel oil in medicinal contexts.

Palm kernel seed oil exhibits pharmacological and medicinal potential through its antimicrobial, skin-protective, cardiovascular, and anti-inflammatory properties, driven by lauric acid, tocopherols, phytosterols, and phenolics. Its traditional use in wound care, infection treatment, and inflammation relief aligns with emerging scientific insights, particularly for topical applications. However, its medicinal value is constrained by low bioactive concentrations, refining losses, and limited clinical validation. While it holds promise as a natural antimicrobial agent or emollient, its role in internal medicine—such as cardiovascular or neurological applications—requires cautious interpretation and further research. As a bridge between traditional remedies and modern pharmacology, palm kernel oil offers a foundation for exploration, particularly in unrefined forms, but it remains a secondary player compared to oils with richer nutritional profiles.

2.4.1 Antimicrobial Properties

One of the most studied pharmacological attributes of palm kernel oil is its antimicrobial activity, largely attributed to lauric acid and its derivative, monolaurin. Lauric acid, a medium-chain fatty acid (MCFA), constitutes nearly half of the oil's composition and has demonstrated broad-spectrum antimicrobial effects against bacteria, fungi, and viruses (Dayrit, 2015). Monolaurin, formed when lauric acid is metabolized, disrupts microbial cell membranes by integrating into their lipid bilayers, leading to leakage and cell death. Studies have shown efficacy against pathogens like *Staphylococcus aureus*, *Escherichia coli*, and *Candida albicans*, making it a candidate for topical treatments or natural preservatives (Kabara and Marshall, 2016). In traditional African and Southeast Asian medicine, palm kernel oil has been applied to wounds and infections, a practice supported by these antimicrobial properties (Ofori-Boateng and Lee, 2016). However, clinical trials validating its use in humans remain limited, and its efficacy is best harnessed in unrefined forms where lauric acid is intact.

2.4.2 Skin Health and Wound Healing

Palm kernel oil’s emollient and occlusive properties, derived from its semi-solid consistency at room temperature, make it a staple in dermatological applications. Its high saturated fat content provides a protective barrier on the skin, locking in moisture and aiding in the repair of damaged tissue (Pantzaris and Basiron, 2017). The presence of tocopherols (20–50 mg/kg), forms of vitamin E, contributes antioxidant effects that mitigate oxidative stress in skin cells, potentially accelerating wound healing and reducing inflammation (Sundram *et al.,* 2019). In traditional settings, it has been used to treat burns, cuts, and dermatitis, often in combination with other herbal extracts. Modern cosmetic formulations leverage these qualities in soaps, creams, and lotions, where its stability and texture enhance product performance (Gunstone, 2020). While preclinical studies support its role in skin barrier enhancement, human trials are sparse, and its benefits are often overshadowed by oils richer in unsaturated fats or antioxidants, like olive oil.

2.4.3 Cardiovascular Health

The impact of palm kernel oil on cardiovascular health is a subject of debate due to its high saturated fat content, which has historically raised concerns about elevating low-density lipoprotein (LDL) cholesterol. However, recent research suggests that lauric acid, unlike longer-chain saturated fats, may have a neutral or even beneficial effect on lipid profiles by increasing high-density lipoprotein (HDL) cholesterol, the “good” cholesterol (Eyres *et al.,* 2016). Additionally, trace phytosterols (50–100 mg/kg) in crude palm kernel oil, such as beta-sitosterol, may inhibit cholesterol absorption in the gut, offering a modest protective effect against atherosclerosis (Tan et al., 2017). These findings align with its use in some traditional diets without evident cardiovascular harm, though its high caloric density and saturation level caution against excessive consumption. Pharmacologically, its potential as a functional ingredient in cholesterol-lowering formulations is underexplored, and refined oil lacks sufficient phytosterols to exert significant effects.

2.4.4 Anti-Inflammatory and Antioxidant Effects

Palm kernel oil contains minor bioactive compounds, including phenolic compounds (1–10 mg/kg) and tocopherols, which exhibit anti-inflammatory and antioxidant properties. Phenolics, such as p-hydroxybenzoic acid, scavenge free radicals, reducing oxidative stress linked to chronic inflammation and diseases like arthritis or diabetes (Tan *et al.,* 2017). Tocopherols further protect cellular lipids from peroxidation, potentially mitigating inflammation in tissues (Sundram *et al.,* 2019). In ethnomedicine, the oil has been used to soothe inflammatory conditions, such as joint pain or skin irritations, often as a massage oil or poultice base (Abdullah *et al.,* 2021). While in vitro studies support these effects, the low concentrations of these compounds in palm kernel oil—especially after refining—limit their therapeutic potency compared to oils like coconut or palm fruit oil, which share similar MCFAs but differ in phytochemical richness.

2.4.5 Other Medicinal Uses

Beyond these primary applications, palm kernel oil has been explored for additional medicinal roles. Its MCFAs, rapidly metabolized by the liver into ketones, have been suggested as an energy source in ketogenic diets or for managing conditions like epilepsy or Alzheimer's disease, though coconut oil is more commonly studied for this purpose (Dayrit, 2015). In some cultures, it is ingested or applied topically as a laxative or to relieve respiratory congestion, though scientific backing for these uses is anecdotal (Ofori-Boateng and Lee, 2016). The oil's stability and fatty acid profile also make it a potential carrier for delivering lipophilic drugs in pharmaceutical formulations, an area ripe for further investigation (Gunstone, 2020).

