INVESTIGATION OF THE PRESERVATION TECHNIQUES FOR PERISHABLE FOOD COMMODITIES THROUGH A COMPARATIVE STUDY OF OKRA, TOMATO, AND FISH.

BY

IDAH PAUL ANOSI

ENG2002036

OCTOBER, 2025.

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A PROJECT SUBMITTED TO THE DEPARTMENT OF CHEMICAL ENGINEERING, FACULTY OF ENGINEERING, UNIVERSITY OF BENIN, BENIN CITY IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF BACHELOR DEGREE IN CHEMICAL ENGINEERING

(B.ENG.)

OCTOBER, 2025.

CERTIFICATION

This serves as confirmation that the mentioned study was carried out by **IDAH PAUL ANOSI** with matriculation number **ENG2002036**, who is associated with the Chemical Engineering Department at the University of Benin, situated in Benin City, Edo State, Nigeria.

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EXTERNAL EXAMINER Date

DEDICATION

I want to dedicate this project work to God Almighty, whose grace, wisdom, and strength made this work possible. To Him be all the glory, honor, and praise. To my family, who taught me the value of hard work and curiosity. Thank you for the countless late-night calls and the constant encouragement to pursue knowledge. Lastly, to the undergraduate student I was when this project began. May this serve as proof that discipline, curiosity, and sheer willpower can conquer any challenge.

ACKNOWLEDGEMENT

I extend my sincere gratitude to my supervisor, Professor E.O Aluyor, for his patience, constructive feedback, and tireless dedication in guiding me throughout this research. His expertise, insightful recommendations, and constant encouragement played a pivotal role in ensuring the successful completion of this work. I truly appreciate his time and effort in refining my research and pushing me toward academic excellence. Also, I want to appreciate the staff of the department of chemical engineering for their unwavering support towards seeing that my undergraduate journey becomes a success, especially Dr. Fred whose unwavering support, mentorship, and encouragement have been a beacon of hope and inspiration. His invaluable guidance over the years has not only shaped my academic path but also instilled in me the discipline, resilience, and determination needed to pursue excellence. His generosity and unwavering belief in my abilities have made my academic pursuit purposeful, and for that, I am forever grateful.

I am profoundly thankful to my Dear father, who have been a spiritual pillar and a source of encouragement in my life. His prayers, wisdom, and unwavering support have strengthened me, especially during moments of doubt and difficulty. Special recognition goes to Japari Lucas, Imafidon Kenneth, Asani Damilola, Akhade Daniel, and Jude Miracle. These remarkable individuals stood by me during my darkest days, offering their support, encouragement, and friendship when I needed it the most. Their unwavering belief in me, along with their constant words of motivation, have been invaluable in my journey. I am truly blessed to have them as part of my life.

Lastly, to everyone who, in one way or another, contributed to the success of this project, whether through prayers, words of encouragement, technical assistance, or moral support, I extend my deepest appreciation. Your contributions have not gone unnoticed, and I remain forever grateful.

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ABSTRACT

Postharvest spoilage of perishable crops such as okra (*Abelmoschus esculentus*), tomato (*Solanum lycopersicum*), and fish (*Clarias gariepinus*) remains a major challenge in Nigeria, leading to food waste, economic loss, and reduced availability of nutrient-rich food. This study aimed to evaluate the effectiveness of an effective preservative method for these commodities and to monitor changes in their nutritional composition during storage by determining optimal preservative parameters, evaluating variations in key nutrients, including protein, carbohydrate, and vitamin C.

Controlled oven-drying was carried out for the three samples at 60°C to ensure uniform heat transfer while preventing oxidative degradation. Moisture, protein, carbohydrate, and vitamin C contents were analyzed using standard laboratory methods. Drying kinetics were studied using first-order reaction models, and the Arrhenius equation was used to estimate the activation energy (Ea) for moisture diffusion. These analyses provided insights into both drying efficiency and nutrient stability across the three samples.

Results revealed that drying significantly reduced the moisture content of all samples, improving shelf life and reducing microbial activity. Protein content increased slightly in fish (24.72 to 25.61%), okra (2.73 to 2.75%), and tomato (1.62 to 1.65%) due to moisture concentration effects. Vitamin C decreased considerably, ranging from 40 to 80% losses, confirming its thermolabile nature, while carbohydrates remained largely stable. Fish further exhibited a distinct drying kinetics, following first-order behavior with drying rate constants (k) of 0.0153, 0.0189, and 0.0191 min^{-1} at 60°C, 80°C, and 100°C, respectively. The calculated activation energy of 6.093 kJ/mol indicated a moderate energy requirement, suggesting that moisture removal occurred primarily through surface evaporation and mild internal diffusion. These findings demonstrate that moderate drying temperatures around 60°C can preserve nutritional quality while enhancing product stability, making them suitable for industrial processing in tropical environments while higher temperature i.e 100°C will result in higher moisture loss.

CHAPTER ONE

1.1. Background of Study

The agricultural sector continues to play a pivotal role in the economic and nutritional security of nations, especially in developing countries like Nigeria (Akpabio *et al*., 2025). Among the various agricultural commodities, vegetables and fish stand out not only as staple food items but also as vital sources of livelihood, foreign exchange, and essential nutrients required for human health and development (Kafui *et al*., 2022; Saba et al., 2024). Vegetables such as okra and tomato are recognized for their high content of vitamins (A, B, C, and K), minerals (such as calcium and iron), fiber, and bioactive compounds that contribute to reducing the risks of chronic diseases like cancer, diabetes, and cardiovascular conditions (Elkhalifa *et al*., 2021; Dantas *et al*., 2021; El-Shaieny *et al*., 2022; Ummah, 2019). Similarly, fish, particularly freshwater and marine species widely consumed in Nigeria, are rich in high-quality proteins, omega-3 fatty acids, vitamin D, iodine, and other essential micronutrients that are crucial for brain development, cardiovascular health, and immune function (Awuchi et al., 2022a; Demelash Abera & Alefe Adimas, 2024).

One of the most economically and nutritionally important vegetables in the tropical and subtropical regions is okra (*Abelmoschus esculentus* L.), popularly known as lady's finger (Al-Dabbas *et al*., 2023). Widely cultivated in Nigeria, okra is highly adaptable to various soil types, grows relatively quickly, and is well-suited to hot and humid climates (Dantas *et al*., 2021). Its agronomic features, such as a short maturity period, drought resistance, and minimal input requirements, make it an ideal crop for both smallholder farmers and large-scale producers (Kafui *et al*., 2022). Nutritionally, okra contains approximately 86.1% moisture, 9.7% carbohydrates, 2.25% protein, 1.0% fiber, 0.2% fat, and 9% ash, along with significant levels of

vitamins A, B, C, and iodine (Kafui *et al*., 2022). It is an excellent source of dietary fiber, comprising both soluble (pectin and gums) and insoluble fiber, which aids digestion, stabilizes blood glucose levels, and lowers cholesterol (Jannah *et al*., 2025). The mucilage in okra, which gives it a slimy texture when cooked, has medicinal and functional properties. It is known to bind bile acids and toxins in the gut, promote smooth bowel movement, and serve as a plasma replacement in medical applications (Badmus *et al*., 2019).

Tomato (*Solanum lycopersicum* L.), another key vegetable crop, is widely grown in Nigeria and is a dietary staple in soups, stews, and sauces (Wakene & Sharew, 2024). It is rich in lycopene, a powerful antioxidant, along with vitamins C, E, and potassium, which contribute to reducing oxidative stress and lowering the risk of chronic diseases (Liu et al., 2022; Wakene & Sharew, 2024). Tomato farming supports a large segment of rural households and generates substantial seasonal income. However, like okra, tomato is highly perishable due to its high moisture content and delicate skin, making it vulnerable to post-harvest losses without adequate preservation measures (Beaulah et al., 2025).

Fish, particularly from Nigeria's artisanal and aquaculture sectors, form a significant part of the national diet and economy (Saba et al., 2024). Beyond its nutritional value, fish production and processing employ millions of Nigerians, particularly women involved in fish smoking, drying, and marketing (Odioko & Becer, 2019). Nonetheless, post-harvest fish losses, often caused by inadequate cold chain facilities, microbial spoilage, and poor handling practices, remain a major challenge, especially in rural fishing communities (Mramba & Mkude, 2022).

Despite the immense value of these commodities, a significant proportion never reaches consumers in optimal condition due to post-harvest deterioration. In developing countries, post-harvest losses of vegetables are estimated at 25% to 50%, while fish losses range from 20% to

40% depending on species and handling methods (Iveren Blessing & Tavershima Richard, 2022; Mramba & Mkude, 2022). For okra, spoilage is primarily caused by mechanical damage, microbial infestation, rapid respiration, oxidative degradation, and poor temperature control during handling and transportation (Cheng *et al*., 2018; Iveren Blessing and Tavershima Richard, 2022a; Gidado *et al*., 2024). Tomatoes face similar issues, with additional challenges from bruising, fungal attacks, and over-ripening during transport (Wakene & Sharew, 2024). In fish, deterioration is largely due to microbial activity and enzymatic breakdown accelerated by high ambient temperatures in tropical climates (Abelti & Teka, 2024).

The situation is exacerbated by inadequate infrastructure, limited cold chain logistics, a lack of affordable preservation technologies, and insufficient research investment in post-harvest management (Ahmed *et al*., 2025; Gouda and Duarte-Sierra, 2024). Unlike developed nations, where scientific innovations have drastically minimized food spoilage through advanced packaging, storage, and transport systems, developing countries like Nigeria are constrained by poor rural-urban linkages, weak regulatory frameworks, and low investment in post-harvest technologies (Gouda and Duarte-Sierra, 2024). Research shows that in Nigeria, 30% to 50% of freshly harvested okra and tomato spoils before reaching the consumer, while fish losses are often highest during peak catch seasons when storage capacity is insufficient (Iveren Blessing and Tavershima Richard, 2022; Wakene & Sharew, 2024). These losses negatively affect farmers and fisherfolk's incomes, national food security, nutrition, and poverty reduction efforts (Abelti & Teka, 2024).

Moreover, there is an imbalance in research attention between production and post-harvest management. While substantial efforts have been directed at increasing the yield of okra, tomato, and fish through improved varieties, aquaculture systems, fertilizers, and pest control, far less

has been done to develop low-cost, effective, and scalable post-harvest preservation techniques suitable for smallholder farmers and artisanal fishers in Nigeria. There remains a critical need to investigate, adapt, and promote practical preservation methods that can be implemented across these value chains to reduce waste, enhance quality, and improve market access.

1.2. Problem Statement

Despite the nutritional, medicinal, and economic importance of okra, tomato, and fish, these commodities are highly perishable and suffer severe post-harvest losses, particularly in developing countries like Nigeria. Post-harvest losses are estimated at 30% to 50% for vegetables such as okra and tomato, and 20% to 40% for fish, occurring mainly due to rapid physiological degradation, microbial spoilage, and lack of adequate preservation facilities. In many parts of Nigeria, freshly harvested okra begins to wilt, decay, or lose market value within 24 to 48 hours of harvest, especially under ambient tropical conditions without refrigeration or protective packaging. Similarly, tomato, due to its high moisture content, delicate skin, and susceptibility to bruising, often deteriorates rapidly through fungal attacks, over-ripening, and physical damage during transportation. Fresh fish, whether from artisanal fisheries or aquaculture, begins to spoil within hours after harvest at tropical temperatures if not stored in ice or processed promptly, as microbial activity and enzymatic reactions quickly degrade its texture, color, and flavor.

The high-water activity of okra and tomato, as well as the mucilaginous nature of okra and the soft flesh of fish, while nutritionally beneficial, accelerate microbial growth and biochemical reactions that compromise sensory quality and safety. Compounding these biological challenges are systemic issues such as poor rural infrastructure, limited access to affordable storage technologies, lack of cold chain logistics, and weak supply chain linkages between producers and

urban markets. Even when preservation methods are available, they are often expensive, technically demanding, or unsuitable for small-scale applications. Furthermore, public policies and agricultural extension services rarely prioritize post-harvest preservation for vegetables and fish, resulting in significant knowledge gaps among farmers, fishers, traders, and food handlers.

These cumulative losses reduce producer profits, discourage investment in vegetable and fish farming, limit the availability of nutrient-rich foods in urban diets, and diminish Nigeria's competitiveness in both domestic and international markets. This situation calls for urgent interventions to develop cost-effective and locally adaptable preservation techniques that can reduce losses, extend shelf life, and enhance the quality and availability of okra, tomato, and fish across Nigerian markets.

1.3. Aim and Objectives

Aim:

To evaluate the effectiveness of preservative methods for okra, tomato, and fish, and to monitor changes in their nutritional composition during storage over time.

Objectives:

I. To assess the physiological, biochemical, and environmental factors that contribute to the rapid spoilage of okra, tomato, and fish after harvest.

II. To determine optimal drying parameters for okra, tomato, and fish under Nigerian environmental conditions.

III. To monitor and quantify changes in key nutritional components (such as carbohydrate, protein, fat, vitamin, and mineral contents) of dried okra, tomato, and fish during defined storage periods.

IV. To evaluate the relationship between drying method, storage duration, and nutrient retention for okra, tomato, and fish.

V. To recommend drying and storage practices that are cost-effective, scalable, and suitable for smallholder farmers, artisanal fishers, and local vendors.

1.4. Scope of Study

This research focuses on post-harvest preservation of okra, tomato, and fish in Nigeria, specifically using drying as the main preservation method. It investigates the causes of spoilage, determines optimal drying parameters, and monitors nutrient changes during storage. The study considers physical, microbial, and biochemical changes under local environmental and economic conditions. Cultivation, breeding, and marketing aspects are excluded, with emphasis placed on practical, low-cost, and scalable solutions for farmers, fishers, and market vendors.

1.5. Significance of the Study

Post-harvest losses of okra, tomato, and fish remain a significant challenge in Nigeria, leading to reduced farmer incomes, increased food prices, and limited year-round availability of nutrient-rich foods. This study seeks to address these challenges by developing and validating evidence-based drying and storage techniques that are specifically adapted to tropical climatic conditions. By focusing on low-cost and locally adaptable solutions, the research will empower farmers, fishers, and small-scale traders to extend the shelf life of their produce, reduce spoilage during transportation and storage, and maintain the sensory and nutritional qualities of the products over time.

For consumers, the adoption of these methods will result in increased access to safe, affordable, and nutrient-dense food options, thereby improving dietary diversity and overall public health.

