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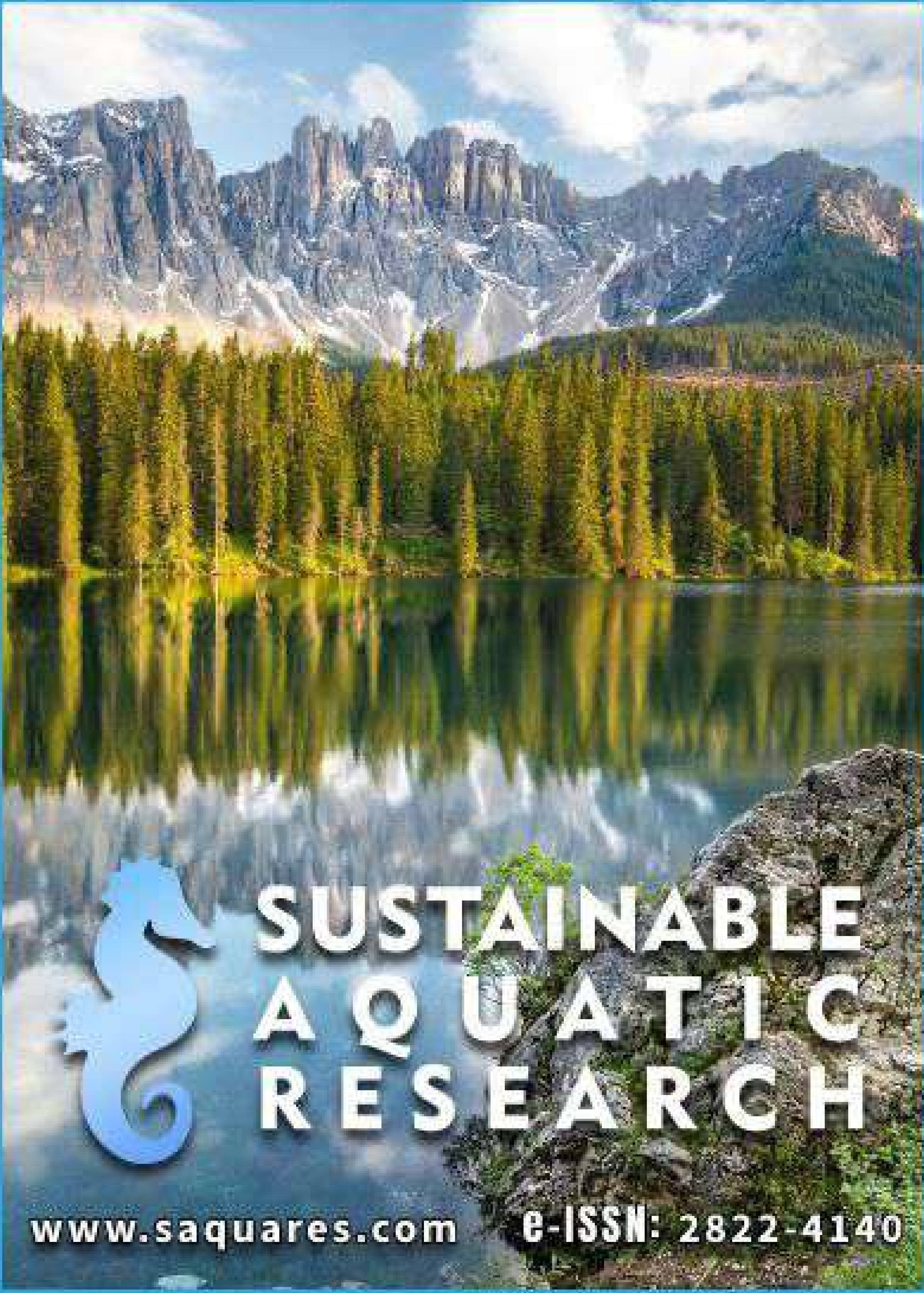

SUSTAINABLE AQUATIC RESEARCH

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SUSTAINABLE AQUATIC RESEARCH
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How sustainable is sustainable living without sustainable aquatic research?

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Aims & Scope

Aims

SUSTAINABLE AQUATIC RESEARCH (SAquaRes) aims to play an important role in advancing and understanding of aquatic sustainability. The most important aim of SAquares is “to put the research on aquatic sustainability at the focus of science. Sustainable life in the world will be realized with a sustainable aquatic ecosystem."

Scope

The scope of SAquaRes includes papers from non-traditional scientific areas such as sustainability science, social-ecological systems, ornamental, conservation, and restoration, and also the traditional priorities of its sections related to aquatic environments *(the list below is given in alphabetical order)*:

- Alternate Aquatic Energy Technologies
- Aquatic Sustainability
- Aquaculture and Fisheries
- Aquatic Environmental Interactions
- Aquatic biochemistry
- Aquaculture and environment
- Aquaculture and risk assessment
- Aquatic ecotoxicology
- Aquatic living resources
- Aquatic Biofuels
- Aquatic Biotechnology
- Climate Change and global warming
- Coastal Zone Management
- Ecofriendly aquaculture studies
- Environmental impacts of aquaculture
- Fish Health and Welfare
- Human and Environmental Risk Assessment
- Hydrology and Water Resources
- Impacts of global environmental changes
- Innovative livestock and farming systems
- Marine and Freshwater Biology
- Marine and Freshwater Pollution
- Seafood Quality and Safety
- Sustainable and Renewable Resources
- Sustainable Aquatic Ecosystem
- Sustainability assessment and design of aquacultural systems and decision support tools
- Water Quality and Pollution
- Wastewater Treatment
- And more research focused on sustainability

SUSTAINABLE AQUATIC RESEARCH

2025 •Volume 4 • Issue 1
www.saquares.com

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TABLE OF CONTENTS

Vol. 3 No. 1 (2024): SAquaRes
Published: 2024-04-30

Editorial

Original Articles

SUSTAINABLE AQUATIC RESEARCH

2025 •Volume 4 • Issue 1
www.saquares.com

How sustainable is sustainable living without sustainable aquatic research?

Review Articles

SUSTAINABLE AQUATIC RESEARCH
www.saquares.com

Sustainable Aquatic Research (2025) 4(1):1-3
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EDITORIAL

How much water is in prison in our world?

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The hydrological cycle describes the continuous movement of water above and below the Earth's surface. This cycle includes the journey of water from the oceans and seas to the atmosphere, from the atmosphere to the Earth's surface, and back to the seas and oceans. This term reflects the fact that Earth's water resources neither increase nor decrease over time. Is the hydrological cycle sustainable today? Could it be delayed due to unnatural processes?

About 97.5% of the total amount of water in the world is found in oceans, as salt water. A large part of the remaining 2.5% is trapped as fresh water in groundwater and glaciers. 68% of this fresh water is found in glaciers and glaciel areas, 30% in groundwater, and 0.3% in lakes and rivers. In other words, most of the fresh water on the planet is inaccessible to us. Nature is the source of water; therefore our ability to support additional human lives on planet Earth depends upon the protection of nature and the continued operation of the water cycle (Hunt 2004).