2.4.6 Limitations and Challenges

Despite its pharmacological promise, palm kernel oil faces several hurdles in medicinal contexts. Refining reduces its bioactive components—tocopherols, phytosterols, and phenolics—diminishing its therapeutic potential (Pantzaris and Basiron, 2017). Its high saturated fat content raises concerns for long-term internal use, necessitating moderation and further clinical studies to clarify cardiovascular impacts (Eyres *et al.,* 2016). Moreover, most evidence supporting its medicinal use is preclinical or derived from traditional practices, lacking robust, large-scale human trials to establish efficacy and safety profiles (Abdullah *et al.,* 2021). Compared to coconut oil, which shares a similar lauric acid dominance, palm kernel oil is less studied, possibly due to its lower phytochemical diversity and industrial focus.

2.5 Minerals in Palm Kernel Seed Oil

Palm kernel seed oil is a globally utilized tropical oil celebrated for its high saturated fatty acid content, with lauric acid comprising 45–55% of its composition (Pantzaris and Basiron, 2017). This oil’s prominence in food production (e.g., margarine, confectionery), cosmetics (e.g., soaps, creams), and industrial applications (e.g., biofuels) stems from its lipid profile. However, its mineral content—though present in trace amounts—provides critical insights into its quality, safety, and biochemical implications. These minerals include essential elements like iron, zinc, and copper, vital for human biochemical processes, and non-essential or potentially toxic ones such as cadmium, nitrogen, and mercury. This analysis delves deeply into these minerals, emphasizing iron, zinc, copper, cadmium, nitrogen, and mercury, with a focus on their biochemical functions, presence, sources, and significance in palm kernel oil.

2.5.1 Trace Essential and Non-Essential Minerals in Palm Kernel Seed Oil

Vegetable oils like palm kernel oil are not primary mineral sources due to their lipophilic nature, favoring fats over water-soluble or mineral components. Extraction processes—mechanical pressing or solvent-based—separate the oil from the kernel's solid matrix, leaving most minerals in the palm kernel meal (PKM) (Sundram *et al.,* 2019). Trace minerals enter the oil through environmental factors (e.g., soil, water, air), agricultural inputs (e.g., fertilizers), or processing equipment. Refining steps—degumming, bleaching, neutralization, and deodorization—reduce these levels to parts per billion (ppb) or low parts per million (ppm), yielding a purified product (Gunstone, 2020). The minerals of interest—iron, zinc, copper, cadmium, nitrogen, and mercury—span essential and non-essential categories, each with distinct biochemical roles and implications for oil quality and human health.

2.5.2 Iron

Iron, an essential trace mineral, is detectable in crude palm kernel oil at 0.1–5 ppm, primarily from contamination via iron-based equipment like mills or storage tanks (Ofori-Boateng and Lee, 2016). Refining reduces this to below 0.1 ppm, aligning with Codex standards (Pantzaris and Basiron, 2017). Biochemically, iron is a cornerstone of human metabolism, integral to hemoglobin and myoglobin for oxygen transport, cytochrome enzymes in the electron transport chain for ATP production, and antioxidant defenses via catalase and peroxidase (Abbaspour *et al.,* 2015). It cycles between ferrous (Fe^{2+}) and ferric (Fe^{3+}) states, enabling redox reactions critical to cellular respiration.

In palm kernel oil, iron's biochemical role shifts to a pro-oxidant function. It catalyzes lipid peroxidation by generating reactive oxygen species (ROS) like hydroxyl radicals via the Fenton reaction ($Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^- + OH\cdot$), oxidizing fatty acids and producing hydroperoxides (Tan et al., 2017). These degrade into aldehydes, causing rancidity and reducing shelf life. Though palm kernel oil's high saturation (80–85%) mitigates this compared to unsaturated oils, iron's presence remains a quality concern, necessitating refining to minimize oxidative damage. Nutritionally, its trace levels (micrograms per serving) are insignificant compared to the 8–18 mg daily requirement, offering no dietary benefit.

2.5.3 Zinc

Zinc appears in crude palm kernel oil at 0.01–0.5 ppm, sourced from soil uptake or galvanized equipment, dropping to near-undetectable levels post-refining (Sundram *et al.,* 2019). Biochemically, zinc is a cofactor for over 300 enzymes, including superoxide dismutase (SOD), which neutralizes superoxide radicals, protecting cells from oxidative stress (Prasad, 2017). It stabilizes protein structures (e.g., zinc fingers in DNA-binding proteins) and supports immune function, wound healing, and cell division. Zinc's redox inactivity distinguishes it from iron and copper, as it does not directly participate in electron transfer but modulates enzymatic activity via structural roles.

In the oil, zinc's biochemical function as a mild pro-oxidant emerges, though less potent than iron or copper. It can weakly catalyze lipid peroxidation by interacting with peroxides, contributing to oxidative stress over time (Gunstone, 2020). This effect is minimal due to its low concentration and the oil's saturated nature, but it justifies monitoring in crude oil to prevent stability issues. Nutritionally, zinc's trace presence is negligible against the 8–11 mg daily requirement, rendering it irrelevant as a dietary source in palm kernel oil.