At a broader level, the study will enrich academic and practical understanding of integrated preservation strategies for perishable crops and animal products. It will also contribute to food security initiatives, reduce post-harvest economic losses, and enhance Nigeria's ability to compete in both domestic and international markets by ensuring consistent quality and supply.

CHAPTER TWO

LITERATURE REVIEW

2.1. Agricultural Produce and Its Nutritional and Industrial Benefits

Agricultural produce plays a vital role in human nutrition, economic growth, and industrial development, particularly in countries with rich biodiversity and favorable climates such as Nigeria. Among these, okra, tomato, and fish stand out for their high nutritional content and broad applications in food systems and industry (Kafui *et al*., 2022; Saba et al., 2024).

2.1.1. Okra

Okra (*Abelmoschus esculentus* L.), often referred to as gumbo or lady's finger, is a widely cultivated vegetable crop belonging to the family Malvaceae (Al-Dabbas et al., 2023), which also includes economically important plants such as cotton (*Gossypium spp*.), roselle (*Hibiscus sabdariffa*), and kenaf (*Hibiscus cannabinus*) (Rababah et al., 2023). It thrives in tropical, subtropical, and increasingly Mediterranean climates and is grown primarily for its edible green pods. In many developing countries, okra is regarded as both a staple food and an important cash crop due to its resilience under hot conditions and its short growth cycle (Elkhalifa et al., 2021). According to Rababah et al. (2023), the global cultivation of okra is expanding rapidly, with an estimated annual production exceeding 10 million metric tons, largely concentrated in West Africa, India, Sudan, and the Middle East (Elkhalifa et al., 2021). Nigeria is among the top global producers, accounting for a significant share of Africa's okra yield. The plant grows well in a variety of soil types and requires minimal agronomic input, making it suitable for subsistence and commercial farming (Adeniyi, 2025).

Figure 2- 1: Okra pods, plant, and seeds (Ummah, 2019).

Nutritionally, okra is a valuable source of essential nutrients, particularly dietary fiber, vitamin C, vitamin K, folate, and magnesium. According to data from the USDA SR-21 dataset, 100 grams of fresh okra pods contain approximately 33 kcal, 2.0 % g of protein, 7.0 % g of carbohydrates, 0.1 % g of fat, and 3.2 % g of dietary fiber (Badmus et al., 2019). The pods are also rich in minerals such as calcium, iron, potassium, and zinc, all of which are vital for maintaining human health. The dietary fiber in okra consists of both soluble components like gums and pectins, which have cholesterol-lowering properties, and insoluble fibers that aid in digestive health (Rababah et al., 2023). In addition to its pods, okra seeds are of considerable nutritional interest. The seeds contain 20 to 40 percent oil by weight, and the oil is particularly rich in linoleic acid, an essential polyunsaturated omega-6 fatty acid required in human diets. The protein content of okra seeds is notable for its balance of essential amino acids, making it a valuable plant-based protein source for populations with limited access to animal protein. These proteins are easily

digestible and possess high biological value, which further enhances the dietary relevance of the crop (Elkhalifa et al., 2021).

Okra is also known for its mucilaginous (gel-like) content, which has been utilized in both culinary and medicinal contexts. The mucilage not only contributes to the characteristic texture of okra-based dishes but also has functional benefits, such as acting as a natural emulsifier, aiding blood sugar regulation, soothing gastrointestinal irritation, and enhancing bowel movement (Jannah et al., 2025). These attributes position okra as a functional food with multiple applications in preventive healthcare and therapeutic diets. The health benefits of okra extend to managing cardiovascular conditions, reducing blood glucose levels in diabetic patients, and alleviating inflammation (Islam, 2019). It has also been linked to potential protective effects against some types of cancer and respiratory conditions such as asthma and bronchitis (Durazzo et al., 2019).

These benefits are largely attributed to its rich reserve of bioactive phytochemicals, which are discussed in the following section.

2.1.2. Tomatoes

Tomato (*Solanum lycopersicum* L.) is one of the most widely cultivated and consumed vegetable crops globally, belonging to the family Solanaceae, which also includes economically important crops such as potato (*Solanum tuberosum*), eggplant (*Solanum melongena*), and pepper (*Capsicum spp*.) (Mustafa et al., 2025). Originating from South America, tomatoes are now grown in a wide range of climates, from temperate to tropical regions, and have become a dietary staple in many countries (Ayvaz, 2024). In Nigeria, tomato production plays a key role in both food security and rural livelihoods, with cultivation occurring across the northern and central regions due to favorable growing conditions. The crop is consumed fresh or processed into

products such as paste, puree, juice, sauces, and ketchup, which adds significant value to its market potential (J. Zhang et al., 2023).

Nutritionally, tomatoes are an excellent source of essential vitamins and minerals, including vitamin C, vitamin A (in the form of provitamin A carotenoids), vitamin E, potassium, and folate (J. Zhang et al., 2023). A distinctive feature of tomatoes is their high lycopene content, a carotenoid pigment responsible for their red coloration, which functions as a powerful antioxidant associated with reduced risks of cardiovascular disease, prostate cancer, and other oxidative stress–related conditions (Wakene & Sharew, 2024). Also, 100 grams of raw tomato contain approximately 18 kcal, 0.9 g protein, 3.9 g carbohydrates, and 1.2 g dietary fiber, with negligible fat content. These nutritional attributes make tomatoes a vital component of a healthy diet and an important contributor to the micronutrient intake of populations in developing countries (Y. Ali et al., 2021).

In addition to their dietary value, tomatoes have significant industrial relevance. The global tomato processing industry transforms fresh produce into shelf-stable products that extend availability beyond the harvest season and reduce post-harvest losses (Beaulah et al., 2025). In Nigeria, however, post-harvest loss rates for fresh tomatoes can exceed 40% due to inadequate storage, transportation, and handling infrastructure. Such losses not only reduce farmer income but also contribute to seasonal shortages and price instability. Technological interventions such as solar drying, cold storage, and improved packaging have been shown to extend tomato shelf life, retain nutritional quality, and expand market opportunities (Ogundele, 2022). Furthermore, tomato by-products such as skins and seeds, which are often discarded during processing, are rich in lycopene, dietary fiber, and seed oil, offering potential for further value addition in the nutraceutical and cosmetic industries (Chabi et al., 2024).

Beyond nutrition and industry, tomatoes hold socio-economic importance. Their short production cycle allows for multiple harvests within a year, creating a steady source of income for smallholder farmers (Wongnaa et al., 2023). Moreover, tomato farming and processing generate employment across the value chain, from cultivation and harvesting to transportation, processing, and retailing. As consumer demand for fresh and processed tomato products continues to grow, enhancing the efficiency of production and post-harvest handling remains critical for maximizing both nutritional and economic benefits (J. Zhang et al., 2023).

2.1.3. Fish

Fish is an essential source of high-quality protein, supplying all essential amino acids required for human growth and maintenance. It is rich in omega-3 polyunsaturated fatty acids, particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which are vital for cardiovascular health, brain development, and immune function (Noreen et al., 2025). In tropical regions such as Nigeria, both freshwater and marine species form a significant part of the diet, contributing not only to protein intake but also to the supply of vitamins D, A, and B12, and minerals such as iodine, selenium, and zinc (Naeem & Selamoglu, 2023).

Beyond nutrition, fish plays an important role in industrial and economic development. It supports livelihoods through fishing, aquaculture, processing, and trade, generating employment across the value chain (Muhammad Bakhsh et al., 2023). Fish by-products, including fish oil, fish meal, and collagen, are valuable raw materials in industries such as pharmaceuticals, animal feed production, cosmetics, and biofertilizers (Naeem & Selamoglu, 2023; Noreen et al., 2025). In Nigeria, processed fish products such as dried, smoked, or frozen varieties are widely traded domestically and exported to regional markets, thereby contributing to foreign exchange earnings (Ogunji & Wuertz, 2023).

However, post-harvest losses remain a major challenge, with microbial spoilage, poor handling, and inadequate cold chain infrastructure causing significant deterioration within hours of harvest in warm climates (Ogunji & Wuertz, 2023). Effective preservation methods, including improved drying, smoking, chilling, and packaging technologies, are therefore essential to extend shelf life, maintain nutrient integrity, and ensure food safety. Integrating such preservation strategies into rural fishing communities can reduce waste, enhance profitability, and improve access to nutrient-rich fish products year-round (Ariyamuthu et al., 2022).

2.2. Composition and Properties of Okra, Tomatoes, and Fish

2.2.1. Phytochemical Composition and Antioxidant Properties of Okra

Okra is exceptionally rich in a wide variety of phytochemicals, which are natural compounds found in plants that contribute to their color, flavor, and resistance to disease, and also confer numerous health benefits when consumed (Kafui et al., 2022). Among the most important bioactive compounds in okra are phenolic acids**,** flavonoids**,** anthocyanins**,** tannins**,** carotenoids, and vitamins C and E, all of which exhibit strong antioxidant properties (Al-Dabbas et al., 2023). Phenolic compounds are secondary plant metabolites that include simple phenols, hydroxybenzoic acids, flavonols, and tannins (Elkhalifa et al., 2021). In okra, prominent phenolics such as quercetin**,** catechin**,** and chlorogenic acid have been identified in both the pods and seeds (Jannah et al., 2025) . These compounds function as free radical scavengers, helping to neutralize oxidative stress, which is a contributing factor in chronic conditions such as cancer, cardiovascular diseases, and neurodegenerative disorders (Islam, 2019; Jannah et al., 2025).

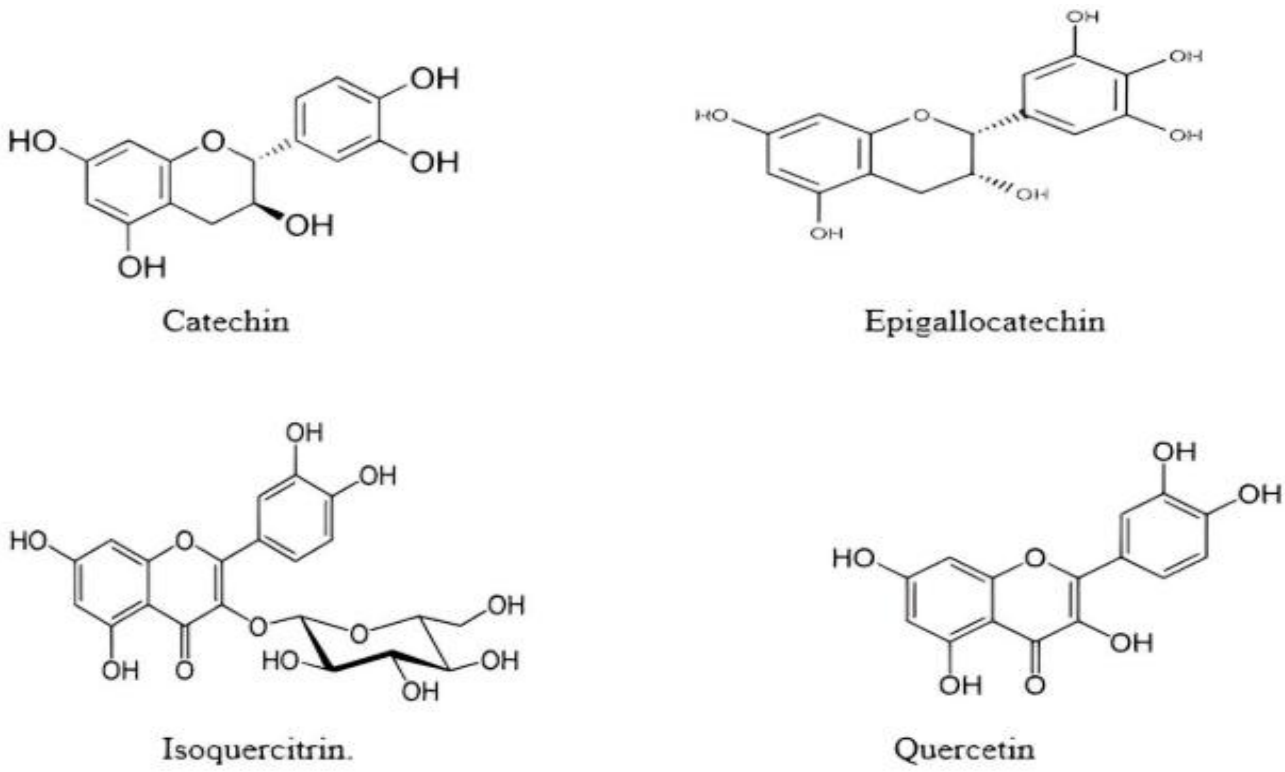

Figure 2- 2: Chemical compositions of a few okra-derived phenolic compounds (Al-Dabbas et al., 2023).

Flavonoids, a subclass of phenolic compounds, are particularly abundant in okra and play a significant role in its antioxidant and anti-inflammatory activity (Al-Dabbas et al., 2023). Flavonoid derivatives found in okra include quercetin glycosides, isorhamnetin, and kaempferol, which have been shown to modulate enzymatic activity, reduce lipid peroxidation, and improve capillary integrity (Al-Dabbas et al., 2023; Yang et al., 2022). Anthocyanins, the pigments responsible for red, purple, and blue hues in fruits and vegetables, are another class of polyphenolics present in okra, particularly in colored varieties. These compounds have demonstrated anti-cancer, anti-diabetic, and cardioprotective properties in various in vitro and in vivo studies (Pashazadeh et al., 2025). Their antioxidant activity supports cell membrane stability and reduces inflammatory responses at the molecular level (W. Li et al., 2022; Qi et al., 2023; Y. Zhang et al., 2021). Also, okra is a rich source of carotenoids such as β-carotene and

lutein, which are provitamin A compounds that support vision, immune function, and skin health. Together with vitamins C and E, these antioxidants form a synergistic defense mechanism against reactive oxygen species (Rababah et al., 2023). The mucilage from okra is not only a polysaccharide with gelling properties but also a carrier of bioactives that possess hypoglycemic effects, helping to regulate postprandial blood glucose levels. This action is particularly beneficial for managing type 2 diabetes mellitus (Elkhalifa et al., 2021). Studies have also linked okra polysaccharides to antibacterial, hepatoprotective, and immunomodulatory activities (Al-Dabbas et al., 2023; Kafui et al., 2022; W. Li et al., 2022; Qi et al., 2023; Rababah et al., 2023; Y. Zhang et al., 2021). The abundance and diversity of these phytochemicals underscore okra's classification as a functional food, making it not only a dietary staple but also a potential raw material for nutraceuticals and therapeutic applications.