Can water in prison be expressed, especially water trapped in groundwater and glaciers or is it more accurate to express it as a reserve? If these sources are inaccessible, the amount of directly usable fresh water is quite low. For example, only 0.3% of the usable fresh water on Earth is found in lakes, rivers and the atmosphere. But doesn't this water enter the hydrological circulation? Yes, water sources, such as groundwater and glaciers, enter hydrological circulation, but this process is very slow and in some cases takes an extremely long time. The hydrological cycle is a system in which water constantly moves in the atmosphere, on the ground, and in underground reservoirs (Linton, J. 2008). However, the speeds at which groundwater and glaciers enter the hydrological cycle are different. For example, groundwater is formed when rainwater filters through the ground surface and passes underground. This water is stored in underground aquifers, where it moves more slowly than other water sources in the hydrological cycle. Glaciers store most of the water in frozen form (Scanlon et al., 2023). Over time, this water melts especially with climate change and temperature increases, becomes liquid and participates in the hydrological cycle. The water formed by the melting of glaciers usually reaches the oceans through groundwater or rivers. However, this process may take many years.

Although groundwater and glaciers are included in the hydrological cycle, their access and the speed at which they participate in the cycle are limited. Therefore, these resources may generally be considered "reserves", and it takes a very long time for them to be included in the water cycle. Is it possible to measure this speed? Is it related to climate change and global warming?

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The rate of glacier melting varies depending on climatic factors, especially temperature increase and precipitation. Glacier melting may be monitored by processes, such as glacier mass loss and the inclusion of meltwater in the hydrological cycle. Satellite and aerial photographs and Glacier Monitoring Stations are used to measure the rate of glacier melting (Scanlon et al., 2023).

Climate change may alter precipitation patterns. For example, more precipitation can increase the rate of groundwater renewal in some regions. However, increasing temperatures and greater evaporation may also reduce water resources. In addition, extreme droughts may negatively affect the rate of groundwater renewal. Global warming directly affects the rate at which glaciers melt. Rising temperatures accelerate the rate at which glaciers melt, allowing more freshwater to flow into rivers and oceans. This process raises sea levels and alters local ecosystems. Glacial melt may also have an impact on groundwater levels. Melted glacier water may recharge groundwater reservoirs, but only in certain areas (Kuang et al., 2024). For example, when glaciers in mountainous areas melt, they may seep into the ground, increasing groundwater levels.

The rate at which both groundwater and glaciers participate in the hydrological cycle may be approximated and monitored by various methods. However, since these processes are very slow, long-term observations are required to understand their effects. Climate change and global warming may accelerate these processes, and could have significant effects, especially in terms of melting glaciers and changes in the groundwater cycle. Therefore, climate change may affect the accessibility and distribution of these resources, making water resource management extremely difficult (Douville et al., 2022; Kuang et al., 2024).

However, what we really want to emphasize in this article concerns “liquids in bottles that are discarded”, this is a different issues and concerns every individual and whose use has increased relatively in the last 100 years and continues to do so. Changing this practice is the responsibility of every individual.

When we were about to throw away the last quarter liter of drinks, we realized that there was liquid in them (like fresh water and cola in plastic bottles). What should we do? We poured the fresh water into the flowers and the cola into the sink. We could estimate how long that water would remain trapped in plastic bottles. About 200 years. We have always paid attention to this since then, if it becomes more widespread, it will affect all foods containing liquid. Ice left in cold drinks, water wasted with meals... We got very interesting answers when we asked our students. What do you do with the liquids left in plastic bottles? Some give them to aquariums, some to flowers. We ask in the restaurants we go to... what do you do? By the way, how much water or liquid is currently bottled in the world and not in the natural cycle? This is also a subject that needs to be investigated... Another research question could be plastic contamination of the water waiting in plastic bottles... Is it possible to stop using plastic? If not, shouldn't we limit it or be careful?

The total number of people who have lived (and continue to live) in the last 100 years is ~100-110 billion individuals (8.2 billion of them are still alive). How many of these individuals discard plastic bottles containing potable water? Moreover, plastic, which has entered human society in recent years, has another negative effect on natüre, i.e. the lack of decomposition These plastic bottles trap potable water. The question to be answered concerns how much water a person may waste by entrapment in plastic bottles throughout their lifespan? The answer is likely to be a staggering amount!Isn't throwing water in the trash a temporary interruption to the water cycle? Which is more important - freeing water or recycling plastic bottles.

Come on, let's recycle plastic bottles from now on, and free the water inside them to nature.

Our environment needs to be made aware of the sustainable use of water, one of the basic resources of life Especially our water, which is used unconsciously, does not take place in the normal hydrological cycle and remains in plastic materials -the risk of contamination of microplastics to the water is another issue to be disscuss at this duration-, and it takes centuries for these materials to decompose in nature.

The primary element that needs to be planned is to raise awareness of the importance of water in children starting from their basic education, and the state needs to educate the public on this issue with encouraging meetings. Both scientific and educational meetings should be organized on the fact that water is a necessary element not only for humans but also for all living things around us and the ecological order of the world.

Water is life. Let's protect our lives.

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RESEARCH PAPER

Nutritional Profile of Economically Valuable Fish Species in the Lake Victoria Basin: Implications for Food and Nutrition Security Among Local Communities

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Abstract

Fish can help address human nutrient deficiencies but is often overlooked in nutrition policies due to insufficient evidence. This study evaluates the nutritional profiles of five economically significant fish species in the Lake Victoria Basin: Nile tilapia (*Oreochromis niloticus*), Nile perch (*Lates niloticus*), Silver cyprinid (*Rastrineobola argentea*), African catfish (*Clarias gariepinus*), and lungfish (*Protopterus aethiopicus*). A comprehensive literature search was conducted across Google Scholar, PubMed, Web of Science, and Scopus. Studies were screened based on their relevance, methodological rigor, and focus on moisture, ash, lipid, protein content, and fatty acid composition, resulting in the selection of 46 peer-reviewed studies published within the last 20 years. Nile tilapia contains 69.36%–80.03% moisture, 16.40%–23.47% protein, 0.08%–3.77% lipid, and significant omega-3 polyunsaturated fatty acids (PUFAs) (18.9%–33.0%). Nile perch exhibits similar moisture (67.30%–79.6%) and protein (15.93%–22.51%) levels, with lipid content of 0.59%–4.16% and omega-3 PUFAs (12.47%–33.0%). Silver cyprinid shows high variability in protein (15.44%–79.44%) and lipid (0.09%–22.38%) content, with PUFAs comprising 21.68%–35.78%. African catfish has 69.16%–73.54% moisture, 19.93%–23.06% protein, and omega-3 PUFAs ranging from 27.9%–36.9%. Lungfish stands out for its fatty acid diversity, including 35.2%–49.2% PUFAs (13.0%–27.9% omega-3, 11.7%–30.0% omega-6). Although nutritional profiles vary due to environmental and biological factors, all species are nutrient-dense. Thus, promoting the sustainable harvesting and consumption of these fish can contribute substantially to improving dietary quality and nutrition security in communities reliant on Lake Victoria's fisheries.