2.5.4 Copper

Copper, present at 0.01–0.1 ppm in crude palm kernel oil and below 0.05 ppm in refined oil, originates from copper-alloy equipment (Ofori-Boateng and Lee, 2016). Biochemically, copper is essential for redox-active enzymes, such as cytochrome c oxidase in mitochondrial ATP synthesis, SOD for antioxidant defense, and lysyl oxidase for connective tissue formation (Uriu-Adams and Keen, 2015). It shuttles between Cu^+ and Cu^{2+} states, facilitating electron transfer in metabolic pathways, including iron mobilization via ceruloplasmin.

In palm kernel oil, copper's redox activity makes it a potent pro-oxidant, accelerating lipid peroxidation more aggressively than iron or zinc. It generates ROS via reactions like $Cu^+ + H_2O_2 \rightarrow Cu^{2+} + OH^- + OH\cdot$, breaking down fatty acids into volatile compounds that impair quality (Tan et al., 2017). Despite the oil's saturation reducing this risk, copper's presence affects stability in applications like frying, necessitating levels below 0.1 ppm per Codex guidelines (Pantzaris and Basiron, 2017). Its nutritional contribution (0.9 mg/day requirement) is trivial at these levels, overshadowed by its quality implications.

2.5.5 Cadmium

Cadmium, a non-essential heavy metal, is found in crude palm kernel oil below 0.01 ppm, introduced via contaminated soil, water, or fertilizers, and removed to undetectable levels by refining (Sundram *et al.,* 2019). Biochemically, cadmium has no beneficial role in humans but exerts toxicity by mimicking essential metals like zinc and calcium. It binds to metallothionein, disrupting enzyme function, and inhibits antioxidant enzymes (e.g., SOD, catalase), increasing ROS and oxidative damage (Cuypers *et al.,* 2016). Chronic exposure damages kidneys (via tubular dysfunction) and bones (via calcium displacement), making it a public health concern.

In palm kernel oil, cadmium's biochemical impact is negligible due to its low concentration and removal during refining, meeting European Union (EU) limits of 0.1 ppm (Abdullah *et al.,* 2021). It does not affect oil stability or quality directly, as it lacks pro-oxidant activity in this context, but its potential presence reflects environmental contamination risks. Cadmium's toxicity underscores the need for sustainable farming to prevent its entry, though it poses no practical issue in the oil itself.

2.5.6 Nitrogen

Nitrogen in palm kernel oil exists not as a free mineral but within organic compounds like residual proteins or amines, with levels below 0.01 ppm in crude oil and nearly absent in refined forms (Gunstone, 2020). Biochemically, nitrogen is a fundamental element in amino acids, proteins, and nucleotides, essential for protein synthesis, enzyme function, and DNA replication (Marschner, 2015). In plants, it supports growth via chlorophyll and amino acid production, but in oil, it reflects trace organic residues rather than free nitrogen.

In palm kernel oil, nitrogen has no direct biochemical function, as it is not metabolically active in this form. It does not influence stability or quality, unlike pro-oxidant metals, and is more significant in PKM, where proteins (14–20%) provide nitrogen for animal nutrition (Sundu *et al.,* 2020). Its presence indicates extraction efficiency rather than a mineral role, making it a minor consideration compared to true metallic elements.

2.5.7 Broader Mineral Context and Implications

Other minerals like calcium, magnesium, or potassium may occur below 0.1 ppm in refined palm kernel oil, concentrating more in PKM (Sundu *et al.,* 2020). Essential minerals—iron, zinc, copper—drive biochemical functions in humans (e.g., redox reactions, enzyme activity) but are nutritionally insignificant in the oil, instead affecting quality as pro-oxidants. Non-essential minerals—cadmium, mercury—disrupt biochemical pathways toxically but are negligible here, while nitrogen ties to organic residues without functional impact. This profile highlights palm kernel oil's lipid focus, with refining optimizing stability and safety.

2.6 Factors Influencing Mineral Composition of Palm Kernel Seed Oil

The mineral composition of palm kernel seed oil, derived from the kernel of the oil palm (*Elaeis guineensis*), is shaped by a variety of environmental, agricultural, and processing factors. Although this oil contains only trace amounts of minerals—such as iron (Fe), zinc (Zn), copper (Cu), cadmium (Cd), and nitrogen (N)—measured in parts per million (ppm) or parts per billion (ppb), these levels are not intrinsic to the kernel itself but are introduced through external influences during cultivation, harvesting, and production. Understanding these factors is essential for controlling the oil's quality, ensuring its safety for consumption, and maintaining its stability for applications in food, cosmetics, and industrial products.