2.2.2. Phytochemical Composition, Nutritional Profile, and Antioxidant Properties of Tomato

Tomato (*Solanum lycopersicum*), a member of the Solanaceae family, is one of the most widely consumed vegetables globally and serves as a significant dietary source of bioactive compounds and essential nutrients (Y. Ali et al., 2021). Beyond its culinary versatility, the tomato is valued for its phytochemical richness, which contributes to its characteristic color, flavor, and numerous health benefits (Duranova et al., 2022). Fresh tomatoes contain an average of sucrose, glucose, fructose, and total fiber levels of 2.88%, 2.45%, 0.02%, and 11.44 g/100 gram, respectively (Chabi et al., 2024). Its composition includes a variety of phenolic acids, flavonoids, carotenoids, vitamins, glycoalkaloids, and phytosterols, all of which possess antioxidant properties that protect the body from oxidative stress and related chronic diseases (A. Kumar et al., 2020).

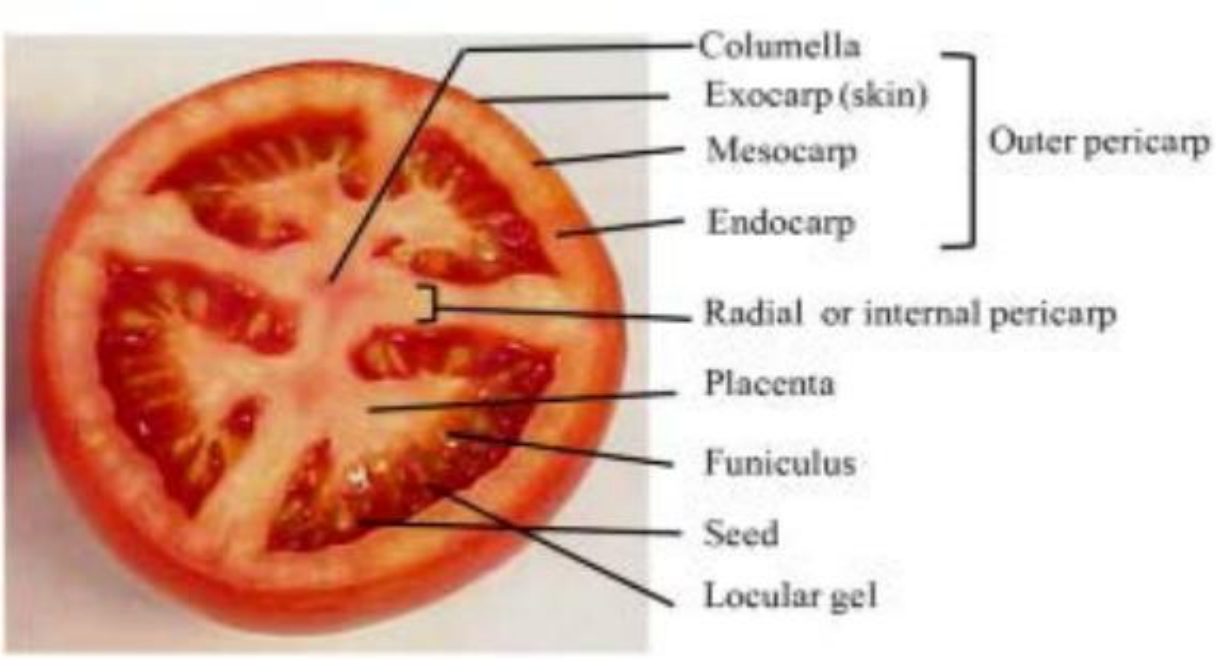

Figure 2- 3: Anatomy Structure of Tomato (Emmanuel Umeohia & Adekunle Olapade, 2024).

Phenolic acids and flavonoids are abundant in tomatoes and include compounds such as chlorogenic acid, caffeic acid, quercetin, kaempferol, naringenin, ferulic acid, and luteolin (Duranova et al., 2022). These compounds, present in both free and bound forms, have demonstrated strong antioxidant activity by scavenging reactive oxygen species (ROS) and reducing lipid peroxidation. Notably, naringenin chalcone, a prominent polyphenol in ripe tomatoes, plays a critical role in anti-inflammatory and cardiovascular protection. These phenolics also contribute to the stabilization of cell membranes and the prevention of oxidative damage, which is linked to conditions such as cancer, cardiovascular diseases, and neurodegenerative disorders (A. Kumar et al., 2020).

Carotenoids form another essential phytochemical group in tomatoes, with lycopene being the most notable (Nagarajan et al., 2020). Lycopene is responsible for the fruit's red color and is recognized for its exceptional singlet oxygen-quenching capacity, surpassing that of β-carotene

and α-tocopherol (Palomo et al., 2019). Other carotenoids such as β-carotene and lutein contribute to vision health, immune function, and skin protection. The bioavailability of lycopene is enhanced through cooking or processing, as heat converts it from the all-trans to the more absorbable cis isomers. This makes tomato-based products such as paste and sauces valuable sources of bioactive carotenoids (Concha-Meyer et al., 2020).

Tomatoes are also rich in essential vitamins, particularly vitamin C (ascorbic acid) and vitamin E (α-tocopherol), which work synergistically with carotenoids and phenolics to enhance antioxidant defense systems (M. Kumar et al., 2022; Pereira et al., 2022). In addition, glycoalkaloids such as tomatine and phytosterols like β-sitosterol, campesterol, and stigmasterol have been identified in tomatoes. These compounds have demonstrated anti-inflammatory, anti-atherogenic, and anticancer properties, further supporting their role as functional food components (A. Kumar et al., 2020).

From a macronutrient perspective, tomatoes are composed of approximately 95% water, making them low in calories yet hydrating. A 100 g serving of raw tomato typically contains about 3.9 g of carbohydrates, of which ~2.6 g are natural sugars and ~1.2 g are dietary fiber. They also provide around 0.9 g of protein and negligible fat. While the protein content is modest, tomatoes contribute small amounts of essential amino acids that complement other dietary protein sources. The fiber fraction supports digestive health and helps regulate blood glucose levels, while the natural sugars offer a mild energy boost without excessive caloric load (Raigón et al., 2022).

The antioxidant potential of tomatoes is significantly concentrated in their skin and seeds, which contain higher levels of lycopene, phenolics, and vitamin C compared to the pulp (M. Y. Ali et al., 2021). This highlights the nutritional advantage of consuming whole tomatoes rather than peeled products. Processing methods such as cooking and drying can enhance certain

phytochemicals like lycopene but may reduce heat-sensitive compounds such as vitamin C (Hassan et al., 2021). Nevertheless, both fresh and processed tomato products remain important contributors to antioxidant intake in the human diet (Y. Ali et al., 2021; El Mashad et al., 2019; Hassan et al., 2021).

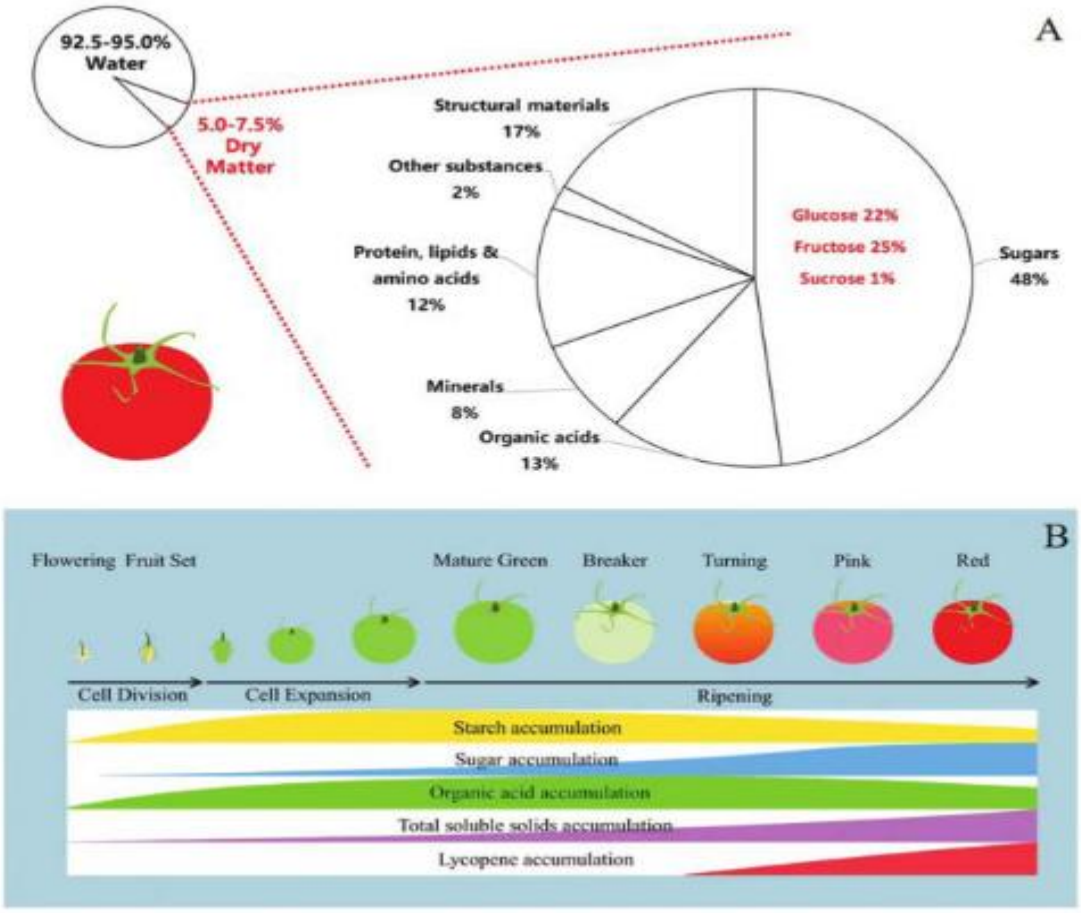

Figure 2- 4: Dry matter composition in tomato fruits (Hou et al., 2019).

The combined presence of phenolics, carotenoids, vitamins, glycoalkaloids, and modest macronutrients underscores the value of tomatoes as a functional food. Regular consumption has been associated with reduced risks of chronic diseases, improved cardiovascular health, and enhanced immune function (A. Kumar et al., 2020). This phytochemical and nutritional synergy

makes tomatoes not only a staple in global cuisines but also a potent dietary ally for promoting long-term health (Y. Ali et al., 2021; El Mashad et al., 2019; Hassan et al., 2021).

2.2.3. Nutritional Composition, Bioactive Complexity, and Health Benefits of Fish

Fish, both freshwater and marine species, are among the most nutrient-dense foods available and play a crucial role in human nutrition. They are rich sources of high-quality protein, providing all essential amino acids required for growth, tissue repair, and overall body function (Naeem & Selamoglu, 2023). In addition to protein, fish contain healthy fats, particularly omega-3 fatty acids such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which are vital for brain development, cognitive function, and cardiovascular health (Awuchi et al., 2022b; Prabhakar et al., 2020).

Many species of fish are excellent sources of essential vitamins, including vitamin D, which supports bone health and immune function, and vitamin B12, which is critical for nerve health and red blood cell formation. They also provide important minerals such as iodine, selenium, and zinc, which contribute to thyroid regulation, antioxidant defense, and metabolic function (Naeem & Selamoglu, 2023). Beyond their nutrient profile, regular fish consumption has been linked to reduced risk of chronic diseases, including heart disease, stroke, and certain inflammatory conditions. In particular, omega-3 fatty acids in fish help reduce triglyceride levels, lower blood pressure, and improve arterial flexibility (Awuchi et al., 2022a).

The carbohydrate content of fish is negligible, making it an excellent protein source for low-carbohydrate diets. On average, a 100-gram serving of cooked fish provides about 20–25 grams of protein, less than 5 grams of fat, and minimal carbohydrates, while delivering roughly 100–200 calories depending on the species and cooking method (Awuchi et al., 2022a). Fish is not only beneficial for human health but also forms an important component of food security and

livelihoods in many communities worldwide. Integrating fish into diets, especially in developing regions, can help address protein-energy malnutrition and micronutrient deficiencies, contributing to overall health and well-being (Naeem & Selamoglu, 2023).

2.3. Physiological and Post-Harvest Characteristics of Okra

Despite being a non-climactic fruit, okra is alive and carries out all of the activities of a living tissue after harvest. The fruit's postharvest quality can only be maintained after harvest; no postharvest method may enhance it (Iveren Blessing & Tavershima Richard, 2022). These characteristic limits its shelf life and affect how it responds to storage conditions.

2.3.1. Maturity and Respiration

Okra pods are harvested 3-7 days after flowering, once they are bright green, tender, and with seeds still small (Kafui et al., 2022). Delay in harvesting causes pods to become pithy, fibrous, and reduces mucilage content. Post-harvest, okra exhibits high respiration rates, especially at elevated temperatures (Iveren Blessing & Tavershima Richard, 2022). At 20 °C, respiration can reach 124–137 ml CO_2/kg·hr, compared to only 27–30 ml CO_2/kg·hr at 5 °C. This intense respiration rapidly consumes sugars and elevates metabolic heat, accelerating physical deterioration (Iveren Blessing & Tavershima Richard, 2022).

2.3.2. Water Loss and Texture Degradation

Okra possesses a high surface area-to-volume ratio and a delicate, thin epidermis, which collectively enhance its susceptibility to rapid moisture loss through transpiration and evaporation. At ambient temperatures, this physiological trait results in significant water loss, up to 14% of its original weight within just five days (Iveren Blessing & Tavershima Richard, 2022). Such dehydration contributes to visible shriveling, wilting, and a substantial reduction in the pod’s firmness and crispness. In contrast, storage under low-temperature conditions, particularly

around 4 °C with high relative humidity, helps minimize moisture loss to less than 1%, thereby preserving okra's freshness, texture, and market quality (Iveren Blessing & Tavershima Richard, 2022).

2.3.3. Optimal Conditions for Storage

The combination of low temperature (7–10 °C) and high relative humidity (95–100%) offers the best post-harvest environment for okra, helping maintain freshness for up to 7–10 days. Lower temperatures, such as 4 °C (Cheng et al., 2018), further limit water loss and help preserve firmness, soluble protein content, vitamin C levels, and chlorophyll. However, prolonged storage at low temperatures increases the risk of chilling injury, leading to symptoms like pitting, water-soaked lesions, browning, and increased decay. Chilling injury is associated with oxidative stress, cell membrane damage, and increased permeability due to lipid peroxidation (Cheng et al., 2018).