Introduction

Lake Victoria, the largest freshwater lake in Africa, is a vital socio-economic linchpin for the East African region, underpinning the livelihoods, food security, and well-being of millions of people (Gesimba, 2020). With an estimated annual production exceeding 500,000 tonnes of fish (Outa et al., 2020), this vast water body not only generates substantial employment but also contributes significantly to both local and regional markets. While the lake supports a diverse array of fish species, only a handful—particularly silver cyprinid (*Rastrineobola argentea*, locally “omena”), Nile perch (*Lates niloticus*), and Nile tilapia (*Oreochromis niloticus*)—have emerged as commercially dominant (SDBF, 2023). Nile perch primarily caters to lucrative regional and international markets, while “omena” and Nile tilapia sustain more localized trade networks. Although indigenous species such as lungfish (*Protopterus aethiopicus*) and catfish (*Clarias gariepinus*) receive less attention in formal catch statistics, they remain culturally and nutritionally important to riparian communities (Okechi, 2022). Over generations, these fisheries have shaped dietary habits, economic structures, and culinary traditions, ensuring steady access to nutrient-rich fish for households around the lake (Aura et al., 2022). The reliance on these fisheries is not merely an economic convenience but a nutritional necessity, as fish consumption in this region represents a crucial strategy for mitigating protein deficiencies and supporting balanced diets.

In recent decades, global fish consumption has surged, reflecting a growing appreciation of fish as a source of high-quality protein and health-promoting nutrients (Bakhsh et al., 2024). This trend is mirrored in the Lake Victoria Basin, where escalating demand for fish aligns with broader nutritional imperatives and health objectives. Central to fish’s appeal are their n-3 long-chain polyunsaturated fatty acids (LC-PUFAs)—notably eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA)—which have been associated with cardiovascular benefits, optimal neurodevelopment, and reduced risk of metabolic disorders (Martínez-Martínez et al., 2020; Mesa et al., 2021). Beyond lipids, fish also offer a dense matrix of essential nutrients, including high-quality proteins, peptides, and amino acids like methionine, lysine, and taurine, which are often limited in terrestrial meats (Khalili Tilami & Sampels, 2018; Erbay & Yesilsu, 2021). These amino acids and bioactive peptides have drawn scientific interest due to their potential in supporting muscle growth, immune functions, and overall health, making fish a critical ingredient in strategies aimed at alleviating malnutrition and micronutrient deficiencies in vulnerable populations.

However, the nutritional profile of any given fish species is not fixed; it can vary markedly due to multiple ecological and physiological factors. Diet composition, trophic level, and the underlying productivity of the aquatic ecosystem all shape the nutrient content of fish tissues (da Silveira et al., 2020). In Lake Victoria, this variability is particularly salient, given ongoing ecological changes, fluctuating water quality, and shifts in species composition. Additionally, differences in feeding habits—whether planktivorous, benthivorous, or piscivorous—can influence fatty acid profiles and protein content. Environmental conditions such as temperature, dissolved oxygen, and nutrient availability may also affect fish metabolism and nutrient accumulation, adding another layer of complexity to understanding fish-based nutrition within the region (da Silveira et al., 2020). Further, wild fish in Lake Victoria consume natural diets consisting of plankton and benthos, thereby acquiring LC-PUFAs directly from algae—the foundational producers of these beneficial fatty acids (Tilami et al., 2018; Hundal et al., 2021). Freshwater, non-carnivorous species are particularly adept at converting α-linolenic acid (ALA) into more physiologically relevant LC-PUFAs, a trait that not only elevates their nutritional value but also aligns with calls for sustainable, ecosystem-based fisheries management (Tilami et al., 2018).

Despite the crucial role of fisheries in supporting local diets and the evident nutritional value of fish, their contributions often remain underrepresented in policies and dietary guidelines. Decision-makers require detailed, species-specific nutritional data to develop interventions that leverage fish for public health improvements, address micronutrient deficiencies, and promote food system resilience. Yet, the current literature on the nutrient composition of Lake Victoria's most economically significant species is fragmented, with limited quantitative data on their proximate composition, fatty acid profiles, mineral and vitamin content. This paucity of standardized, reliable nutritional information hampers the ability of health practitioners, nutritionists, and community leaders to design evidence-based nutrition programs (Koehn et al., 2022). It also constrains efforts to align fisheries production with evolving dietary recommendations and sustainability goals—objectives that are gaining urgency as governments and international agencies emphasize nutritious, low-impact food sources to achieve sustainable development targets.

As global emphasis intensifies on biodiversity conservation, climate-smart food systems, and nutrition-sensitive policies, a comprehensive understanding of the nutrient profiles of key fish species from Lake Victoria could inform more nuanced approaches to fisheries governance and food security strategies. Detailed insights into the protein, lipid, and micronutrient composition of these fish can help pinpoint their contributions to human health, guiding interventions that bolster dietary diversity and long-term well-being. Such knowledge is particularly relevant for Kenya and other East African nations striving to enhance their nutrition policies, support small-scale fisheries, and respond proactively to environmental changes threatening freshwater ecosystems.

This study aims to address these knowledge gaps by synthesizing the available literature on the nutritional composition of five economically important fish species from the Lake Victoria Basin: Nile tilapia (*O. niloticus*), Nile perch (*L. niloticus*), African catfish (*C. gariepinus*), silver cyprinid (*R. argentea*), and Marbled lungfish (*P. aethiopicus*). Specifically, it compiles data on proximate composition—moisture, ash, lipid, protein content—and fatty acid profiles, as well as minerals and other essential nutrients. In doing so, it provides a baseline for policymakers, nutrition experts, and fisheries managers to harness the full potential of these species, improving nutrition security, guiding sustainable resource management, and contributing to socio-economic development in the Lake Victoria region. This study sets the stage for more targeted interventions, informed dietary recommendations, and strategic frameworks that maximize the health benefits and sustainability of freshwater fisheries.