2.6.1 Environmental Factors

Environmental conditions play a foundational role in determining the mineral content of palm kernel seed oil. Soil composition is a critical factor, as oil palms absorb minerals like iron (Fe), zinc (Zn), and copper (Cu) from the soil through their root systems. Soils naturally rich in these elements, due to geological features or weathering processes, can increase their availability to the plant, though most minerals remain concentrated in the kernel's solid matrix rather than transferring significantly into the oil (Sundram *et al.,* 2019). Contaminated soils, particularly in regions near industrial activities or mining operations, may introduce toxic heavy metals such as cadmium (Cd). These contaminants can be translocated to the kernel in minute quantities, influenced by soil pH, organic matter content, and metal bioavailability (Abdullah *et al.,* 2021). Water quality, including irrigation sources or rainfall, also contributes; polluted water containing heavy metals can deposit these elements into the plant system. Additionally, atmospheric deposition—such as dust, particulate matter, or pollutants from nearby factories or vehicular emissions—can settle on palm fruits, further elevating trace mineral levels, especially in open plantations exposed to industrial zones (Ofori-Boateng and Lee, 2016).

2.6.2 Agricultural Practices

Agricultural practices directly impact the mineral profile of palm kernel seed oil. Fertilizers, widely applied to boost oil palm productivity, often contain micronutrients like zinc (Zn) and copper (Cu), intentionally added to address soil deficiencies and enhance growth. These can increase the mineral content in the kernel, though the oil retains only traces (Pantzaris and Basiron, 2017). Conversely, phosphate fertilizers may inadvertently introduce cadmium (Cd) as an impurity, a common issue in regions with lax regulatory oversight, posing contamination risks if not carefully managed. Pesticides or fungicides, such as copper-based compounds (e.g., copper oxychloride), used to combat pests and diseases, can elevate copper (Cu) levels in the plant, some of which may persist into the kernel (Gunstone, 2020). Cultivation techniques, including soil tillage, crop rotation, and irrigation practices, influence mineral availability; intensive farming may deplete essential minerals over time or accumulate toxins in the soil, indirectly affecting the kernel's composition. The frequency and timing of fertilizer application also matter—overuse can lead to higher metal uptake, while balanced practices minimize such risks (Sundu *et al.,* 2020).

2.6.3 Processing Techniques

Processing techniques are arguably the most significant determinants of the final mineral composition in palm kernel seed oil. During extraction—whether through mechanical pressing or solvent methods—minerals from the kernel can migrate into the crude oil, though the majority remain in the palm kernel meal (PKM) due to their affinity for the solid phase (Sundu *et al.,* 2020). The type and condition of processing equipment heavily influence this transfer. Iron (Fe) and copper (Cu) often leach from steel or alloy machinery, particularly if corrosion occurs, while zinc (Zn) may originate from galvanized surfaces or worn equipment parts (Tan *et al.,* 2017). Refining processes—degumming, bleaching, neutralization, and deodorization—dramatically reduce mineral levels, often to below 0.1 ppm, by employing adsorbents like activated clay or silica to remove impurities (Gunstone, 2020). The intensity and sequence of these steps, along with equipment maintenance (e.g., using stainless steel to minimize leaching), dictate the extent of mineral retention. Storage conditions post-extraction, such as the use of metal versus inert containers, can also introduce contaminants like iron (Fe) if rust is present (Ofori-Boateng and Lee, 2016).

2.6.4 Additional Factors

Beyond these primary influences, additional factors contribute to mineral composition. Genetic variations among oil palm cultivars may affect mineral uptake efficiency, though this impact is subtle compared to environmental and processing effects. The maturity of the palm fruit at harvest influences kernel development, potentially altering mineral distribution, albeit marginally. Post-harvest handling such as storage duration, temperature, and hygiene—can introduce contaminants if kernels are exposed to unclean surfaces or prolonged moisture, encouraging metal leaching (Pantzaris and Basiron, 2017). Together, these factors—environmental conditions, agricultural practices, processing techniques, and secondary influences—collectively determine the trace mineral profile of palm kernel seed oil, with refining serving as the final control point to ensure minimal levels for optimal quality and safety.

2.7 Analytic Techniques for Mineral Composition in Oils

The determination of mineral composition in oils, such as palm kernel seed oil derived from *Elaeis guineensis*, is critical for assessing quality, safety, and compliance with regulatory standards. Minerals like iron (Fe), zinc (Zn), copper (Cu), cadmium (Cd), and nitrogen (N) are present in trace amounts—often in parts per million (ppm) or parts per billion (ppb)—and their accurate quantification requires sophisticated analytical techniques. These methods must address challenges posed by the oil's lipophilic matrix, low mineral concentrations, and potential interferences from organic components. This discussion explores the primary analytic techniques used for mineral analysis in oils, including atomic absorption spectroscopy (AAS), inductively coupled plasma mass spectrometry (ICP-MS), inductively coupled plasma optical emission spectroscopy (ICP-OES), X-ray fluorescence (XRF), neutron activation analysis (NAA), and wet chemistry methods, detailing their principles, applications, advantages, and limitations.

2.7.1 Atomic Absorption Spectroscopy (AAS)

Atomic Absorption Spectroscopy (AAS) is a widely used technique for detecting trace metals in oils, such as iron (Fe), zinc (Zn), and copper (Cu). It operates on the principle that atoms in the ground state absorb light at specific wavelengths corresponding to their electronic transitions. In AAS, the oil sample is typically prepared by ashing (dry or wet) to remove organic matter, followed by dissolution in an acid solution (e.g., nitric acid [HNO_3]). The resulting solution is atomized in a flame or graphite furnace, and a light source (hollow cathode lamp) emits wavelengths unique to each element, which are absorbed by the atomized sample (Gunstone, 2020). The absorbance is proportional to the mineral concentration, calibrated against standards.