2.3.4. Oxidative Stress and Antioxidant Response

Chilling stress in okra leads to excessive production of reactive oxygen species (ROS), including superoxide radicals, hydrogen peroxide, and hydroxyl radicals (Phornvillay, Prongprasert, et al., 2020). These highly reactive molecules cause oxidative damage to essential cellular components such as lipids, proteins, and nucleic acids, compromising membrane integrity and overall cell function. Although okra possesses natural antioxidant defenses like phenolic compounds, ascorbic acid, and enzymatic systems such as superoxide dismutase and catalase, its protective capacity is limited. Under severe chilling conditions, these defenses become overwhelmed, resulting in irreversible cellular damage and a decline in post-harvest quality (Phornvillay, Prongprasert, et al., 2020).

2.3.5. Mechanical Damage and Microbial Spoilage

Okra pods are highly vulnerable to mechanical injury during post-harvest handling, transportation, and packaging, particularly along delicate areas such as the ridges and calyx. These parts are easily bruised or damaged under pressure or rough handling, resulting in superficial cuts or abrasions (Iveren Blessing & Tavershima Richard, 2022). Such injuries compromise the integrity of the pod's outer surface, making it more susceptible to microbial invasion. Opportunistic spoilage organisms, such as Rhizopus, Geotrichum, and Pseudomonas species, rapidly colonize damaged tissues, accelerating decay, discoloration, and sliminess, which significantly reduce the marketability and shelf life of okra during storage (Iveren Blessing & Tavershima Richard, 2022).

2.4. Physiological and Post-Harvest Characteristics of Tomato

Tomato (*Solanum lycopersicum*) is a climacteric fruit, meaning it continues to ripen after harvest under the influence of ethylene and a notable rise in respiration, unlike non-climacteric fruits that do not ripen post-harvest (Emmanuel Umeohia & Adekunle Olapade, 2024). The physiological processes following harvest, namely respiration, transpiration, and ethylene production, play critical roles in determining shelf life and quality. Harvested tomatoes continue metabolic activity that cannot be reversed by any post-harvest method; interventions can only maintain, not improve, prior quality (Emmanuel Umeohia & Adekunle Olapade, 2024).

2.4.1. Physiological Characteristics

2.4.1.1. Maturity, Ripening, and Respiration

Tomatoes are often harvested at the mature-green stage to prevent overripening during transport. Stored at approximately 12.5 °C, mature-green tomatoes can retain their color development and sensory quality for up to 14 days before ripening. However, once ripened (light-red or firm-ripe stages), they are optimally stored at slightly lower temperatures (7–10 °C) to extend shelf life by

8–10 days. Cold storage suppresses respiration and helps preserve soluble solids (TSS), titratable acidity, and vitamin C levels (Saltveit, 2019).

2.4.1.2. Water Loss, Firmness, and Quality Degradation

As ripening progresses, tomato moisture content increases, ranging from about 89 % in green fruit to 93 % in red fruit, reflecting changes in firmness and texture. Elevated respiration rates following harvest accelerate degradation, leading to softness, loss of juiciness, and diminished market quality. High temperatures and poor handling amplify these loss mechanisms, such as initial cooling, sanitizing, sorting, and packing are vital to preserving quality and minimizing deterioration (Emmanuel Umeohia & Adekunle Olapade, 2024; Kandasamy, 2022).

2.3.2. Physiological Disorder

Chilling damage is a physiological disease that causes degradation of tomato quality after harvest. It is an irreversible process identified in plant tissue that occurs when chilling-sensitive plants or fruits are exposed to temperatures below a certain threshold. Tomatoes are very susceptible to cold damage when exposed to temperatures below 12 to 13 ºC (Biswas et al., 2017). As a tropical fruit, exposure to low temperatures has a deleterious influence on the tomato. Ripe fruit suffers chilling harm when temperatures fall below 10 degrees Celsius. Chilling damage also affects ripe green fruits at temperatures below 12.5 degrees. Injury from cold temperatures of chilling has a cumulative impact that is directly proportionate to time of exposure and temperature. Tomato fruit is harmed after being stored at 5 degrees Celsius (41 degrees Fahrenheit) for longer than six days. Chilling damage to tomato fruits causes increased postharvest degradation, off-flavor development, seed browning, water-soaked lesions, surface pitting, premature softening, and uneven color development. Tomatoes get weaker because they are unable to sustain their normal metabolic activity at such low temperatures. Cold shock

causes several physiological and biochemical alterations, as well as cellular diseases, in vulnerable cultivars (Yadav et al., 2021). If the chilling pressure is applied for an extended period of time, the plant's cellular structure will be altered, ethylene production will be triggered, ATP production will be disrupted, the movement of the fluid substance (cytoplasm) within the plant will be slowed, activation energy will rise, permeability will increase, the production of oxygen and energy in the form of sugar will be reduced, enzymes will be deactivated, and membranes will malfunction (Emmanuel Umeohia & Adekunle Olapade, 2024).

2.3.3. Mechanical damage.

Mechanical damage is a significant issue that impacts the postharvest quality of fresh fruit, particularly tomatoes. Fresh tomatoes are vulnerable to physical harm during harvest and management procedures following harvest, including transportation. Harvesting approaches and methods should cause as little damage as possible. Vegetables should not be damaged by packing machines or containers (Arah, 2015). Furthermore, the absence of enough transportation and packing in poor nations contributed significantly to postharvest tomato loss throughout the physical distribution chain. They may experience damage while loading, unloading, and organizing operational tasks, as well as when being transported. Fresh tomato injuries cause a variety of physiological and morphological effects. The wounds may be visible and easy to locate. The above manifests as skin discolouration and tissue with unusual tastes. Because the surface colour tends to mask internal injuries, the lesions may be invisible from the outside. Physical damage is a significant contributor to post-harvest waste. As a consequence, efforts should be taken to minimize physical stress during post-harvest procedures. Furthermore, physical trauma enhances ethylene gas production and respiratory metabolism in tomatoes, hastening aging (Abera et al., 2020; Emmanuel Umeohia & Adekunle Olapade, 2024).

2.3.4. Pathological and microbiological

Microbial deterioration is another major cause of postharvest losses in tomatoes. Microbial contamination may occur before to or after harvest. Quiescent contamination, also known as latent contamination, occurs when a product gets infected prior to harvesting but does not exhibit any symptoms until the bacteria are revived by the onset of favorable conditions, such as optimum temperatures or fruit ripening (Khadka et al., 2017). Anthracnose, caused by the fungus Colletotrichum gloeosporioides, is a good example of a disease with concealed contamination. Because contaminated food is difficult to remove before storage, it typically results in rapid and severe postharvest deterioration. Microbes rapidly infect and flourish on commodities due to the lack of a protective mechanism in the tissue, along with high levels of moisture and nutrients that promote their proliferation (Peralta-Ruiz et al., 2023). Microbial deterioration is most often increased when the natural fruit skin of tomatoes is destroyed by wounds and/or abrasion, allowing spoilage bacteria to enter. Fungal diseases include buckeye rot, *Alternaria solani, Rhyzopus stolonifera, Botrytis cinerea, Alternaria alternata, Colletotrichum coccodes,* and *Phytophthora infestans*, while bacterial degradation is caused by *Pseudomonas syringae* and *Xanthomonas campestris*. *Alternaria alternata* is the most prevalent fungal pathogen for tomatoes. *A. alternata* may penetrate fresh tomatoes before, during, and after harvest via wounds and natural openings . The dematiaceous fungus *A. alternata* causes black patches on tomato fruit. Lesions on the fruit's euvesicatoria are a characteristic of this genus's species. At the bloom terminal or at the stem scar. The disease affects flat or leaves and stems, causing circular to sinken areas with asymmetrical black mycelium and a moderate greasy texture usually covers them (Emmanuel Umeohia & Adekunle Olapade, 2024; Peralta-Ruiz et al., 2023).

2.5. Physiological and Post-Harvest Characteristics of Fish

The physiological and post-harvest behavior of fish differs fundamentally from plant tissues, given that fish is harvested as an animal product and degradation begins immediately after death (Awuchi et al., 2022a).

2.5.1. Rigor Mortis, Stress, and Muscle Changes

Following harvest, stressed fish experience a rapid onset of rigor mortis, driven by depletion of ATP (adenosine triphosphate) and accumulation of lactic acid, which leads to a drop in muscle pH. This process affects texture, initially making fillets tougher but eventually resulting in softening and increased drip loss. High stress during harvest can accelerate oxidative degradation of polyunsaturated fatty acids (PUFAs), generating reactive oxygen metabolites that impair flavor, nutritional quality, and consumer acceptance (Scocco & De Felice, 2025).

2.5.2. Microbial and Biochemical Spoilage

Spoilage starts almost immediately after death, marked by biochemical changes including muscle autolysis and microbial growth. These produce off-odors, softening of tissues, discoloration, and flavor loss. Once the quality of fresh fish deteriorates, it cannot be restored (Comi, 2017; Tavares et al., 2021).

2.5.3. Temperature Control and Preservation

Rapid chilling (by icing or refrigerated seawater) following harvest is essential to slow microbial and enzymatic spoilage. Techniques such as ice slurry or slurry ice are particularly effective, offering faster cooling and minimizing cold damage compared to block ice. Preservation methods also include drying, salting, smoking, refrigeration, freezing, and controlled-atmosphere storage, often used in combination (“hurdle technologies”) to extend shelf life while maintaining quality (Tavares et al., 2021).

2.5.4. Handling and Post-Harvest Management

Proper handling from catch to landing is critical. This includes graded sorting, bleeding, gutting, washing, chilling, and hygienic packing to preserve fish integrity and prevent microbial contamination. Post-harvest deterioration begins immediately and can drastically reduce value, so maintaining original quality through effective management is vital for safety, price, and nutritional benefits (Tavares et al., 2021).

2.6. Major Causes of Spoilage in Okra

Spoilage in postharvest okra results from an interplay of physical, biological, physiological (Jain et al., 2023), and chemical degradative processes, all of which dramatically reduce pod quality, aesthetic appeal, and shelf life.

2.6.1. Physical Damage

Okra pods possess a delicate, thin epidermis and pronounced ridges, particularly along the shoulders and calyx region, making them extremely susceptible to mechanical injury during harvesting, sorting, packaging, and transit (Cheng et al., 2018). Physical stresses such as bruising, compression, cutting, and abrasion can easily rupture the outer protective layer. Even minor abrasions or pressure points disrupt cellular integrity, reducing the pods' ability to retain moisture and causing localized tissue collapse (Cheng et al., 2018). According to Gidado et al. (2024), postharvest studies have identified that damage, especially at the ridges, serves as a hotspot for water loss and enzymatic browning, even under cold-chain storage systems designed to prolong freshness. Such injuries often initiate a cascade of deterioration marked by accelerated dehydration, midrib collapse, and visual discoloration, which significantly diminishes both the aesthetic and nutritional value of the pods (Gidado et al., 2024). Research confirms that mechanical injuries are among the leading causes of early okra spoilage. Once the outer tissues are compromised, moisture loss increases dramatically as internal turgor pressure equilibrates

with ambient conditions, resulting in visible shriveling, wilting, and collapsed texture even before microbial spoilage sets in (Jain et al., 2023).

In addition to okra, physical factors are recognized broadly as a primary cause of postharvest deterioration in fruits and vegetables. Mechanical damage exposes inner tissues to oxidative reactions and microbial invasion, hastening decay (Kong & Singh, 2016). Transportation-related stresses, including vibration and temperature fluctuations, further compound this problem by exacerbating bruising and dehydration (Melini & Melini, 2018). To mitigate these issues, the implementation of appropriate handling and packaging technologies is essential. Gentle harvesting, use of padded crates or trays, vacuum sealing, plastic wraps, and even emerging nanotechnology-based packaging have proven effective in extending shelf life and maintaining quality (Jain et al., 2023).

2.6.2. Biological Spoilage

Once the protective outer layer of okra pods is breached, microbial spoilage accelerates rapidly. The integument serves as a natural barrier against microbial invasion, and any mechanical injury or abrasion compromises this defense, making the underlying tissues highly susceptible to infection (Ren et al., 2021). Spoilage fungi such as *Rhizopus stolonifer*, *Geotrichum candidum*, and *Fusarium oxysporum*, along with bacteria like *Pseudomonas fluorescens*, readily colonize wounded tissues. These microorganisms metabolize cellular contents and secrete enzymes that break down structural components such as pectins, proteins, and cell walls (Melini & Melini, 2018). Research indicates that fungal colonization may initiate within just 48 hours under moderate humidity and temperature conditions, particularly when injury is present. The infected pods exhibit softening, water-soaked lesions, the appearance of fungal growth or fuzz, unpleasant odors, and leakage of cellular fluids. As spores spread to adjacent pods, these

conditions worsen and lead to batch-wide contamination. Biological spoilage is further intensified by the high moisture content retained in injured tissues (Jain et al., 2023). While intact okra pods possess waxy cuticles and antimicrobial phytochemicals that provide natural resistance, damage to these defenses allows spoilage organisms to overwhelm the tissue, rapidly degrading it into mushy, slimy masses. These changes also deplete antioxidant content in the affected areas, allowing for deeper microbial penetration and faster spoilage progression (Jain et al., 2023).

Biological deterioration of fruits and vegetables, including okra, is influenced by multiple factors. Enzymatic browning, microbial invasion, and diseases like blight or fruit rot are key contributors. Microorganisms, including bacteria, molds, and yeasts, play primary roles in spoilage, with some produce types more prone due to their physiology. While enzyme inhibitors, pH adjustments, and preservatives are employed to limit microbial activity, genetic modification and improved hygiene during storage offer long-term solutions (Nath et al., 2022).

2.6.3. Physiological Deterioration

Physiological spoilage in okra encompasses enzymatically driven changes that reduce textural quality and appearance. Fresh okra contains active enzymes such as polyphenol oxidase (PPO), phenylalanine ammonia-lyase (PAL), and peroxidases, which respond to postharvest stress. PPO catalyzes the oxidation of phenolic compounds to quinones, leading to brown pigments (Phornvillay, Pongprasert, et al., 2020). PAL drives the phenylpropanoid pathway, aiding lignin synthesis and hardening of the cell wall, while peroxidases cross-link lignin and phenolic fragments. Following harvest, PPO, PAL, and POD activity intensifies due to mechanical stress or chilling exposure, leading to rapid browning of cut surfaces and ridge areas (Sierocka & Swieca, 2017). Each enzymatic reaction is accelerated by ethylene and wound signals.