Materials and methods

The selection of fish species for this study was guided by their economic significance within the Lake Victoria Basin. Species chosen for the review were based on their prominence in local fisheries, market demand, and contribution to the socio-economic well-being of communities around the lake (SDBF, 2023). The species included in this study are Nile tilapia, Nile perch, silver cyprinid, African catfish, and lungfish. A comprehensive literature search was conducted to identify relevant studies on the nutritional composition of the selected fish species. For the literature search, we used multiple electronic databases, including Google Scholar, PubMed, Web of Science, and Scopus. Keywords used in the search included:

- "Nutritive value" AND ("Lake Victoria Basin" OR "East Africa")
- "Nile tilapia," "Nile perch," "Silver cyprinid," "African catfish," "lungfish" AND ("fatty acid composition" OR "protein content" OR "lipid content" OR "mineral content")
- "Influence of temperature on fish nutrition" OR "seasonal variations in fish nutrient composition"
- "Effect of processing methods (smoking, drying, salting, freezing) on fish nutrition"
- "Age and size considerations in fish proximate composition"
- "Sex-based differences in fish nutrient profiles"
- "Sampling and analytical techniques for fish nutrient profiling"

The initial pool of articles was screened in two steps: first, by reviewing titles and abstract to eliminate irrelevant studies, and second, by examining full-texts to ensure they met all inclusion criteria. To be included, studies were preferably peer-reviewed articles, theses, or reports published in English; specifically analysing the nutritional composition (moisture, ash, lipid, protein content, and fatty acid profiles) of selected fish species from the Lake Victoria

Basin. Additionally, the research needed to be conducted within the past 20 years to ensure relevance and up-to-date information. Studies were excluded if they focused on fish species outside the Lake Victoria Basin, did not provide specific quantitative data on nutritional composition, or were published in languages other than English. Following this rigorous selection process, 46 papers were identified as suitable for the review, offering comprehensive and relevant data on the nutritional composition of the fish species in the Lake Victoria Basin.

Data extraction involved collecting quantitative data on the nutritional parameters of interest: moisture, ash, lipid, protein content, and fatty acid profiles, including the proportions of saturated, monounsaturated, and polyunsaturated fatty acids, and n-3 and n-6 fatty acids. Information on mineral content i.e., calcium, iron, magnesium, phosphorus, zinc, and copper was also extracted. The data from each study were tabulated, and the ranges of each nutritional component were calculated. This information was synthesized to provide a comprehensive overview of the nutritional composition of each fish species. The synthesis also involved identifying common trends and variations across studies to understand the influence of environmental, biological, and methodological factors.

Results and Discussion

Nutritional and mineral composition of selected fish species

Nile tilapia (Oreochromis niloticus)

Moisture content is a critical factor influencing the overall quality and shelf life of fish. Raymond et al. (2021) reported a moisture content range of 70.14% to 73.48%, while Muchiri et al. (2015) documented a higher range of 77.93% to 80.03% for tilapia caught from Lake Victoria. Abdulkarim et al. (2016) found moisture content ranging from 69.36% to 74.57% in tilapia collected during different seasons from Mwanza, Magu, and Sengerema on the Tanzanian portion of Lake Victoria. Therefore, the moisture content of Nile tilapia from Lake Victoria ranges from 69.36% to 80.03%, indicating the influence of environmental conditions and seasonal changes on the water content of Nile tilapia.

Ash content, indicative of the mineral composition of fish, varies across different studies. Raymond et al. (2021) reported an ash content of 1.59% to 2.07%, while Muchiri et al. (2015) found a lower range of 0.82% to 1.46%. Abdulkarim et al. (2016) observed a higher ash content ranging from 3.22% to 5.12%. These differences can be attributed to mineral availability in different habitats and seasons. Thus, the ash content of Nile tilapia from Lake Victoria ranges from 0.82% to 5.12%. Lipid content in Nile tilapia is an essential component that impacts the fish's flavor and energy value. Raymond et al. (2021) reported lipid content between 2.85% and 3.77%, while Muchiri et al. (2015) documented a slightly lower range of 1.67% to 3.35%. Abdulkarim et al. (2016) observed a broader range of 0.08% to 3.66%, reflecting the influence of dietary intake and environmental factors on fat accumulation in fish. This relatively low-fat content classifies Nile tilapia as a lean fish, making it a healthy option for consumers looking to reduce their fat intake. Therefore, the lipid content of Nile tilapia from Lake Victoria ranges from 0.08% to 3.77%.

Protein content is a crucial nutritional parameter, especially in regions where fish is a primary protein source. Raymond et al. (2021) reported protein content ranging from 18.72% to 23.47% in Nile tilapia, indicating its high protein value. Muchiri et al. (2015) found protein levels between 16.69% and 18.73%, while Abdulkarim et al. (2016) documented a range of 16.40% to 23.02%. Thus, the protein content of Nile tilapia from Lake Victoria ranges from 16.40% to 23.47%.

The fatty acid composition of Nile tilapia includes both saturated and unsaturated fatty acids, contributing to its nutritional and health benefits. The primary saturated fatty acids reported by Raymond et al. (2021) include caprylic acid (0.77%-1.03%), capric acid (0.05%-0.39%), lauric acid (1.10%-1.50%), myristic acid (2.77%-3.10%), palmitic acid (32.33%-37.30%), stearic acid (12.13%-14.37%), and arachidic acid (0.33%-0.70%). Kwetegyeka et al. (2006) reported myristic ranging 1.3% to 2.3%, pentadecanoic ranging 0.32% to 0.8%, palmitic acid ranging from 19.0% to 30.0% and stearic acid from 9.0% to 13.0% and Arachidic (2%-0.42%). Masa et al. (2011) found myristic acid (0.4%-

1.2%), pentadecanoic (1.1%-1.3%, palmitic acid (23.3%-27.9%), and stearic acid (10.6%-11.6%). Kwetegyeka et al. (2008) documented myristic acid (1.5%-2.3%), pentadecanoic (0.33%-0.41%), palmitic acid (21%-23%), and stearic acid (8.4%-10.4%) and Arachidic 0.21%-0.29%. The presence of these saturated fatty acids is essential for maintaining cellular integrity and metabolic functions. Based on the studies, the ranges for these saturated fatty acids in Nile tilapia from Lake Victoria are as follows: caprylic acid (0.77%-1.03%), capric acid (0.05%-0.39%), lauric acid (1.10%-1.50%), myristic acid (0.4%-3.10%), pentadecanoic (0.32%-1.3%), palmitic acid (19.0%-37.30%), stearic acid (8.4%-14.37%), and arachidic acid (0.2%-0.70%).