AAS is highly sensitive, with detection limits in the ppb range for graphite furnace AAS, making it ideal for trace analysis in oils (Tan *et al.,* 2017). It is cost-effective and widely available, suitable for routine analysis of essential metals like iron (Fe) and copper (Cu) that affect oil stability. However, it analyzes one element at a time, requiring separate lamps and calibrations, which can be time-consuming for multi-element analysis. Sample preparation is labor-intensive, and organic residues may cause matrix interferences if not fully removed.

2.7.2 Inductively Coupled Plasma Mass Spectrometry (ICP-MS)

Inductively Coupled Plasma Mass Spectrometry (ICP-MS) is a powerful technique for multi-element analysis of minerals in oils, including iron (Fe), zinc (Zn), copper (Cu), cadmium (Cd), and mercury (Hg). It uses a high-temperature argon plasma (approximately 6000–10,000 K) to ionize the sample, which is then introduced as an aerosol after digestion (e.g., microwave-assisted digestion with HNO_3). The ions are separated by mass-to-charge ratio in a mass spectrometer, typically a quadrupole or time-of-flight system, and detected with exceptional sensitivity—detection limits in the parts per trillion (ppt) range (Sundram *et al.,* 2019).

ICP-MS excels in its ability to simultaneously quantify multiple elements, making it efficient for comprehensive mineral profiling in oils. Its high sensitivity and low detection limits are ideal for toxic metals like cadmium (Cd) and mercury (Hg), which require stringent monitoring for safety (Abdullah et al., 2021). However, it is expensive, requiring skilled operators and maintenance, and matrix effects from residual carbon or polyatomic interferences (e.g., argon oxide [ArO^+] mimicking iron [Fe^+]) can complicate results, necessitating careful sample preparation and calibration with matrix-matched standards.

2.7.3 Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES)

Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), also known as ICP-Atomic Emission Spectroscopy (ICP-AES), is another multi-element technique used for mineral analysis in oils. Like ICP-MS, it employs an argon plasma to excite atoms and ions in the sample, which emit light at characteristic wavelengths upon returning to their ground state. The emitted light is detected by an optical spectrometer, and intensity is correlated to concentration (Ofori-Boateng and Lee, 2016). Sample preparation mirrors ICP-MS, involving acid digestion to break down the oil matrix.

ICP-OES offers detection limits in the low ppb to ppm range, suitable for elements like iron (Fe), zinc (Zn), and copper (Cu) in palm kernel seed oil. It is less sensitive than ICP-MS but more robust for higher concentrations and less prone to polyatomic interferences, making it a practical choice for routine quality control (Pantzaris and Basiron, 2017). Its simultaneous multi-element capability enhances efficiency, though it requires larger sample volumes and may struggle with ultra-trace elements like mercury (Hg). Equipment costs are moderate compared to ICP-MS, balancing sensitivity and accessibility.

2.7.4 X-Ray Fluorescence (XRF)

X-Ray Fluorescence (XRF) is a non-destructive technique for mineral analysis in oils, applicable to elements like iron (Fe), zinc (Zn), and copper (Cu). It works by irradiating the sample with high-energy X-rays, causing inner-shell electrons to be ejected. Outer-shell electrons then fill these vacancies, emitting fluorescent X-rays at wavelengths unique to each element, which are detected and quantified (Gunstone, 2020). For oils, samples can be analyzed directly (e.g., in a liquid cell) or after ashing to concentrate minerals.

XRF is rapid and requires minimal sample preparation, making it attractive for high-throughput analysis. It detects a broad range of elements simultaneously, with detection limits in the ppm range, suitable for quality assessments in oils (Tan *et al.,* 2017). However, its sensitivity is lower than ICP-MS or AAS, limiting its use for ultra-trace elements like cadmium (Cd) or mercury (Hg). Matrix effects from the oil's organic components can also reduce accuracy, often requiring calibration with oil-specific standards. Portable XRF units enhance field applicability, though laboratory-grade systems offer greater precision.

2.7.5 Neutron Activation Analysis (NAA)

Neutron Activation Analysis (NAA) is a highly sensitive technique for detecting trace minerals in oils, including iron (Fe), zinc (Zn), copper (Cu), cadmium (Cd), and mercury (Hg). It involves irradiating the sample with neutrons in a nuclear reactor, causing atomic nuclei to capture neutrons and become radioactive isotopes. These isotopes decay, emitting gamma rays at characteristic energies, which are measured with a gamma spectrometer (Sundram *et al.,* 2019). Oils may be analyzed directly or after drying to minimize hydrogen interference.

NAA offers exceptional sensitivity (ppt to ppb range) and specificity, requiring little sample preparation, as it is unaffected by the organic matrix (Ofori-Boateng and Lee, 2016). It is ideal for multi-element analysis and ultra-trace detection, such as mercury (Hg) in safety assessments. However, its reliance on a neutron source (e.g., reactor) makes it expensive and inaccessible for routine use, limiting it to specialized research settings. The radioactive nature of samples post-analysis also poses handling challenges, reducing its practicality for oil industries.