Lignification increases cell wall rigidity and decreases digestibility; it begins within hours of harvesting and becomes noticeable within days, resulting in pods that are tough and woody (Phornvillay, Pongprasert, et al., 2020).

Studies reveal lignin deposition occurs along the epidermis and vascular bundles, reducing mucilage content and compromising the soft, juicy texture preferred by consumers. Tissue hardness increases, and overall elasticity diminishes. Enzyme inhibitors or blanching treatments can delay these physiological processes. However, they do not fully prevent them. Certain MAP configurations (e.g., lowered O_2) also reduce enzyme activity. As the shelf life progresses, a combination of enzymatic browning, lignification, and mucilage loss drives consumers to reject pods due to reduced palatability and mouthfeel (Sierocka & Swieca, 2017).

2.6.4. Chemical Oxidation

Okra's chemical spoilage is rooted in oxidative damage to phenolic compounds, vitamins, lipids, and polysaccharides. The presence of oxygen, light, and heat induces the spontaneous oxidation of phenols and ascorbic acid. Phenolic oxidation produces quinones that polymerize into brown, insoluble melanins, darkening both pod surface and cut edges (Wu et al., 2020). Simultaneously, vitamin C oxidation leads to dehydroascorbic acid formation, with further breakdown producing brown pigments and off-flavors. Reactive oxygen species (ROS), generated through respiration and chilling-induced stress, exacerbate lipid peroxidation in cell membranes. This compromises membrane integrity and increases solute leakage, influencing moisture loss and microbial susceptibility (Wu et al., 2020). Oxidation also alters mucilage and polysaccharide stability, diminishing viscosity and gelling properties, which directly affects the culinary and industrial quality of okra, reducing its thickening properties for soups and sauces (Zhu & Obara, 2022).

2.7. Major Causes of Spoilage in Tomato

Spoilage in post-harvest tomatoes arises from a combination of physical, biological, physiological, and chemical processes that severely diminish fruit quality and shelf life (Khalid et al., 2024).

2.7.1. Physical Damage

Tomatoes are delicate and prone to physical injury during harvesting, sorting, transportation, and storage (Zewdie et al., 2021). Mechanical stresses, including bruising, crushing, and pressure, can compromise the skin and underlying tissues. Such damage accelerates water loss, facilitates pathogen entry, and hastens softening and decay. Rough handling and inappropriate packaging are among the most significant contributors to market losses of tomatoes, with bruising and compression playing substantial roles in shelf-life reduction (Pathare & Al-Dairi, 2021; Spricigo et al., 2021).

2.7.2. Biological Spoilage

Once the tomato's natural protective barriers are breached, fungi and bacteria swiftly colonize the fruit. Common rot-causing fungi include *Rhizopus stolonifer, Aspergillus niger, Penicillium expansum,* and *Botrytis cinerea,* which lead to soft rot and mold growth. Estimates indicate that between twenty to fifty percent of harvested tomatoes are lost to microbial spoilage, particularly in regions where post-harvest practices are less controlled (Khalid et al., 2024).

2.7.3. Physiological Deterioration

Tomatoes are climacteric fruits that continue to respire and ripen post-harvest. Elevated respiration rates accelerate loss of firmness, sugar-acid balance, and overall quality. Their high moisture and metabolic activity predispose them to rapid deterioration. Ripening and senescence processes diminish nutritional and sensory attributes, particularly when storage conditions, such as temperature and humidity, are not optimized (Khalid et al., 2024).

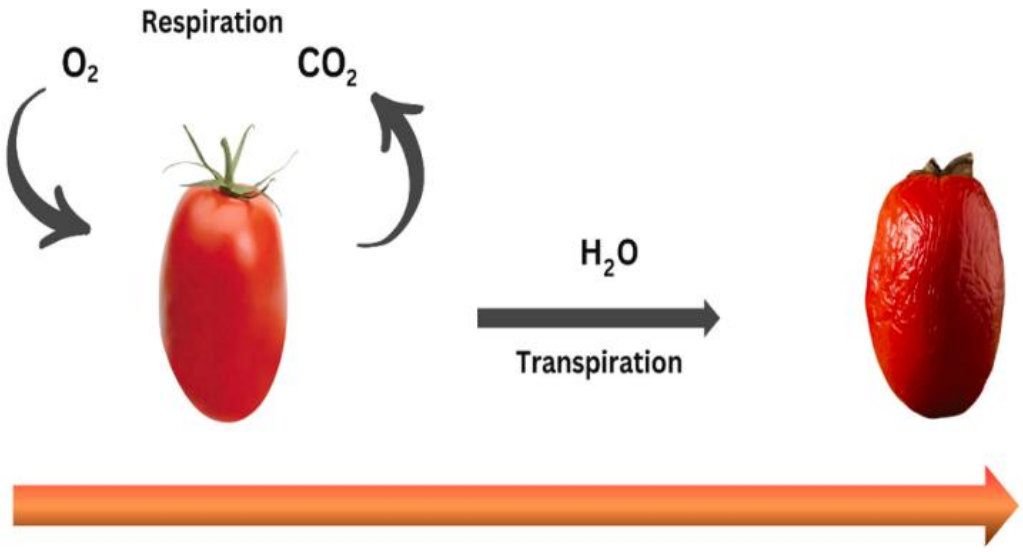

Figure 2- 5: Illustration of how tomato deterioration occurs as a result of increased respiration (Khalid et al., 2024).

2.7.4. Chemical and Metabolic Changes

Internal degradation of quality in tomatoes is also driven by chemical and metabolic reactions. Chlorophyll breakdown, degradation of pigments like lycopene, and oxidation of internal compounds cause visible color changes, reduced antioxidant levels, and flavor loss. High respiration, ethylene production, and moisture content contribute significantly to these chemical transformations, which are key factors in limiting shelf life to about five to seven days (Emmanuel Umeohia & Adekunle Olapade, 2024).

2.8. Major Causes of Spoilage in Fish

Fish spoilage is a rapid and complex process involving physical, chemical, enzymatic, and microbial degradation soon after harvest, which drastically diminishes quality and safety (Comi, 2017; Tavares et al., 2021; Wang & Zheng, 2025).

2.5.1 Physical Losses and Handling Injuries

Spoilage in fish begins the moment they die. Improper handling, inadequate packaging, infestation by insects, and exposure to environmental elements all contribute to physical loss. In

tropical regions, high ambient temperature and substandard drying or handling conditions often lead to severe fish spoilage within hours of landing (PS et al., 2022; Singh & Singh, 2020).

2.5.2 Enzymatic Autolysis

Fish muscles contain active enzymes that, after death, begin degrading proteins and lipids. This autolytic activity breaks down tissue integrity, resulting in textural degradation and off-odors. The process starts rapidly and is a significant driver of early spoilage (PS et al., 2022; Singh & Singh, 2020).

2.5.3 Oxidative Degradation

Fish are rich in unsaturated fatty acids prone to oxidation. Lipid peroxidation undermines cell membranes, generating rancid flavors and compromising the nutritional integrity of the fish. This oxidation is intensified by exposure to oxygen and elevated temperatures (Singh & Singh, 2020).

2.5.4 Microbial Proliferation

Microbial growth on fish surfaces and inside tissues drives spoilage, yielding changes in odor, texture, and appearance. Bacteria thrive in fish due to high moisture, neutral pH, and abundant nutrients. The interplay of enzymatic autolysis, oxidation, and microbial activity cascades rapidly, transforming fresh fish into an unappealing and unsafe product (Wang & Zheng, 2025).

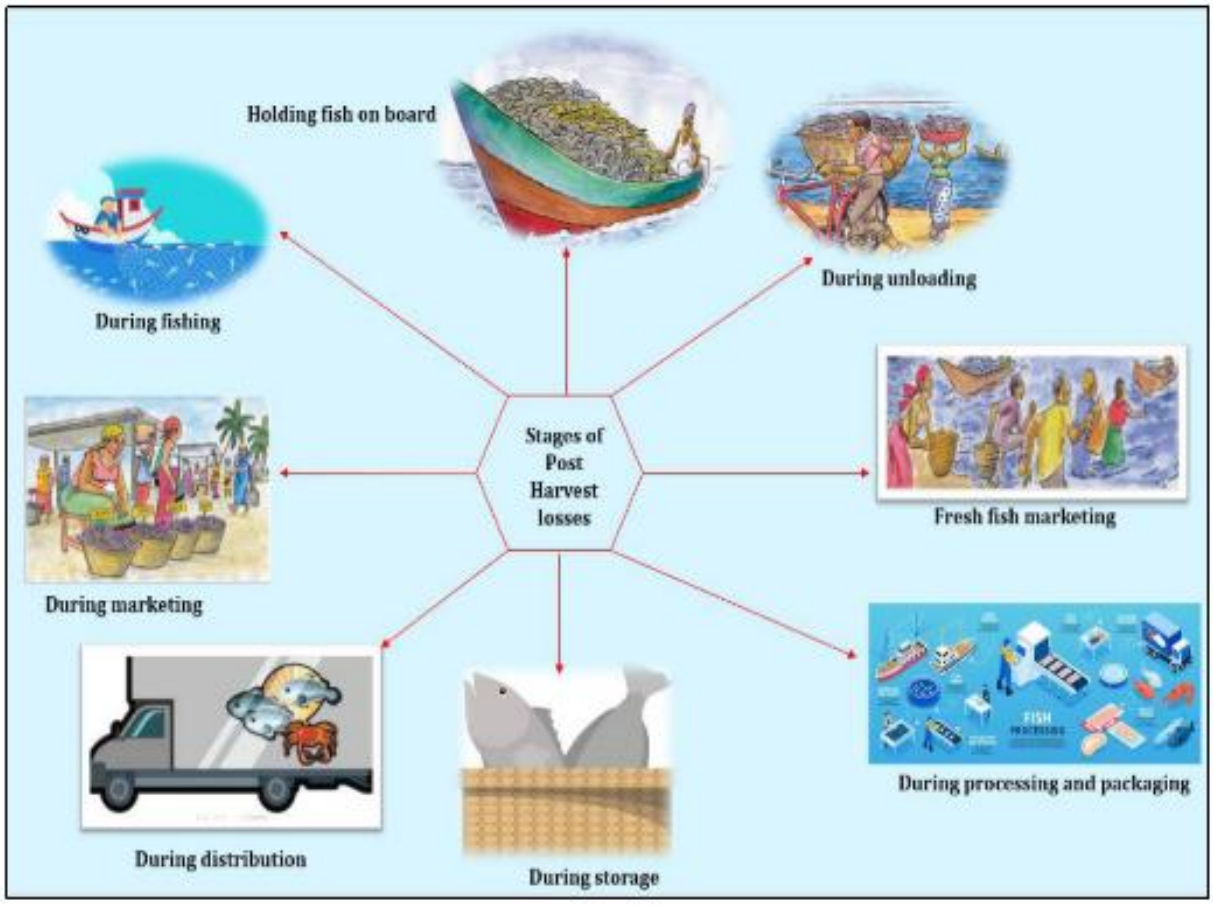

Figure 2- 6: Stages of post-harvest loss for fish (PS et al., 2022)

2.9. Preservation Technologies

2.9.1. Preservative techniques for Okra

Okra (*Abelmoschus esculentus*) is a highly perishable vegetable due to its high moisture content, soft texture, and rapid metabolic activity after harvest. Postharvest losses are often significant, particularly in tropical regions where ambient temperatures and humidity accelerate deterioration. Preservation methods, therefore, aim to slow respiration, reduce microbial spoilage, and maintain nutritional and sensory qualities (Paulus et al., 2021).

2.9.1.1. Low-Temperature Storage

Temperature management is the most common preservation method for okra. Refrigeration at 8–10 °C reduces respiration and water loss, extending shelf life from 3–4 days under ambient storage to 7–10 days. However, storing below 7 °C often results in chilling injury, characterized by surface pitting, discoloration, and increased susceptibility to fungal attack. Freezing can preserve okra for longer durations, but thawing often leads to texture degradation and excessive mucilage release, which limits its consumer acceptability. Super-chilling (−0.5 to −2 °C) has been investigated as a balance between refrigeration and freezing, reducing microbial activity while limiting tissue damage (Iveren Blessing & Tavershima Richard, 2022).

2.9.1.2. Chemical and Biological Coatings

Edible coatings and films are gaining popularity in okra preservation. Aloe vera gel, chitosan, gum arabic, and starch-based coatings act as semipermeable barriers, reducing moisture loss and delaying microbial colonization. Chitosan in particular exhibits intrinsic antimicrobial activity, reducing fungal growth and preserving chlorophyll content. When fortified with essential oils such as clove, thyme, or cinnamon, these coatings further enhance antioxidant and antimicrobial effects. Such combinations have been reported to extend okra shelf life to more than 12 days under refrigeration. Natural antioxidant dips, such as ascorbic acid, also delay enzymatic browning, preserving both visual and nutritional quality (Iveren Blessing & Tavershima Richard, 2022).

2.9.1.3. Packaging-Based Preservation

Modified atmosphere packaging (MAP) provides another effective method for preserving okra. By adjusting oxygen and carbon dioxide concentrations, MAP slows respiration, reduces ethylene production, and delays microbial growth. High CO_2 concentrations (5–10%) have been shown to reduce fungal growth and maintain green color, although excessive levels may

accelerate softening and off-flavors. Biodegradable packaging materials combined with MAP are increasingly being studied as eco-friendly alternatives to conventional plastics (Paulus et al., 2021).

2.9.1.4. Ozonation and Novel Approaches

Ozonated water has been explored as a postharvest treatment to reduce microbial load on okra pods. While effective, prolonged exposure may damage tissue and affect flavor. Recent innovations also include nanotechnology-based preservation, where nanoemulsions of essential oils are incorporated into coatings to enhance antimicrobial activity. Hurdle technology, which combines refrigeration, edible coatings, and MAP, has shown promise in extending okra's shelf life up to two weeks while maintaining acceptable sensory attributes. These integrated systems are considered the future of okra preservation, particularly in reducing postharvest losses that often exceed 30% in developing regions (Iveren Blessing & Tavershima Richard, 2022;Paulus et al., 2021).