Unsaturated fatty acids, known for their health benefits, are also present in Nile tilapia. Raymond et al. (2021) reported palmitoleic acid (5.00%-6.70%), oleic acid (20.70%-21.00%), linoleic acid (6.90%-9.60%), alpha-linolenic acid (0.53%-0.80%), gamma-linolenic acid (0.40%-0.90%), eicosapentaenoic acid (2.17%-2.41%), and docosahexaenoic acid (3.03%-3.70%). Kwetegyeka et al. (2006) reported palmitoleic acid (2-4.5%), oleic acid (4.5%-6.1%), linoleic acid (1.90%-3.40%), alpha-linolenic acid (1.30%-2.50%), gamma-linolenic acid (0.32%-0.58%), eicosapentaenoic acid (2.8%-5.3%), and docosahexaenoic acid (10.0%-16.0%). Masa et al. (2011) found palmitoleic acid (1.70-2.50%), oleic acid (3.6%-4.2%), docosapentaenoic acid (10.0%-16.0%), alpha-linolenic acid (2.0%-2.6%), gamma-linolenic acid (0.5%-2.1%), eicosapentaenoic acid (3.1%-4.3%), and docosahexaenoic acid (12.9%-14.5%). Kwetegyeka et al. (2008) documented palmitoleic acid (3.5%-3.7%), oleic acid (4.2%-6.2%), linoleic acid (1.5%-2.5%), alpha-linolenic acid (2.0%-2.2%), gamma-linolenic acid (0.1-0.3), eicosapentaenoic acid (4.2%-5.0%), and docosahexaenoic acid (18.2%-22.6%). These unsaturated fatty acids, particularly omega-3 and omega-6 fatty acids, are known for their beneficial effects on cardiovascular health, anti-inflammatory properties, and essential roles in brain function. Therefore, the ranges for these unsaturated fatty acids in Nile tilapia from Lake Victoria are as follows: palmitoleic acid (3.5%-6.70%), oleic acid (4.2%-21.00%), linoleic acid (1.5%-9.60%), alpha-linolenic acid (0.53%-2.6%), gamma-linolenic acid (0.1%-2.1%), eicosapentaenoic acid (2.17%-5.3%), and docosahexaenoic acid (3.03%-22.6%) and docosapentaenoic acid (0.9%-6.2%).

The total fatty acid composition of Nile tilapia includes saturated fatty acids ranging from 32% to 50.14%, monounsaturated fatty acids from 11.0% to 21.83%, and polyunsaturated fatty acids from 27.98% to 48.4%. The polyunsaturated fatty acids include omega-3 fatty acids ranging from 18.9% to 33.0% and omega-6 fatty acids from 8.18% to 17% as reported by Kwetegyeka et al. (2006), Masa et al. (2011), and Kwetegyeka et al. (2008). These ranges indicate the diversity of fatty acid profiles in Nile tilapia from different studies.

The mineral composition of Nile tilapia includes calcium, iron, magnesium, phosphorus, and zinc. Raymond et al. (2021) reported calcium levels ranging from 0.377 mg/g to 0.487 mg/g, iron from 0.026 mg/g to 0.031 mg/g, magnesium from 1.221 mg/g to 1.423 mg/g, phosphorus from 0.272 mg/g to 0.328 mg/g, and zinc from 0.046 mg/g to 0.062 mg/g. These minerals are essential for various bodily functions, including bone health, oxygen transport, enzyme function, and cellular metabolism. The mineral content ranges for Nile tilapia from Lake Victoria are as follows: calcium (0.377-0.487 mg/g), iron (0.026-0.031 mg/g), magnesium (1.221-1.423 mg/g), phosphorus (0.272-0.328 mg/g), and zinc (0.046-0.062 mg/g). The ranges for various nutrients and mineral composition of Nile tilapia are summarized in Table 1.

Nile perch (Lates niloticus)

Moisture content is a critical attribute of Nile perch, influencing its texture, taste, and shelf life. Abdulkarim et al. (2016) reported a moisture content range of 67.30% to 75.04%, whereas Okeyo et al. (2009) observed a slightly higher range between 78.5% and 79.6%. High moisture content is typical of freshwater fish and contributes to their desirable tenderness and juiciness, essential for consumer preference.

Ash content, representing the total mineral content, varies significantly across different studies. Abdulkarim et al. (2016) reported ash content ranging from 2.97% to 5.98%, while Okeyo et al. (2009) found much lower values between 0.55% and 0.63%. Higher ash content indicates a rich presence of essential minerals such as calcium, iron, and phosphorus. The lipid content in Nile perch is relatively low, which is advantageous for health-conscious consumers. Abdulkarim et al. (2016) documented lipid levels ranging from 1.48% to 4.16%, and Okeyo et al. (2009) reported even lower lipid content, from 0.59% to 0.63%. Despite its low overall fat content, Nile perch contains a beneficial profile of fatty acids essential for maintaining good health. The low lipid content, coupled with high-quality fats, makes Nile perch an excellent dietary choice for reducing the risk of cardiovascular diseases.

Protein content is a significant attribute of Nile perch, making it a valuable source of high-quality protein for the local population. Abdulkarim et al. (2016) reported protein levels between 15.93% and 22.51%, while Okeyo et al. (2009) found slightly lower values, ranging from 17.7% to 19.8% (Table 2).

Table 1. Nutrient and mineral content ranges for wild Nile tilapia from Lake Victoria

Nutrients	Ranges	Reference
Moisture (%)	69.36-80.03	Raymond et al. (2021); Muchiri et al. (2015); Abdulkarim et al. (2016)
Ash (%)	0.82-5.12	
Lipid (%)	0.08-3.77	
Protein (%)	16.4-23.47	
Saturated fatty acids		
Caprylic Acid (C8:0)	0.77-1.03	Raymond et al. (2021); Kwetegyeka et al. (2006); Masa et al. (2011); Kwetegyeka et al. (2008)
Capric Acid (C10:0)	0.05-0.39	
Lauric Acid (C12:0)	1.1-1.5	
Myristic Acid (C14:0)	0.4-3.1	
Pentadecanoic (C15:0)	0.32-1.3	
Palmitic Acid (C16:0)	19.0-37.3	
Stearic Acid (C18:0)	8.4-14.37	
Arachidic Acid (C20:0)	0.2-0.7	
Unsaturated Fatty Acid		
Palmitoleic Acid (C16:1n-7)	3.5-6.7	Raymond et al. (2021); Kwetegyeka et al. (2006); Masa et al. (2011); Kwetegyeka et al. (2008)
Oleic Acid (C18:1n-9)	4.2-21.0	
Linoleic Acid (C18:2n-6)	1.5-9.6	
Alpha-Linolenic Acid (C18:3n-3)	0.53-2.6	
Gamma-Linolenic Acid (C18:3)	0.1-2.1	
Eicosapentaenoic Acid (C20:5)	2.17-5.3	
Docosahexaenoic Acid (C22:6)	3.03-22.06	
Docosapentaenoic acid (DHA;C22:5n-3)	0.9-6.2	
Total Fatty acids		
Saturated fatty acids (%)	32.0-50.14	Kwetegyeka et al. (2006); Masa et al. (2011); Kwetegyeka et al. (2008)
Monounsaturated fatty acids (MUFA) (%)	11.0-21.83	
Polyunsaturated fatty acids (PUFA) (%)	27.98-48.4	
PUFA N-3 (%)	18.9-33.0	
PUFA N-6 (%)	8.18-17.0	
Mineral Composition (mg/g)		
Calcium	0.377-0.487	Raymond et al. (2021)
Iron	0.026-0.031	
Magnesium	1.221-1.423	
Phosphorus	0.272-0.328	
Zinc	0.046-0.062	
Copper	0.0046-0.0073	