2.7.6 Wet Chemistry Methods

Wet chemistry methods, such as colorimetric or titrimetric techniques, are traditional approaches for mineral analysis in oils, often used for nitrogen (N) or specific metals. For nitrogen (N), the

Kjeldahl method is common: the sample is digested with sulfuric acid (H_2SO_4) to convert organic nitrogen (N) to ammonium (NH_4^+), which is then titrated to quantify total nitrogen (N) (Gunstone, 2020). For metals like iron (Fe) or copper (Cu), colorimetric methods involve ashing the oil, dissolving it in acid, and reacting it with reagents (e.g., 1.10-phenanthroline for iron [Fe]) to form colored complexes measured spectrophotometrically (Pantzaris and Basiron, 2017).

These methods are inexpensive and accessible, suitable for nitrogen (N) in crude oils or single-element analysis in resource-limited labs. However, they lack the sensitivity (ppm range) and multi-element capability of modern techniques, and digestion processes are time-consuming and prone to contamination (Tan *et al.,* 2017). They are less common today, overshadowed by instrumental methods for trace mineral analysis.

2.7.7 Practical Considerations and Applications

Selecting an analytic technique depends on the target minerals, required sensitivity, and available resources. For palm kernel seed oil, ICP-MS and ICP-OES are preferred for comprehensive profiling, detecting both essential metals (iron [Fe], zinc [Zn], copper [Cu]) affecting stability and toxic elements (cadmium [Cd] for safety (Abdullah *et al.,* 2021). AAS is practical for routine monitoring of pro-oxidant metals, while XRF suits rapid, non-destructive screening. NAA is reserved for research requiring ultra-trace precision, and wet chemistry persists for nitrogen (N) or basic assessments. Sample preparation—ashing or digestion—is a common prerequisite, except for XRF and NAA, and must minimize contamination (e.g., using high-purity acids). Calibration with certified standards ensures accuracy, particularly for regulatory compliance (e.g., Codex Alimentarius limits).

2.7.8 Advantages and Limitations

AAS offers sensitivity and affordability but is slow for multi-element analysis. ICP-MS provides unmatched sensitivity and versatility, though at high cost and complexity. ICP-OES balances sensitivity and robustness, ideal for routine use, but struggles with ultra-trace levels. XRF is fast and non-destructive, yet less sensitive, while NAA excels in precision but is impractical for widespread use. Wet chemistry is simple but outdated for trace analysis. Each technique's strengths and limitations dictate its role in oil mineral analysis, with modern methods like ICP-MS and ICP-OES dominating due to their comprehensive capabilities.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Apparatus and Reagents

The apparatus and reagents used in the analysis of iron, zinc, copper, cadmium, nitrogen, and mercury in palm kernel seed oil included a 50-milliliter (ml) conical flask from Pyrex (United Kingdom), a digestion block/heater (Model DBH-2000, LabTech, China), a 100-ml volumetric flask from Pyrex (United Kingdom), Whatman filter paper No. 42 from Whatman (United Kingdom), funnels from Pyrex (United Kingdom), a Pg Instrument AA500F Atomic Absorption Spectrometer from Pg Instruments (United Kingdom), a blender (Model BL-500, Philips, Netherlands), a refrigerator (Model RF-300, LG, South Korea), a glass petri dish from Pyrex (United Kingdom), an analytical balance (Model AB-204-S, Mettler Toledo, Switzerland), a mortar and pestle from local manufacture (Nigeria), a hot plate with magnetic stirrer (Model HP-200, IKA, Germany), pipettes of 1 ml and 10 ml from Eppendorf (Germany), graduated cylinders from Pyrex (United Kingdom), a fume hood (Model FH-1500, Labconco, USA), an oven (Model OVN-100, Memmert, Germany), and a Milli-Q water purification system from Millipore (USA), along with nitric acid (HNO_3) with batch number HNO_3-2023-001 from Sigma-Aldrich (USA), perchloric acid ($HClO_4$) with batch number $HClO_4$-2023-002 from Sigma-Aldrich (USA), 1000 milligrams per liter (mg/l) stock standards of iron (Fe) with batch number Fe-2023-101 from Merck (Germany), zinc (Zn) with batch number Zn-2023-102 from Merck (Germany), copper (Cu) with batch number Cu-2023-103 from Merck (Germany), cadmium (Cd) with batch number

Cd-2023-104 from Merck (Germany), nitrogen (N) with batch number N-2023-105 from Merck (Germany), and hydrochloric acid (HCl) from Sigma-Aldrich (USA).

3.2 Collection of Plant

Palm kernels were procured from New Benin Market in Benin Metropolis, Edo State, Nigeria. This local market provided a sample that mirrored traditional processing practices in the region, ensuring that the study captured the characteristics of palm kernel seed oil as produced and consumed locally.