2.9.2. Preservative techniques for Tomato

Postharvest technologies are essential for reducing losses in tomatoes, which are often caused by poor transportation, mechanical damage, and inadequate storage. Physiological changes such as respiration, pigmentation, and firmness loss further compromise quality during handling and distribution. The goal of postharvest technology is to slow deterioration while ensuring high market value. Preservation methods act by controlling enzymatic activity, inactivating microorganisms, and managing physiological disorders, using approaches such as chlorinated water, temperature control, ozone, UV radiation, ultrasound, edible coatings, modified atmosphere packaging (MAP), 1-methylcyclopropene, and calcium chloride (Emmanuel Umeohia & Adekunle Olapade, 2024).

2.9.2.1. Preservation by Physical Actions

Temperature regulation is one of the most effective preservation strategies. Low-temperature storage slows respiration and ripening in tomatoes, though tropical varieties must be stored above 12°C to avoid chilling injury (Umeohia & Olapade, 2024). Precooling immediately after harvest, using forced air, vacuum, or hydrocooling, is critical in reducing field heat and extending shelf life (Elansari et al., 2019). Modified atmosphere packaging (MAP) further prolongs freshness by reducing oxygen and increasing CO_2 concentrations around fruits, thereby slowing respiration and ethylene production (Emmanuel Umeohia & Adekunle Olapade, 2024). In addition, 1-methylcyclopropene (1-MCP) has been shown to inhibit ethylene biosynthesis, delay ripening, and extend shelf life by up to 70%. Heat treatments, such as hot water or hot air exposure, reduce fungal infection, delay ripening, and minimize chilling injury, although excessive heat can impair lycopene development and flavor. Other physical methods include ultrasound treatment, which inactivates microbes via cavitation and free radical generation, though high equipment costs remain a challenge. Similarly, UV-C radiation has been applied as a surface treatment to stimulate beneficial stress responses in tomatoes. Finally, edible coatings made from proteins, polysaccharides, or lipids provide a barrier to gas exchange and water loss, enhancing fruit appearance and prolonging shelf life (Emmanuel Umeohia & Adekunle Olapade, 2024).

2.9.2.2. Preservation via Chemical Application

Chemical treatments provide another line of defense against spoilage. Chlorinated water is commonly used for sanitizing tomatoes due to its low cost and broad bactericidal activity, though issues such as toxic byproducts and reduced efficacy in the presence of organic matter limit its appeal. Ozonated water, recognized as GRAS, is effective against microorganisms and may substitute refrigeration in resource-limited settings, but it can negatively impact ascorbic acid

levels and flavor. Electrolyzed oxidizing water (EOW), generated by electrolysis of diluted salts, provides strong antibacterial action with minimal environmental impact, reverting to plain water after use. Acidic EOW (AcEW) in particular is effective against pathogens and is gaining attention as a sustainable sanitation method (Emmanuel Umeohia & Adekunle Olapade, 2024).

2.9.2 3. Emerging Technologies and Innovation

Emerging preservation techniques for tomatoes include nanotechnology-based coatings, pulsed electric fields (PEF), high-pressure processing (HPP), cold plasma, smart packaging, and blockchain-enabled traceability. These methods aim to enhance shelf life, reduce losses, and maintain nutritional quality, although their adoption depends on cost, regulatory considerations, and consumer acceptance (Emmanuel Umeohia & Adekunle Olapade, 2024).

2.9.3. Preservation Technology and Optimization for Fish

Fish preservation integrates multiple strategies to slow spoilage, maintain nutritional quality, and extend shelf life. These approaches are broadly categorized into physical, chemical, biological, and packaging-based methods. Each technique targets specific spoilage mechanisms such as enzymatic autolysis, microbial proliferation, and lipid oxidation, and recent advances increasingly focus on synergistic applications that optimize preservation outcomes (Wang & Zheng, 2025).

2.9.3.1. Physical Preservation

Low-temperature techniques remain the cornerstone of fish preservation. Refrigeration at 0 - 4 °C reduces microbial growth and delays enzymatic autolysis, extending freshness by several days compared with room temperature storage. Super-chilling, which maintains the fish slightly below its initial freezing point (- 0.5 to -2.8 °C), slows spoilage without causing significant tissue damage and is particularly effective when combined with modified atmosphere packaging

(MAP). Freezing, especially at - 40 °C, halts microbial and enzymatic activity altogether, though quality may be compromised by ice crystal formation. Advances such as high-pressure freezing and cryogenic freezing generate smaller ice crystals, reducing textural damage and nutrient loss compared with conventional freezing methods (Wang & Zheng, 2025).

High-pressure processing (HPP) is a non-thermal preservation technology that applies pressures of 200–600 MPa to inactivate microorganisms. This technique can extend shelf life from a few days to more than three weeks, while controlling pathogens such as Listeria monocytogenes. However, HPP may alter color and texture depending on species and processing conditions (Wang & Zheng, 2025). Pulsed electric field (PEF) technology provides another physical intervention, using short bursts of electricity to disrupt microbial membranes without heating the fish. PEF has shown promise in controlling spoilage bacteria, maintaining nutritional quality, and prolonging the shelf life of species such as shrimp during chilled storage (Wang & Zheng, 2025).

2.9.3.2. Chemical and Biological Preservation

Chemical and biologically based methods complement physical preservation by directly suppressing microbial activity and oxidative reactions. Nanoemulsions, often formulated with essential oils such as cumin, thyme, or clove, act as antimicrobial and antioxidant coatings. They inhibit microbial growth, scavenge free radicals, and can extend fish freshness by up to 10 days under refrigerated storage (de Mendonça Silva & Gonçalves, 2017; Durmus, 2020; Jamali et al., 2021). Ozonation, applied in gas or aqueous form at concentrations of 0.5–2 ppm, reduces microbial load by up to 3 log CFU/g. While effective, excessive ozonation can accelerate lipid oxidation and negatively impact sensory attributes if not carefully managed (Phornvillay, Pongprasert, et al., 2020).

Essential oils (EOs), including thymol, carvacrol, and eugenol, demonstrate strong antimicrobial action by disrupting bacterial membranes and interfering with enzymatic activity. Their incorporation into coatings, sprays, or edible films has been shown to extend the freshness of cod, carp, and trout by 6–15 days (Wang & Zheng, 2025). Antimicrobial coatings made from polymers and biopolymers further enhance preservation. Materials such as polylactic acid (PLA), chitosan, and alginate can be combined with essential oils or nanoparticles to produce controlled antimicrobial effects, typically prolonging shelf life by 8–12 days (Ameur et al., 2022).

2.9.3.3. Packaging-Based Preservation

Modified atmosphere packaging (MAP) is one of the most effective techniques for maintaining fish quality during chilled storage. By replacing air with specific ratios of CO2, N2, and O2, MAP slows microbial growth, retards lipid oxidation, and sustains sensory attributes. CO2-enriched packaging in particular has demonstrated shelf life extension in species such as sea bass, cod, turbot, and tilapia. MAP often performs better than vacuum packaging and achieves optimal results when integrated with super-chilling or high-pressure treatments (Wang & Zheng, 2025).

2.9.3.4. Emerging and Future Trends

Recent advances in fish preservation highlight the role of nanotechnology, hurdle technology, and intelligent packaging. Nanotechnology enables the development of nanoemulsion-based coatings and films capable of delivering bioactive compounds in a controlled manner, although concerns remain regarding nanoparticle migration and potential toxicity (Liu et al., 2024). Multi-hurdle preservation, which combines non-thermal approaches such as HPP or PEF with MAP and bioactive coatings, shows potential to double shelf life without compromising sensory properties, though cost and energy demands limit industrial adoption. Intelligent packaging, incorporating freshness indicators, oxygen scavengers, and RFID-based sensors, provides real-

time monitoring of product quality. While promising, these technologies face barriers related to regulatory approval, sensor precision, and consumer acceptance (L. Li et al., 2025). Continued development in toxicology testing, equipment affordability, and predictive spoilage modeling will be critical for advancing these innovative preservation systems.

CHAPTER THREE

MATERIALS AND METHODS

3.1. MATERIALS

3.1.1. Reagents and Raw Materials Used

Fresh samples of okra (*Abelmoschus esculentus*), tomato (*Solanum lycopersicum*), and fish (*Clarias gariepinus*) were purchased from Uselu local market, Ugbowo, Benin City, Edo state, Nigeria. The market was chosen for its accessibility and its representation of typical retail conditions within southeastern Nigeria, reflecting real postharvest handling environments. The selection of the materials was based on strict criteria to ensure uniformity and quality. Okra pods and tomato fruits were chosen based on uniform size, bright coloration, and absence of visible mechanical damage, bruising, or microbial infection. Fish samples were obtained fresh to prevent biochemical degradation associated with postmortem handling.

The reagents used in this study were of analytical grade to ensure accuracy and reproducibility of experimental results. All solutions were prepared using distilled water, and standard concentrations were freshly made before each analysis. The reagents employed and their specific applications in the experiment are listed in **Table 3.1**.

Table 3.1: List of Reagents and Their Functions in the Experiment

S/N	Reagent/Chemical	Function in the Experiment
1	Concentrated Sulphuric Acid (H_2SO_4)	Used as a digestion reagent in crude protein determination using the Kjeldahl method.

2	Sodium Hydroxide (NaOH)	Employed for neutralization and distillation steps in protein analysis and for adjusting pH during assays.
3	Copper Sulphate ($CuSO_4$)	Catalyzed the digestion stage of protein analysis.
4	Hydrochloric Acid (HCl)	Used for acid-base titrations and as a reagent for hydrolyzing organic compounds.
5	Boric Acid (H_3BO_3)	Functioned as an absorbent for ammonia gas during the distillation process in protein estimation.
6	Dinitrosalicylic Acid (DNS) Reagent	Used for determining reducing sugar content during carbohydrate analysis.
7	Iodine Solution (I_2)	Utilized in iodometric titration for quantifying antioxidant activity.
8	Potassium Iodide (KI)	Served as a stabilizing agent and reducing agent in iodometric reactions.
9	Starch Solution (1% w/v)	Used as an indicator in titrations involving iodine.
10	Distilled Water	Used as a universal solvent for sample dilution and reagent preparation.

3.1.2. List of Equipment / Apparatus

All apparatuses were properly cleaned, rinsed with distilled water, and dried before use to avoid contamination and ensure analytical accuracy, and are presented in **Table 3.2**.

Table 3.2: List of Equipment / Apparatus and Their Functions in the Experiment

S/N	Apparatus/Equipment	Specific Function in the Experiment
1	Beakers	Used for mixing and holding liquid samples during extraction and analysis.
2	Conical flasks	Served for digestion, titration, and reaction processes in chemical analyses.
3	Burettes	Used to accurately deliver titrants during volumetric determinations (e.g., acid-base and iodine titrations).
4	Pipettes	Employed for precise transfer and measurement of liquid reagents and sample solutions.
5	Measuring cylinders	Used to measure volumes of solvents and reagents for preparation of test solutions.
6	Weighing balance (Mettler Toledo)	Used for accurate weighing of samples and analytical reagents prior to analysis.
7	Hot plate	Provided controlled heating for digestion and extraction processes.
8	Oven (Memmert UN55)	Used for drying samples to constant weight during moisture content determination.
9	Distillation unit	Used for the distillation of ammonia during the Kjeldahl protein determination.

10	Spectrophotometer (UV-1800, Shimadzu)	Used to determine absorbance of samples during colorimetric and antioxidant assays.
11	Desiccator	Used to cool and store samples in a moisture-free environment after drying.
12	Water bath	Maintained uniform heating during incubation and enzymatic reaction stages.
13	Digestion tubes	Used for digesting samples during crude protein determination.
14	Evaporating dishes	Used to concentrate and evaporate solvent extracts prior to analysis.

3.2. METHODS

3.2.1. Sample Preparation

Upon collection, all samples of okra (*Abelmoschus esculentus*), tomato (*Solanum lycopersicum*), and fish (*Clarias gariepinus*) were immediately transported to the LUCO Chemical laboratory, just a few walks away from the market, in clean, aerated plastic containers to preserve their structural integrity and minimize biochemical degradation during transit. The total transport time from market to laboratory did not exceed one hour to limit microbial proliferation and oxidative reactions that could affect compositional accuracy. In the laboratory, okra pods and tomatoes were sorted to remove physically damaged or irregular specimens, ensuring uniformity in size, maturity, and appearance. The selected vegetables were thoroughly washed with tap water and rinsed with distilled water to remove adhering dirt, dust particles, and possible microbial contaminants. Washing with distilled water minimizes external contamination without altering tissue chemistry. Excess moisture on the surface was removed using a clean muslin cloth to

prevent microbial growth before drying (Mohammed et al., 2017). The fish samples were gutted, descaled, and eviscerated using sterile stainless-steel knives to prevent cross-contamination. Each fish was then cut into uniform fillets approximately 5 cm thick to enhance surface area exposure and ensure uniform drying, as recommended by for minimizing texture variability and nutrient loss in fish drying studies. Each sample type was divided into two equal portions: one designated for fresh analysis and the other for drying preservation. The drying process was carried out in a thermostatically controlled oven (Memmert UN55) under optimized temperature conditions for 24 hours for each food type at 60°C (Ajao et al., 2025). These temperature settings were chosen based on previous findings that moderate drying temperatures help retain thermolabile nutrients, pigments, and antioxidants in plant and animal tissues (Ajao et al., 2025). The drying continued until a constant weight was achieved, indicating equilibrium moisture content suitable for preservation. After drying, all samples were cooled to room temperature. The dried materials were then transferred into airtight glass containers and stored at ambient temperature before subsequent physicochemical analyses. This sample preparation procedure ensured minimal variability between replicates and maintained the biochemical integrity of the samples throughout the experiment. Comparable approaches have been reported in postharvest preservation studies, which highlight that controlled drying under standardized laboratory conditions improves the reproducibility and reliability of analytical outcomes (Mohammed et al., 2017).

3.2.2. Analytical Procedures

The analytical procedures were carried out to determine the major nutritional and biochemical parameters of the collected samples, including crude protein, moisture content, carbohydrate, and vitamin C concentrations. These parameters were selected because they serve as key indicators

of nutritional quality, stability, and preservation efficiency in perishable food materials such as vegetables and fish. Each analysis was performed following established standard validated through similar laboratory-based food composition studies (Ahmed et al., 2020; Mohammed et al., 2017). The analytical methods adopted were carefully chosen to ensure reproducibility, accuracy, and comparability with previous studies on nutrient retention and degradation during processing and storage. Detailed step-by-step procedures for each analysis are described below.