The fatty acid composition of Nile perch includes both saturated and unsaturated fatty acids, which are essential for various metabolic functions and overall health. Saturated fatty acids reported by Ogwok et al. (2009) include myristic acid (0.5%-1.08%), palmitic acid (22.45%-27.84%), and stearic acid (5.93%-7.74%). Namulawa et al. (2011) noted lauric (0.11%-0.25%), myristic acid (0.89%-4.1%), pentadecanoic (0.32%-1.34%), palmitic acid (20.3%-24.54%), and stearic acid

(8.33%-14.04%). Kwetegyeka et al. (2006) recorded myristic acid (0.71%-2.2%), pentadecanoic (0.3%-0.51%), palmitic acid (18.0%-24.0%), stearic acid (18.0%-12.0%), and arachidic (0.25%-0.39%). Masa et al. (2011) noted myristic acid (1.1%-1.7%), pentadecanoic (0.6%-1.0%), palmitic acid (19.0%-21.8%), and stearic acid (9.3%-10.5%). Kyategyeka et al. (2008) noted myristic acid (1.2%-1.4%), pentadecanoic (0.3%-0.5%), palmitic acid (17.6%-21.0%), stearic acid (9.8%-10.8%) and achidic (0.2%-0.4%).

Unsaturated fatty acids, which are beneficial for cardiovascular health, are well represented in Nile perch. Ogwok et al. (2009) reported ranges for palmitoleic acid (11.82%-17.35%), oleic acid (16.47%-23.47%), linoleic acid (1.32%-2.1%), alpha-linolenic acid (1.61%-2.0%), eicosapentaenoic acid (1.94%-3.96%), docosahexaenoic acid (5.06%-10.02%) and docosapentaenoic (3.32%-5.76%). Namulawa et al. (2011) found palmitoleic acid (2.89%-7.79%), oleic acid (8.54%-16.94%), linoleic acid (0.73%-4.03%), alpha-linolenic acid (0.29%-4.88%), gamma-linolenic acid (0%-12.98%), eicosapentaenoic acid (0.74%-6.0%), docosahexaenoic acid (4.89%-13.72%), and docosapentaenoic acid (3.08%-4.34%). Okoth et al. (2015) documented eicosapentaenoic acid (2.45%-3.07%) and docosahexaenoic acid (7.34%-7.66%). Kwetegyeka et al. (2006) reported palmitoleic acid (1.2%-6.0%), oleic acid (5.7%-8.0%), linoleic acid (1.0%-3.2%), alpha-linolenic acid (0.6%-2.5%), gamma-linolenic acid (0.3%-0.7%), eicosapentaenoic acid (4.4%-7.0%), docosahexaenoic acid (8.0%-17.0%), and docosapentaenoic acid (4.7%-7.0%). Masa et al. (2011) observed palmitoleic acid (4.9%-6.3%), oleic acid (3.2%-4.0%), alpha-linolenic acid (1.5%-2.3%), gamma-linolenic acid (0.5%-1.9%), eicosapentaenoic acid (3.8%-5.2%), docosahexaenoic acid (15.0%-16.8%), and docosapentaenoic acid (1.5%-2.5%). Lastly, Kwetegyeka et al. (2008) found palmitoleic acid (1.8%-3.0%), oleic acid (7.8%-9.6%), linoleic acid (1.6%-2.6%), alpha-linolenic acid (1.4%-1.8%), gamma-linolenic acid (0.1%-0.3%), eicosapentaenoic acid (3.2%-3.6%), docosahexaenoic acid (17.1%-19.1%), and docosapentaenoic acid (4.6%-6.2%).

The total fatty acid composition in Nile perch includes a balance of saturated, monounsaturated, and polyunsaturated fatty acids. Ogwok et al. (2009) reported saturated fatty acids ranging from 32.66% to 42.95%, monounsaturated fatty acids (MUFA) from 32.55% to 41.0%, polyunsaturated fatty acids (PUFA) from 15.67% to 23.52%, PUFA N-3 from 12.47% to 21.45%, and PUFA N-6 from 1.9% to 3.86%. Namulawa et al. (2011) documented saturated fatty acids from 34.44% to 42.68%, MUFA from 20.92% to 33.92%, PUFA from 23.77% to 35.19%, PUFA N-3 from 15.36% to 20.02%, and PUFA N-6 from 11.12% to 13.94%. Kwetegyeka et al. (2006) found saturated fatty acids ranging from 31.0% to 43.0%, MUFA from 14.0% to 27.0%, PUFA from 30.0% to 47.0%, PUFA N-3 from 20.0% to 33.0%, and PUFA N-6 from 10.0% to 18.0%. Masa et al. (2011) reported saturated fatty acids from 30.3% to 35.9%, MUFA from 24.3% to 28.7%, PUFA from 31.9% to 39.9%, PUFA N-3 from 21.8% to 26.8%, and PUFA N-6 from 10.1% to 13.1%. Kwetegyeka et al. (2008) documented saturated fatty acids from 33.6% to 34.6%, MUFA from 18.9% to 19.5%, PUFA from 46.4% to 47.0%, PUFA N-3 from 27.0% to 27.8%, and PUFA N-6 from 14.9% to 15.5%. These ranges highlight the nutritional diversity of Nile perch and its potential health benefits.

Silver cyprinid (Rastrineobola argentea)

The nutritional profile of *R. argentea* is highlighted by various proximate composition analyses, underscoring its importance as a dietary component for local communities. Moisture content in this fish shows considerable variation across different studies. Ogonda et al. (2014) reported moisture content ranging from 72.83% to 76.90% on a wet-weight basis, reflecting the high-water content typical of freshwater fish and contributing to its juiciness and tenderness. In contrast, Abdulkarim et al. (2016) found a slightly broader range from 70.26% to 77.40%. Notably, Chaula et al. (2019) observed a lower moisture content range of 7.85% to 17.84%, likely due to the drying process commonly applied to Dagaa. Kubiriza et al. (2021) reported an even wider range from 5.81% to 20.26%, while Omagor et al. (2020) found moisture content between 16.5% and 27.2%. Overall, the moisture content for *R. argentea* from Lake Victoria ranges from 5.81%

to 77.40%, demonstrating significant variation due to different processing methods and environmental factors.

Ash content, indicative of the total mineral content, also shows considerable variation among studies. Ogonda et al. (2014) reported ash content ranging from 1.88% to 4.38%, while Abdulkarim et al. (2016) found higher values between 3.87% and 7.66%. Kubiriza et al. (2021) observed a wide range from 7.57% to 25.36%, reflecting the significant mineral presence in *R. argentea*. These variations highlight the importance of Omena as a source of essential minerals such as calcium, phosphorus, and iron, which are crucial for bone health, oxygen transport, and metabolic processes. The ash content for *R. argentea* from Lake Victoria ranges from 1.88% to 25.36%.