3.3 Processing of the Seeds

The processing of palm kernels involved several steps to extract palm kernel seed oil for the analysis of iron, zinc, copper, cadmium, and nitrogen. Unwanted materials, such as stones and dirt, were meticulously removed from the dehulled kernels by hand-picking, establishing a clean foundation for subsequent steps. The decorticated kernels were heated in water at approximately 96°C for 10 minutes, softening them to facilitate oil extraction. The kernels were then spread out under the sun to dry, reducing their moisture content to about 5–7% on a dry basis (db), a critical step to prevent spoilage and prepare them for grinding. Grinding was performed using a manually operated grinding machine, transforming the dried kernels into a smooth paste. This paste was mixed with water in a proportion of 1 kilogram (kg) of paste to 2 liters (l) of water, creating a slurry conducive to oil separation. The mixture was cooked over an open fire, evaporating the water until the paste thickened, and palm kernel seed oil emerged, settling on the surface. The extracted oil was carefully scooped into a separate container, while the remaining cake was collected for drying. The scooped oil underwent additional heating to eliminate residual moisture, producing a refined palm kernel seed oil sample suitable for analysis.

3.4 Methods

The methods employed to test for iron, zinc, copper, cadmium, and nitrogen in the palm kernel seed oil included sample processing, digestion, calibration, and analysis, all documented in the past tense to reflect completed actions.

3.4.1 Sample Processing

The palm kernel seed oil sample was placed in a glass petri dish and dried in an oven at 105°C for 24 hours, removing moisture that could interfere with digestion. After drying, any lumps were broken apart with a clean glass rod to ensure the interior was fully exposed for complete drying. The dried sample was ground into a fine powder using a mortar and pestle, increasing its surface area for effective digestion.

3.4.2 Digestion Procedure

The digestion process started when 1 g of the ground sample was weighed into a 50-ml conical flask using an analytical balance. Ten milliliters (ml) of the HNO_3-$HClO_4$ mixture (prepared in a ratio of 150 ml HNO_3 to 50 ml $HClO_4$) was added, and the mixture soaked overnight to initiate organic breakdown. A small glass funnel was inserted as a reflux condenser to retain volatile compounds, and the flask was heated on a digestion block at 150°C for 1 hour. The temperature was gradually increased to 235°C, and when dense white fumes appeared—indicating the action of perchloric acid—heating continued for an additional 2 hours. The sample was removed from the block, cooled to approximately 100°C, and 1 ml of 1:1 hydrochloric acid (HCl) was added. Heating resumed until white fumes reappeared and a colorless solution was obtained, confirming complete digestion. The solution was filtered into a 100-ml volumetric flask through Whatman No. 42 filter paper, and the flask was washed and rinsed five times with distilled water produced by the Milli-Q system to reach the final volume. Blank samples were prepared using the same procedure without oil, serving as a control for reagent purity. We assay the filtrates for iron, zinc, copper, cadmium, nitrogen, and mercury using Atomic Absorption Spectroscopy (AAS).

3.5 Calibration and Analysis

Calibration commenced when single-element standards were prepared by diluting 1000 mg/l stock solutions of iron (Fe), zinc (Zn), copper (Cu), cadmium (Cd), and nitrogen (N) into a minimum of five working solutions ranging from 0.1 mg/l to 10 mg/l, using deionized water from the Milli-Q system. External calibration was performed by running deionized water followed by the suite of calibration standards for each element on the AAS, generating a calibration curve based on absorbance values for each metal. The digested samples and blank were then run on the AAS, and absorbance readings were recorded. Concentrations of iron, zinc, copper, cadmium, and nitrogen in the sample were calculated from the calibration curve's equation (e.g., $y = mx + b$, where y represented absorbance and x represented concentration).

3.6 Quality Assurance

Quality assurance measures were implemented to ensure result reliability. Acidified deionized water from the Milli-Q system was aspirated as blanks to establish a baseline, analyses were conducted in duplicates to confirm precision, and laboratory control samples were run as quality control (QC) samples to validate accuracy, minimizing errors from contamination or instrument variability.

CHAPTER FOUR

RESULTS

4.1 Results

The mineral composition of palm kernel seed oil was analyzed to determine its micronutrient content and compliance with EU standards. The results, presented in Table 4.1, include essential trace elements and a comparison with EU regulatory limits.

Table 4.1: Mineral Analysis of Palm Kernel Seed Oil Compared with EU Standards

Parameters (mg/100g)	Palm Kernel Seed Oil	EU Standard Limit (mg/100g)
Iron (Fe)	2.23 ± 0.21	No established limit
Zinc (Zn)	1.86 ± 0.04	No established limit
Copper (Cu)	0.64 ± 0.49	0.40–1.50
Cadmium (Cd)	0.00 ± 0.00	≤0.10

The EU does not specify maximum limits for essential micronutrients like iron and zinc in edible oils but regulates toxic metals such as cadmium.

The results highlight a distinct micronutrient profile. Iron (2.23 mg/100g) and zinc (1.86 mg/100g) are present at beneficial levels, though the EU does not impose limits on these essential elements. Copper (0.64 mg/100g) falls within the EU permissible range (0.40–1.50 mg/100g), confirming compliance with safety standards. Importantly, cadmium was undetected (0.00 mg/100g), aligning with EU regulations (≤0.10 mg/100g), ensuring the oil is free from toxic contamination.