3.2.3. Crude Protein Determination

About 5 g of sample in a conical flask was digested with 20ml H_2SO_4 and $CuSO_4$ as a catalyst using a hot plate for several minutes until a clear solution was obtained. It was cooled and diluted with 100 mL of distilled water. The tube containing the diluted sample was connected to the distillation unit, and a conical flask containing 25ml of 4% boric acid solution was attached to the condenser outlet. 50ml of 40% NaOH was dispensed into the conical flask, and distillation was carried out for 10 minutes (Ahmed et al., 2020; Mohammed et al., 2017). The ammonium borate solution formed was titrated with 0.1M HCl to a purplish–grey endpoint using methyl red as an indicator.

$$\%CP = \frac{(S - B)N(1.4007)}{w}$$

N is the normality of acid

S is titre value of sample

B is titre value of blank

3.2.4. Moisture Content

The moisture content of the sample was quantitatively determined by the oven drying method at 110^0C for 2 hours. About 5g of oil was weighed into an evaporating dish using the analytical

mass balance. The weight of the evaporating dish and sample obtained together was placed in an oven at 110 degrees (Ajao et al., 2025). At time intervals of 60 minutes, the evaporating dish with the sample was taken out and weighed with a new mass for both the sample and the evaporating dish. The process was continued till a constant weight of the sample was obtained, respectively (Ahmed et al., 2020; Mohammed et al., 2017). The moisture content was calculated using the following equation;

$$\%Moisture = \frac{W_m - W_d}{W_m} \times 100$$

W_m = weight of moist sample

W_d = weight of dry sample

3.2.5. Carbohydrate Determination

Dried test tubes were added 0 to 3ml standard sugar, and the volumes of test tubes were made up to 3ml with distilled water, thereby making concentrations ranging from 0 to 750 mg. 1mL DNS reagent was added to all the test tubes and mixed gently. The test tube was plugged with cotton or marble and placed in a boiling water bath for 5 minutes. The tubes were then removed, allowed to cool to ambient temperature, and immediately placed in a cuvette, and the concentration of sugar was determined in a UV- Vis Spectrophotometer at 540 nm using distilled water as the blank. Total sugar concentrations were estimated from a standard curve by comparing the absorbance of the standard glucose solution to that of the unknown sugar solution (Ahmed et al., 2020; Mohammed et al., 2017).

3.2.6. Determination of Vitamin C

Standard vitamin C solution (ascorbic acid) was prepared in different concentrations of 250, 500, 750, and 1000mg/L. Exactly 10ml of sample was measured into a 250ml conical flask, and

100ml of distilled water. The mixture was swirled gently, and 1.0ml starch solution was added and swirled to mix properly. The mixture was immediately titrated using 0.005M iodine solution prepared by adding 1.3g iodine mixed with 2g potassium iodide in 1000 mL of distilled water. The endpoint of the titration is identified as the first permanent trace of a dark blue-black colour due to the starch-iodine complex. Standard calibration was conducted by the titration of standard solutions of ascorbic acid, aliquot solutions, and noting the titration volume (Ahmed et al., 2020; Mohammed et al., 2017).

3.2.7. Drying Kinetics

3.2.7.1. Drying Rate

The drying rate of the okra and tomato samples was determined using the standard drying rate expression adapted from previous studies (Aregbesola et al., 2020; Mohammed et al., 2017). The drying rate was calculated as the ratio of the change in sample moisture content to the corresponding change in drying time, as shown in Equation (1):

$$Drying\ Rate = \frac{M_{t+\Delta t} - M_t}{\Delta t}$$

Where M_t is the moisture content of the sample at a given time (g H_2O/g dry matter) $M_{t+\Delta t}$ is the moisture content after a specified time interval, and Δt is the corresponding drying period (h).

The calculated drying rates were plotted against drying time to obtain the drying rate curves for okra and tomato samples at the tested temperatures. This approach enabled a comparative analysis of moisture migration and heat transfer behaviors across the two commodities. The methodology aligns with established models for evaluating thin-layer drying kinetics in

biological materials (Zhang et al., 2022; Omodara et al., 2023), which emphasize the transition from the constant-rate to the falling-rate period during dehydration of high-moisture foods.

3.2.7.2. Drying Curve and Arrhenius Relationship

The drying curve describes the relationship between moisture ratio and drying time for fish, okra and tomato samples under varying temperature conditions. The drying rate constant (k) for each temperature was obtained from the exponential form of the moisture ratio equation expressed as:

$$MR = e^{-kt}$$

where MR is the moisture ratio (dimensionless), k is the drying rate constant (min^{-1}), and t is the drying time (min). The slope of the linearized plot of $\ln MR$ against time (t) yielded the k-values for each drying temperature.

The temperature dependence of the drying rate constant was further analyzed using the Arrhenius-type relationship, which correlates the rate constant with absolute temperature (T) as follows:

$$K = k_0 e^{E_a/RT}$$

where k_0 is the pre-exponential factor, E_a is the activation energy (kJ/mol), R is the universal gas constant (8.314 J/mol·K), and T is the absolute temperature (K). A plot of ln(k) against 1/T produced a straight line, and the slope ($-E_0$ /R) was used to determine the activation energy for the drying process.

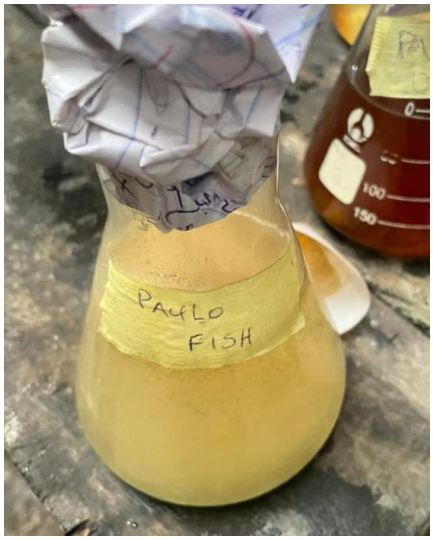

Plate 3.1a: Fish sample

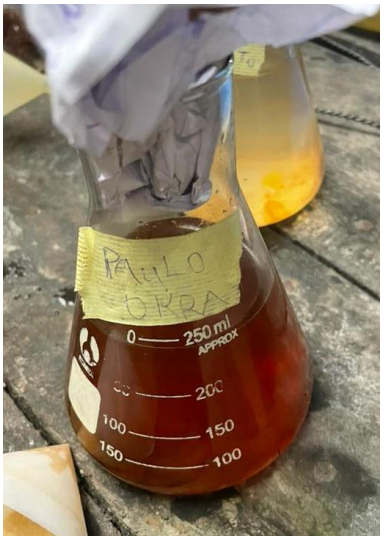

Plate 3.1b: Okra sample

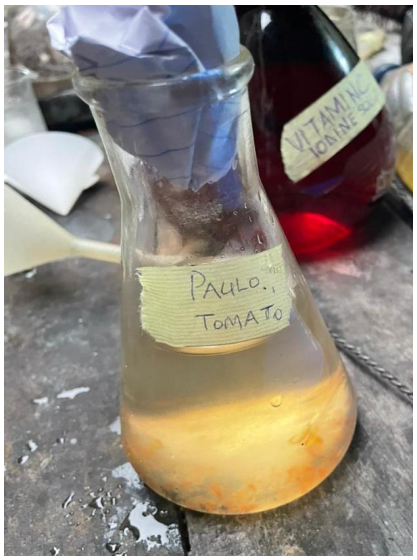

Plate 3.1c: Tomato sample

Plate 3.1d: Okra Mixture

Plate 3- 1: Sample Preparation of the Okra, Tomato, and Fish

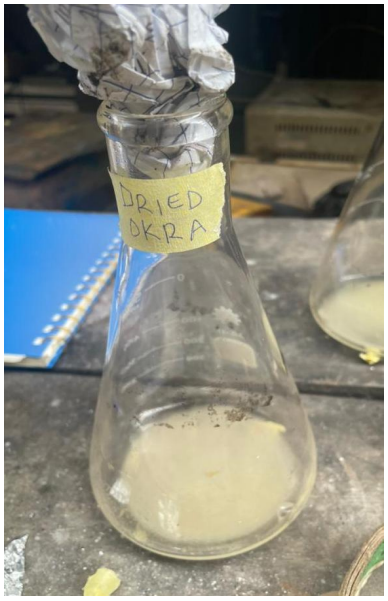

Plate 3.2a: Okra sample

Plate 3.2b: Fish sample

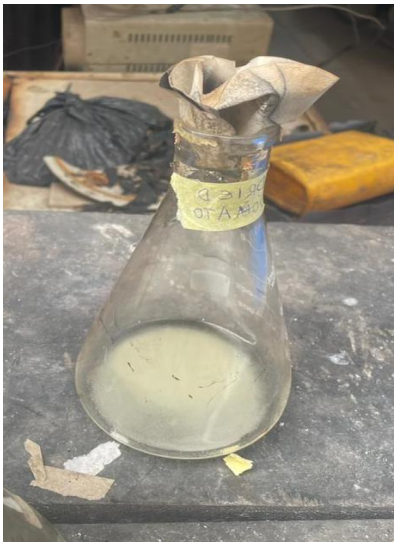

Plate 3.2c: Tomato sample

Plate 3.2d: Filtration set-up

***Plate 3- 2*: Dried pictures of the prepared samples**

CHAPTER FOUR

RESULTS AND DISCUSSION

4.2. Moisture Content Test Result Analysis

Drying is a crucial preservation method that reduces moisture content to inhibit microbial proliferation and enzymatic spoilage (Nakra et al., 2025). However, it may also influence heat-sensitive nutrients such as proteins and vitamins. The experimental results of this study evaluated these effects under controlled oven-drying conditions where okra, tomato, and fish were dried at 60°C to ensure uniform heat transfer and minimize oxidative degradation, as recommended by Ahmed et al. (2020) and Mohammed et al. (2017). The physicochemical analyses of the fresh and dried samples of okra (*Abelmoschus esculentus*), tomato (*Solanum lycopersicum*), and fish (*Clarias gariepinus*) revealed significant variations in nutrient composition following thermal drying. The results are further discussed and summarized in Tables 4.1, 4.2, 4.3, and 4.4, while the graphical representations of drying kinetics and nutrient variations are illustrated in Figures 4.1.

4.3. Crude Protein Content

From Table 4.1, the protein content showed slight increases across all samples after drying. In fish, protein increased from 24.72 % to 25.61 %, in okra from 2.73 % to 2.75 %, and in tomato from 1.62 % to 1.65 %. This increase is attributed to moisture loss, which concentrates macronutrients in the dried matrix rather than indicating an actual increase in protein molecules. Similar observations were reported by Ahmed et al. (2020) and Mohammed et al. (2017), who noted that dehydration effectively enhances the relative proportion of nitrogenous compounds in both plant and animal tissues.

Table 4.1: Protein Content of Fresh and Dried Samples

Sample	**Fresh (%)**	**Dried (%)**
Fish	24.72	25.61
Okra	2.731	2.748
Tomato	1.621	1.647

In fish, the protein stability can also be linked to moderate drying temperature at 60°C, which prevents denaturation and Maillard reactions that typically degrade amino acids at higher temperatures above 80°C (Abraha et al., 2018; Ajao et al., 2025). These findings demonstrate that controlled drying at low temperatures retains essential proteins while ensuring microbial safety.

4.4. Vitamin C Content

Vitamin C content experienced a notable decrease across all samples after drying, as shown in Table 4.2. In fish, it reduced from 0.722 % to 0.125 %, in okra from 19.64 % to 11.71 %, and in tomato from 21.03 % to 13.42 %. The observed losses, which ranged between 40 and 80 % are consistent with the findings of (Pratama et al., 2023) who reported similar reductions during heat exposure due to oxidation of ascorbic acid. Vitamin C is highly thermolabile and degradation occurs via oxidative and hydrolytic mechanisms, especially when moisture and oxygen are present (Ahmed et al., 2020). Despite these losses, residual vitamin C levels remain nutritionally relevant, showing that mild drying conditions below 60°C can preserve a portion of antioxidant potential in both vegetables and fish. This is also established by the study reported by

Giannakourou & Taoukis (2021), which recommended low-temperature drying as a sustainable approach for retaining bioactive compounds in tropical foods.

Table 4.2: Vitamin C Content of Fresh and Dried Samples

Sample	**Fresh (%)**	**Dried (%)**
Fish	0.722	0.125
Okra	19.64	11.712
Tomato	21.034	13.422

4.5. Carbohydrate Content

From the results shown in Table 4.3, Carbohydrate levels showed a negligible change after drying. In fish, carbohydrate remained constant at 3.29 %, in okra it changed slightly from 1.204 % to 1.207 %, and in tomato from 5.113 % to 5.114 %. This indicates that carbohydrates are relatively thermally stable under the temperature range employed. Previous studies by Afolabi et al. (2022) confirm that moderate heat processing does not significantly alter carbohydrate fractions unless caramelization or enzymatic browning occurs, which was prevented in this experiment due to moisture control.

Table 4.3: Carbohydrate Content of Fresh and Dried Samples

Sample	**Fresh (%)**	**Dried (%)**
Fish	3.29	3.29
Okra	1.204	1.207
Tomato	5.113	5.114

4.6. Drying Kinetics of Fish Moisture Removal

4.6.1. Moisture Loss

The drying kinetics of fish are shown in Table 4.4. and Figure 4.1. It revealed that the rate of moisture loss increased proportionally with temperature and time. At 60°C, the maximum moisture removal was 35.29 % after 150 minutes, whereas at 100°C it reached 41.84 % within the same period. The rapid initial drying phase between 0 and 90 minutes corresponds to the constant rate period dominated by surface water evaporation, while the subsequent phase represents the falling rate period where internal diffusion governs moisture migration (Hussein et al., 2018).

Table 4.4: Moisture Loss Profile of Fish at Varying Drying Temperatures

Time	**60°C**	**80°C**	**100°C**
30	3.872	4.961	7.684
60	5.833	6.371	9.935
90	13.628	17.542	19.826
120	21.722	28.833	32.739
150	35.287	39.774	41.836

These results corroborate the diffusion-controlled model of drying described by Mohammed et al. (2017), confirming that higher temperatures enhance evaporation rates but may compromise heat-sensitive nutrients if not controlled. Therefore, 60°C was selected as the optimum drying temperature for further analyses to balance efficiency and nutrient retention.