Lipid content in *R. argentea* is essential for its energy value and flavor. Ogonda et al. (2014) reported lipid content ranging from 1.77% to 7.78%, indicating moderate fat levels that contribute to the fish's taste and caloric value. Abdulkarim et al. (2016) found a lower lipid range from 0.09% to 1.63%, whereas Chaula et al. (2019) documented a broader range from 10.19% to 22.38%, likely due to variations in the fish's diet and environmental conditions. Kubiriza et al. (2021) reported lipid content between 12.09% and 17.11%, and Omagor et al. (2020) found lipid levels ranging from 10.3% to 15.0%. Overall, the lipid content for *R. argentea* from Lake Victoria ranges from 0.09% to 22.38%.

Table 2. Nutrient and mineral content ranges for Nile perch from Lake Victoria

Nutrients	Ranges	Reference
Moisture (%)	67.30-79.6	Abdulkarim et al. (2016); Okeyo et al. (2009)
Ash (%)	0.55-5.98	
Lipid (%)	0.59-4.16	
Protein (%)	15.93-22.51	
Saturated fatty acids		
Lauric Acid (C12:0)	0.11-0.25	
Myristic Acid (C14:0)	0.5-4.1	Namulawa et al. (2011); Ogwok et al. (2009); Kwetegyeka et al. (2006); Masa et al. (2011); Kwetegyeka et al. (2008)
Pentadecanoic (C15:0)	0.3-1.34	
Palmitic Acid (C16:0)	17.6-27.84	
Stearic Acid (C18:0)	5.93-14.04	
Arachidic Acid (C20:0)	0.2-0.4	
Unsaturated Fatty Acid		
Palmitoleic Acid (C16:1n-7)	1.8-17.35	Ogwok et al. (2009); Namulawa et al. (2011); Kwetegyeka et al. (2006); Masa et al. (2011); Kwetegyeka et al. (2008); Okoth et al. (2015)
Oleic Acid (C18:1n-9)	3.2-23.47	
Linoleic Acid (C18:2n-6)	0.73-4.03	
Alpha-Linolenic Acid (C18:3n-3)	0.29-4.88	
Gamma-Linolenic Acid (C18:3)	0.0-12.98	
Eicosapentaenoic Acid (C20:5)	0.74-7.0	
Docosahexaenoic Acid (C22:6)	4.89-19.1	
Docosapentaenoic acid (DHA;C22:5n-3)	1.5-7.0	
Total Fatty acids		
Saturated fatty acids (%)	30.3-43.0	Ogwok et al. (2009); Namulawa et al. (2011); Kwetegyeka et al. (2006); Masa et al. (2011); Kwetegyeka et al. (2008)
Monounsaturated fatty acids (MUFA) (%)	14.0-41.0	
Polyunsaturated fatty acids (PUFA) (%)	15.67-47.0	
PUFA N-3 (%)	12.47-33.0	
PUFA N-6 (%)	1.9-18.0	

Protein content in *R. argentea* is one of its most valuable nutritional attributes, especially in regions where alternative protein sources are limited. Ogonda et al. (2014) reported protein levels ranging from 19.11% to 21.78%, which is relatively high for fish. Abdulkarim et al. (2016)

found a protein range from 15.44% to 21.20%. Chaula et al. (2019) did not provide specific protein values, but Kubiriza et al. (2021) reported exceptionally high protein content ranging from 52.61% to 79.44%, reflecting the fish's importance as a protein source. Omagor et al. (2020) documented protein content from 62.6% to 71.4%.. Therefore, the protein content for *R. argentea* from Lake Victoria ranges from 15.44% to 79.44%.

The fatty acid composition of *R. argentea* includes both saturated and unsaturated fatty acids, which are crucial for various health benefits. Mwanja and Munguti (2010) reported myristic acid (1.24%-2.91%), palmitic acid (22%-37%), stearic acid (12.43%-17.16%), and arachidic acid (0.06%-0.29%). Chaula et al. (2019) documented myristic acid (0.62%-3.63%), pentadecanoic acid (0.55%-0.71%), palmitic acid (12.62%-24.13%), stearic acid (1.77%-7.84%), and arachidic acid (0.22%-0.46%).

Unsaturated fatty acids, known for their cardiovascular benefits, are also well-represented in *R. argentea*. Mwanja and Munguti (2010) reported palmitoleic acid (1.91%-3.79%), oleic acid (7.08%-9.94%), linoleic acid (4.69%-7.77%), alpha-linolenic acid (2.01%-3.83%), eicosapentaenoic acid (1.2%-4.2%), and docosahexaenoic acid (3.2%-8.88%). Chaula et al. (2019) found palmitoleic acid (2.57%-11.92%), oleic acid (2.63%-5.3%), linoleic acid (0.4%-2.78%), alpha-linolenic acid (0.02%-0.47%), gamma-linolenic acid (0.13%-0.31%), eicosapentaenoic acid (1.35%-6.9%), docosahexaenoic acid (6.67%-13.38%), and docosapentaenoic acid (1.58%-2.31%). The presence of these fatty acids in Omena makes it a beneficial dietary component for supporting heart health and cognitive functions.

The total fatty acid composition in *R. argentea*, as reported by Mwanja and Munguti (2010), included 47.57% saturated fatty acids, 16.67% monounsaturated fatty acids (MUFA), and 35.78% polyunsaturated fatty acids (PUFA), with PUFA N-3 and PUFA N-6 accounting for 13.54% and 22.24%, respectively. Chaula et al. (2019) found saturated fatty acids ranging from 14.75% to 42.24%, MUFA from 5.93% to 24.41%, PUFA from 21.68% to 31.68%, PUFA N-3 from 15.13% to 24.59%, and PUFA N-6 from 1.64% to 6.5%. Based on the various studies, the nutrient and mineral content ranges for Silver cyprinid from Lake Victoria have been summarized in Table 3.

African catfish (Clarias gariepinus)

The African catfish (*Clarias gariepinus*) is a prominent fish species in the Lake Victoria Basin, Kenya, valued for both its nutritional content and economic significance. The moisture content in African catfish is notably high (Table 4), a characteristic feature of freshwater fish that contributes to their desirable texture and taste. Raymond et al. (2021) reported moisture levels ranging from 69.16% to 73.54%. Such high moisture content is beneficial as it enhances the fish's tenderness and juiciness, attributes that are particularly appreciated by consumers.

Ash content, which reflects the total mineral content of the fish, varies among studies but consistently shows the presence of significant mineral quantities. Raymond et al. (2021) found ash content ranging from 1.60% to 2.29%. These values indicate a substantial presence of minerals essential for various body functions, including bone formation, enzymatic activities, and overall metabolic processes. The lipid content in African catfish, as reported by Raymond et al. (2021), ranges from 2.84% to 4.13%. Although this places African catfish in a moderate lipid category, the fat content is crucial for energy provision and the absorption of fat-soluble vitamins. Fats also contribute to the fish's flavor profile, making it a vital dietary component. According to Raymond et al. (2021), the protein content of African catfish is notably high, ranging from 19.93% to 23.06%.