A bar chart (Figure 2) visually compares the micronutrient content of palm kernel seed oil with EU limits, reinforcing its nutritional potential and safety.

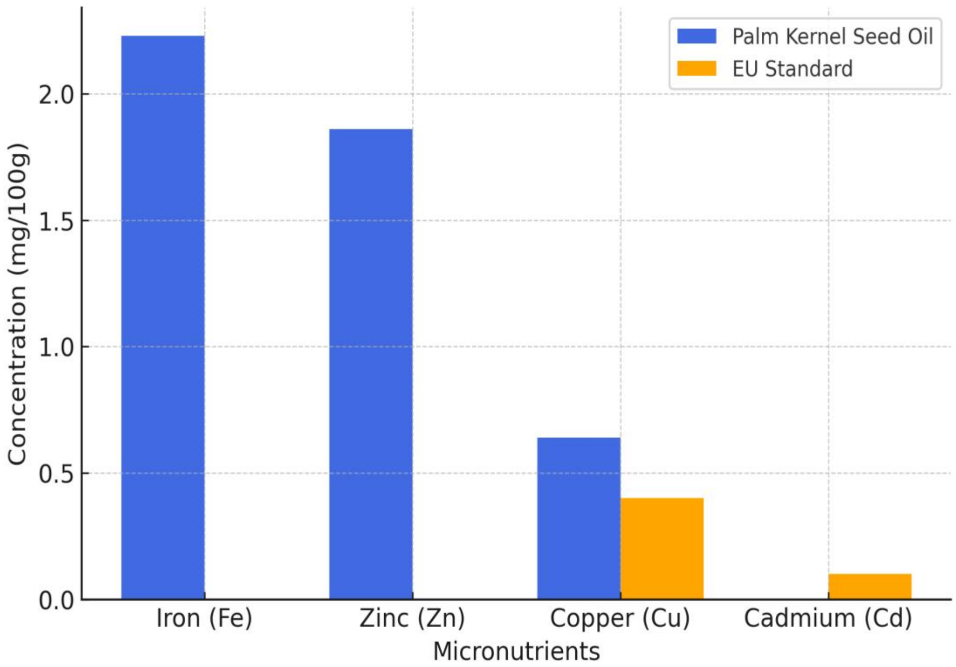

Figure 2: Comparison of Micronutrient Content in Palm Kernel Seed Oil with EU Standards

CHAPTER FIVE

DISCUSSION AND CONCLUSION

5.1 Dicussion

The findings from this study provide valuable insights into the micro-mineral composition of palm kernel seed oil (PKSO) and its compliance with food safety standards. The results indicate that PKSO contains essential trace elements, including iron (Fe), zinc (Zn), and copper (Cu), which contribute to its nutritional value. Additionally, the absence of cadmium (Cd) confirms its safety concerning toxic metal contamination.

Iron plays a fundamental role in biological functions, primarily as a component of hemoglobin responsible for oxygen transport. The presence of Fe (2.23 ± 0.21 mg/100g) in PKSO is beneficial, but its concentration suggests that additional dietary sources may be required to meet daily nutritional needs. Similarly, zinc, detected at 1.86 ± 0.04 mg/100g, is vital for immune function, enzymatic activities, and cellular growth. While there are no specific European Union (EU) limits for Fe and Zn in edible oils, their presence in PKSO contributes positively to dietary intake.

Copper, an essential trace element found at 0.64 ± 0.49 mg/100g, falls within the EU regulatory range (0.40–1.50 mg/100g), ensuring its safety and nutritional adequacy. Copper plays a crucial role in enzymatic reactions, iron metabolism, and connective tissue formation. The balanced presence of these micro-minerals in PKSO suggests its potential as a supplementary dietary source, contributing to overall nutritional well-being.

One of the major concerns in edible oil production is the risk of contamination with toxic heavy metals, which pose significant health hazards. The absence of detectable cadmium (0.00 ± 0.00 mg/100g) in PKSO confirms that it meets EU safety standards, reinforcing its suitability for human consumption. Exposure to cadmium, even at trace levels, has been associated with kidney dysfunction, carcinogenic effects, and metabolic disruptions. The lack of this toxic metal in

PKSO underscores its safety and highlights the importance of stringent quality control measures in oil processing.

Despite the presence of essential micro-minerals, the moderate levels of Fe and Zn in PKSO indicate that it should not be relied upon as the sole dietary source of these nutrients. A diversified diet incorporating multiple nutrient-rich food sources is necessary to achieve optimal nutritional balance. Furthermore, considering the potential for environmental contamination, periodic quality assessments and regulatory supervision are essential to maintain the safety and integrity of edible oils. Future research should explore regional variations in PKSO’s mineral composition to determine the influence of environmental factors on its nutritional profile. Additionally, further studies should expand the scope of analysis to include other toxic metals such as mercury (Hg) to ensure a more comprehensive assessment of PKSO's safety.

5.2 Conclusion

In conclusion, this study underscores the nutritional significance and safety of PKSO as an edible oil containing essential trace elements. Its compliance with EU safety regulations, particularly in terms of cadmium content, reinforces its suitability for human consumption. However, continuous monitoring and further investigations are necessary to ensure its long-term safety and nutritional adequacy in diverse dietary contexts.

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