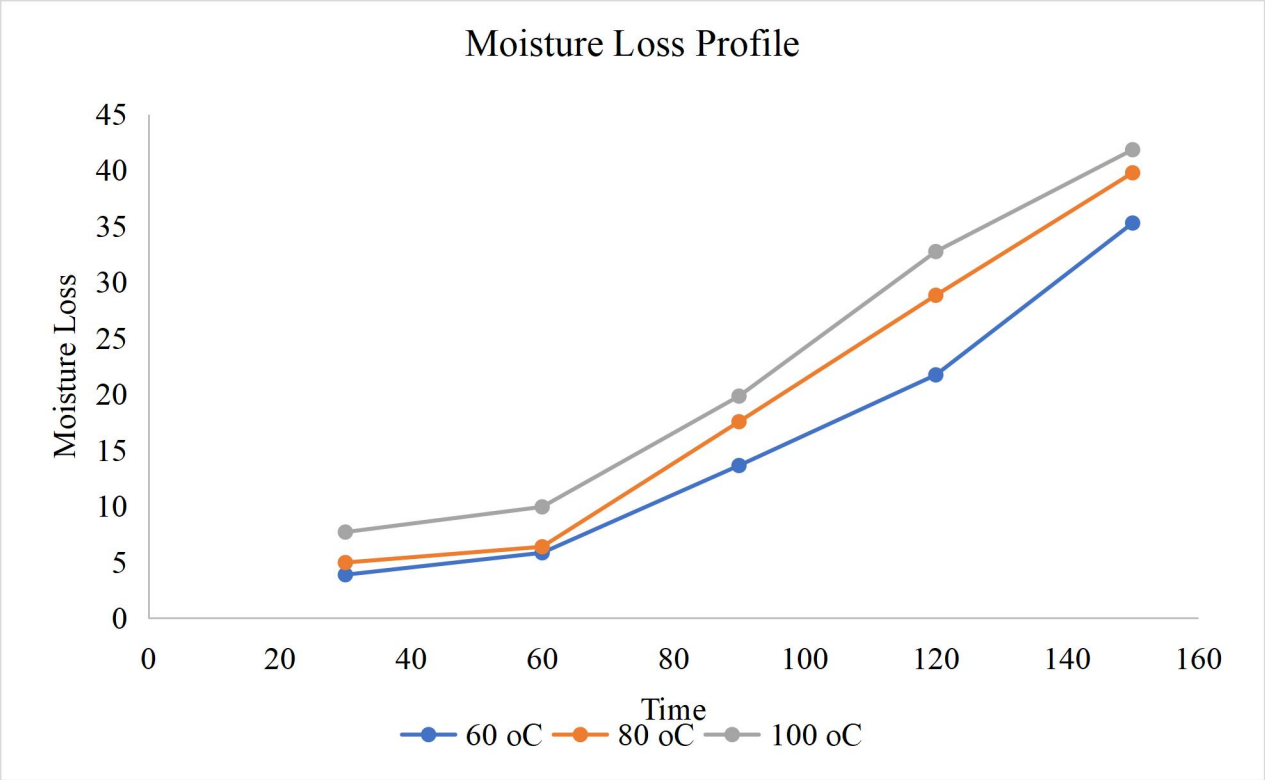

Figure 4- 1: Moisture Loss Profile curve for Fish

4.6.2. Drying Rate and Drying Rate Constant

The drying kinetics of fish at 60°C, 80°C, and 100°C are shown in Figure 4.2, where the natural logarithm of the moisture ratio (Ln MR) was plotted against drying time. The linear trend observed across all three temperatures indicates that the drying process obeys first-order kinetics, implying that the rate of moisture removal is directly proportional to the amount of moisture remaining in the sample. This relationship is consistent with the Newton's law of drying, which assumes that internal moisture diffusion is the dominant mechanism controlling water removal (Mohammed et al., 2017; Ahmed et al., 2020).

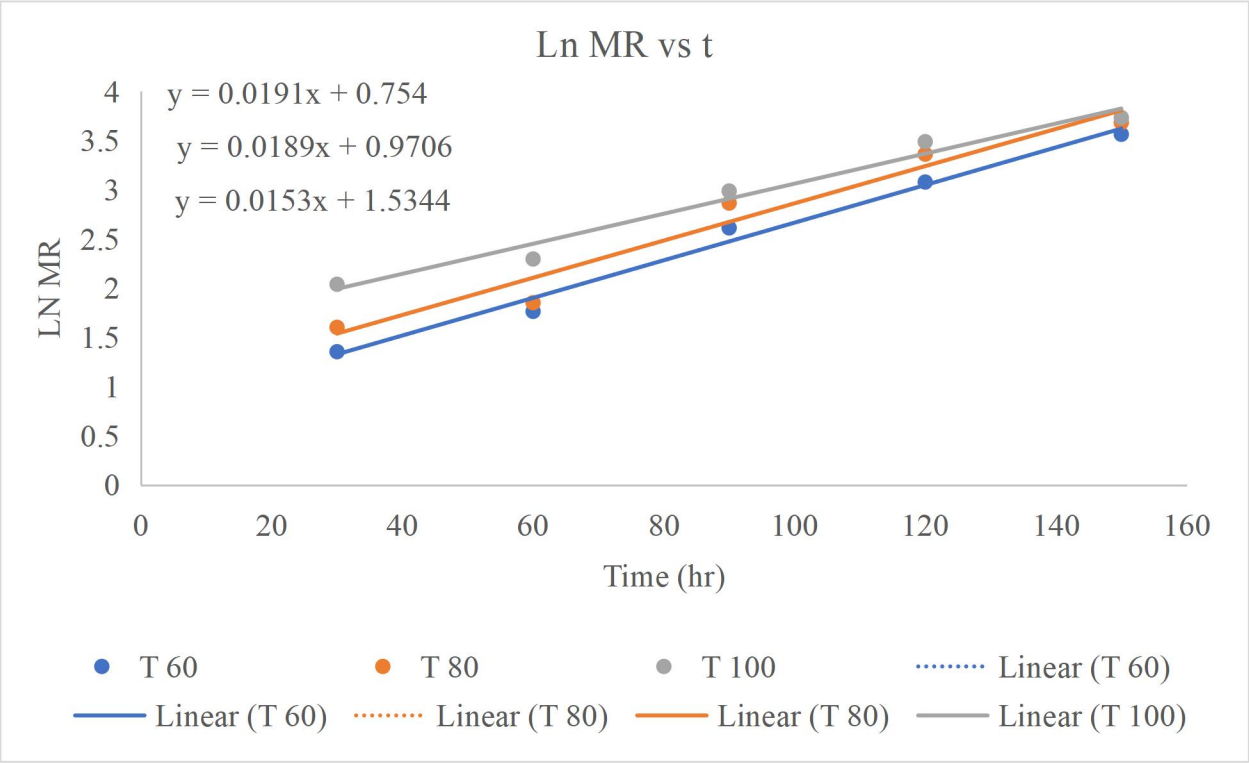

Figure 4- 2: graph of Ln Mr vs t

The linear regression equations derived from the plot were

T 60 ºC: y = 0.0153x + 1.5344

T 80 ºC: y = 0.0189x + 0.9706

T 100 ºC: y = 0.0191x + 0.754

The slope of each line represents the drying rate constant (k), which quantifies how quickly moisture is removed under a specific temperature. The values of k were calculated as 0.0153 min^{-1} for 60°C, 0.0189 min^{-1} for 80°C, and 0.0191 min^{-1} for 100°C. Although the drying rate constant generally increases with temperature due to enhanced molecular diffusion and vapor pressure gradients, the present result shows a slight deviation from the expected order. The drying constant at 100°C was marginally higher than that at 60°C and 80°C, confirming that

prolonged exposure to high heat will result in higher moisture loss. Although the prolonged heating at higher temperature may have altered the microstructure of the fish tissue, causing shrinkage, case hardening, and reduced internal diffusivity This observation is consistent with the findings of Mohammed et al. (2017) and Ahmed et al. (2020), who reported that excessive drying temperatures can lead to the formation of a hardened surface layer that restricts internal moisture movement, thereby lowering the overall drying rate. At moderate temperatures, however, the tissue structure remains more porous, allowing for efficient water migration. From a quality standpoint, lower drying temperatures (around 60°C) provided a favorable balance between efficient moisture removal and nutrient preservation. Higher temperatures (80–100°C) may enhance the drying rate initially, but can result in protein denaturation, lipid oxidation, and significant vitamin loss if not carefully controlled. Therefore, 60°C was considered an optimal drying condition for maintaining both structural integrity and nutritional quality of the fish samples. This drying rate constant result confirms that the thermal application at moderate temperatures ensures efficient drying while preserving the biochemical stability of the fish.

4.6.3. Drying Rate and Arrhenius Relationship

The temperature dependence of the drying rate constant was further analyzed using the Arrhenius-type relationship, which correlates the rate constant with absolute temperature (T), as shown in Figure 4.3.

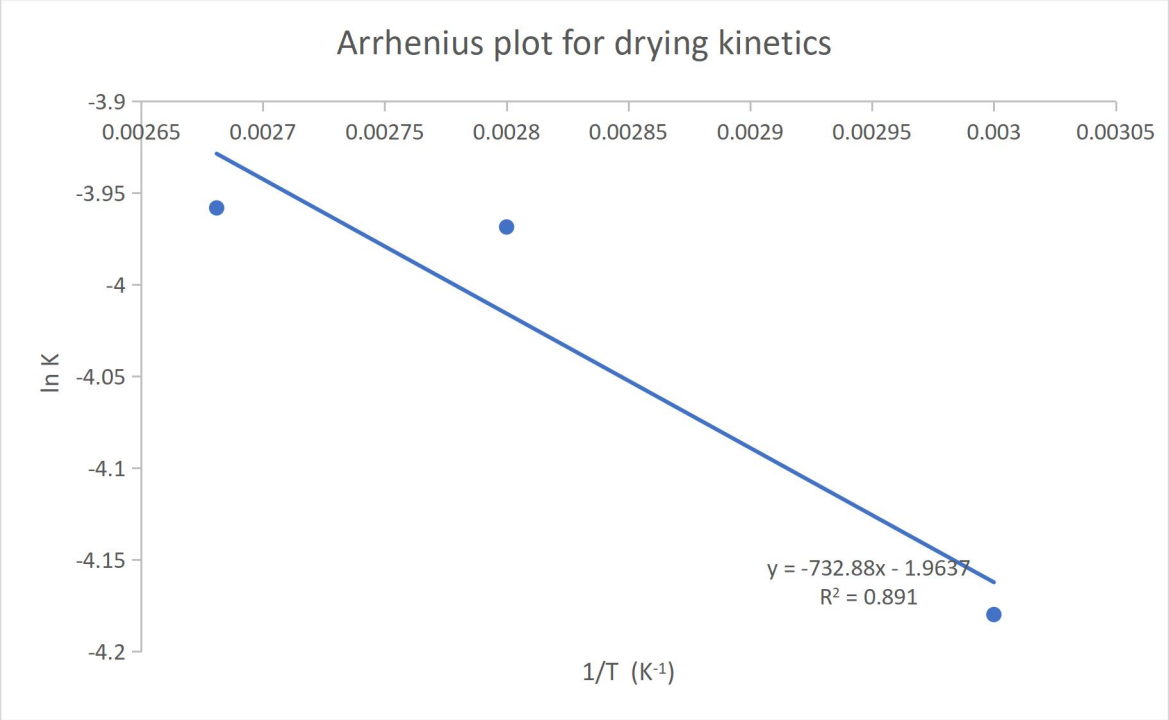

Figure 4- 3: graph of In k vs 1/T

From the regression line, the activation energy (Ea) was calculated to be approximately **6.093 kJ/mol**, suggesting a moderate energy requirement for moisture diffusion during fish drying. This relatively low activation energy indicates that moisture removal occurred primarily through surface evaporation and mild internal diffusion, which aligns with controlled drying conditions aimed at minimizing heat damage to nutrients and structural integrity of the fish (Komolafe et al., 2018).

The same procedure can be applied to Okra and Tomato to obtain results for both.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The study showed that controlled drying of fish (*Clarias gariepinus*), okra (*Abelmoschus esculentus*), and tomato (*Solanum lycopersicum*) effectively reduced moisture content, enhancing shelf stability and preventing microbial spoilage. From the results obtained, Protein content slightly increased due to water loss concentration, vitamin C decreased owing to heat sensitivity, while carbohydrate levels remained stable for all the samples. Also, the drying kinetics showed that 60°C provided the best balance between moisture removal and nutrient preservation, confirming its suitability for maintaining the nutritional and structural integrity of dried fish, okra, and tomato under controlled laboratory conditions. The drying followed first-order kinetics, with drying rate constants (k) of 0.0153, 0.0189, and 0.0191 min^{-1} at 60°C, 80°C, and 100°C, respectively. The activation energy (Ea) of 6.093 kJ/mol indicated a moderate energy requirement for moisture diffusion, indicating that drying was governed mainly by surface evaporation and mild internal diffusion.

5.2 Recommendations

The following suggestions are recommended for future experimental work based on this study:

i. Further research should examine the influence of different drying air velocities and humidity levels on drying rate, nutrient preservation, and product rehydration characteristics.

ii. Studies should be conducted on the application of pre-treatment techniques such as blanching, antioxidant dipping, and osmotic dehydration to improve color retention, texture, and vitamin stability.

iii. The drying kinetics of okra and tomato should be modeled using more advanced equations such as Page, Henderson–Pabis, or Midilli models to better predict drying behavior and moisture diffusivity.

iv. Comparative analysis between solar, convective, and freeze-drying methods should be performed to assess energy efficiency and nutrient retention under tropical conditions.

v. A techno-economic analysis incorporating the activation energy data (5.63 kJ/mol) should be performed to design cost-effective, energy-efficient drying systems suitable for small- and medium-scale food processors.

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APPENDIXES

Table of Ln (MR) VS t

Time	**LN (T 60ºC)**	**LN (T 80ºC)**	**LN (T 100ºC)**
30	1.35377117	1.60160733	2.039140245
60	1.76353145	1.85175644	2.296063876
90	2.6121265	2.86459801	2.986994208
120	3.07832557	3.36152056	3.488567028
150	3.56351462	3.68321343	3.733757213

Table of Ln k vs 1/T

Temperature (°C)	**Temperature (K)**	**1/T (K^{-1})**	**k (min^{-1})**	**ln k**
60	333.15	0.00300165	0.0153	−4.1799
80	353.15	0.00283166	0.0189	−3.9686

100	373.15	0.00267989	0.0191	−3.9581