The fatty acid composition of African catfish is diverse, including both saturated and unsaturated fatty acids. Saturated fatty acids, as reported by Raymond et al. (2021), include caprylic acid (0.77%-1.03%), capric acid (0.06%-0.09%), lauric acid (1.33%-1.70%), myristic acid (2.90%-3.23%), palmitic acid (33.63%-38.20%), stearic acid (10.80%-12.20%), and arachidic acid (0.40%-0.87%). Masa et al. (2011) documented myristic acid (1.1%-2.5%), palmitic acid (21.7%-24.9%), and stearic acid (11.3%-12.7%).

Unsaturated fatty acids, known for their positive health impacts, are well-represented in African catfish. Raymond et al. (2021) reported palmitoleic acid (4.33%-5.20%), oleic acid (20.50%-22.40%), linoleic acid (6.60%-8.60%), alpha-linolenic acid (0.50%-1.17%), gamma-linolenic acid (0.50%-0.90%), eicosapentaenoic acid (1.57%-2.23%), and docosahexaenoic acid (3.33%-3.77%). Masa et al. (2011) found palmitoleic acid (3.6%-4.8%), oleic acid (4.9%-5.9%), alpha-linolenic acid (2.4%-3.2%), gamma-linolenic acid (0.6%-1.8%), eicosapentaenoic acid (3.5%-4.3%), and docosahexaenoic acid (9.9%-12.1%).

The total fatty acid composition shows a balance between different types of fatty acids. Masa et al. (2011) reported saturated fatty acids ranging from 35.5% to 42.1%, monounsaturated fatty acids from 18.4% to 22.4%, and polyunsaturated fatty acids from 29.7% to 36.9%. Polyunsaturated fatty acids include omega-3 fatty acids, which range from 27.9% to 36.9%, and omega-6 fatty acids, ranging from 12.1% to 14.5%.

Table 3. Nutrient and mineral content ranges for Silver cyprinid from Lake Victoria

Nutrients	Ranges	Reference
Moisture (%)	5.81-77.40	Ogonda et al. (2014); Abdulkarim et al. (2016); Chaula et al. (2019); Kubiriza et al. (2021); Omagor et al. (2020)
Ash (%)	1.88-25.36	
Lipid (%)	0.09-22.38	
Protein (%)	15.44-79.44	
Saturated fatty acids		
Myristic Acid (C14:0)	0.62-3.63	Mwanja & Munguti (2010); Chaula et al. (2019)
Pentadecanoic (C15:0)	0.55-0.71	
Palmitic Acid (C16:0)	12.62-37.0	
Stearic Acid (C18:0)	1.77-17.16	
Arachidic Acid (C20:0)	0.06-0.46	
Unsaturated Fatty Acid		
Palmitoleic Acid (C16:1n-7)	1.91-11.92	Mwanja & Munguti (2010); Chaula et al. (2019)
Oleic Acid (C18:1n-9)	2.63-9.94	
Linoleic Acid (C18:2n-6)	0.4-7.77	
Alpha-Linolenic Acid (C18:3n-3)	0.02-3.83	
Gamma-Linolenic Acid (C18:3)	0.13-0.31	
Eicosapentaenoic Acid (C20:5)	1.2-6.9	
Docosahexaenoic Acid (C22:6)	3.2-13.38	
Docosapentaenoic acid (DHA;C22:5n-3)	1.58-2.31	
Total Fatty acids		
Saturated fatty acids (%)	14.75-47.57	Mwanja & Munguti (2010); Chaula et al. (2019)
Monounsaturated fatty acids (MUFA) (%)	5.93-24.41	
Polyunsaturated fatty acids (PUFA) (%)	21.68-35.78	
PUFA N-3 (%)	13.54-24.59	
PUFA N-6 (%)	1.64-22.24	

The mineral composition of African catfish includes vital elements such as calcium, iron, magnesium, phosphorus, zinc, and copper. Raymond et al. (2021) reported calcium levels ranging from 0.413 mg/g to 0.46 mg/g, which are essential for bone health and muscle function. Iron content ranges from 0.024 mg/g to 0.036 mg/g, playing a crucial role in oxygen transport and preventing anemia, particularly in women and children. Magnesium levels, ranging from 1.274 mg/g to 1.385 mg/g, are important for muscle and nerve function, while phosphorus, at 0.28 mg/g to 0.325 mg/g, is vital for energy metabolism and bone health. Zinc levels between 0.044 mg/g to 0.063 mg/g support immune function and wound healing, and copper, ranging from 0.0054 mg/g to 0.007 mg/g, is involved in cardiovascular health and the formation of red blood cells.

Table 4. Nutrient and mineral content ranges for African catfish from Lake Victoria

Nutrients	Ranges	Reference
Moisture (%)	69.16-73.54	Raymond et al. (2021)
Ash (%)	1.6-2.29	
Lipid (%)	2.84-4.13	
Protein (%)	19.93-23.06	
Saturated fatty acids		
Caprylic Acid (C8:0)	0.77 - 1.03	Raymond et al. (2021); Masa et al. (2011)
Capric Acid (C10:0)	0.06 - 0.09	
Lauric Acid (C12:0)	1.33 - 1.70	
Myristic Acid (C14:0)	1.1-3.23	
Pentadecanoic (C15:0)	0.6-0.8	
Palmitic Acid (C16:0)	21.7-38.20	
Stearic Acid (C18:0)	10.80-12.7	
Arachidic Acid (C20:0)	0.40 - 0.87	
Unsaturated Fatty Acid		
Palmitoleic Acid (C16:1n-7)	3.6-5.2	Raymond et al. (2021); Masa et al. (2011)
Oleic Acid (C18:1n-9)	4.9-22.4	
Linoleic Acid (C18:2n-6)	6.60 - 8.60	
Alpha-Linolenic Acid (C18:3n-3)	0.50-3.2	
Gamma-Linolenic Acid (C18:3)	0.50-1.8	
Eicosapentaenoic Acid (C20:5)	1.57-4.3	
Docosahexaenoic Acid (C22:6)	3.33-12.1	
Docosapentaenoic acid (DHA;C22:5n-3)	1.8-2.8	
Total Fatty acids		
Saturated fatty acids (%)	35.5-42.1	Masa et al. (2011)
Monounsaturated fatty acids (MUFA) (%)	18.4-22.4	
Polyunsaturated fatty acids(PUFA) (%)	29.7-36.9	
PUFA N-3 (%)	27.9-36.9	
PUFA N-6 (%)	12.1-14.5	
Mineral Composition (mg/g)		
Calcium	0.413-0.46	Raymond et al. (2021)
Iron	0.024-0.036	
Magnesium	1.274-1.385	
Phosphorus	0.280-0.325	
Zinc	0.044-0.063	
Copper	0.0054-0.007	

Lungfish (Protopterus aethiopicus)

Lungfish (*Protopterus aethiopicus*) from Lake Victoria is an essential part of the local diet due to its rich nutritional profile, particularly in fatty acids. The saturated fatty acid composition of lungfish reveals significant variation among different studies. Masa et al. (2011) reported myristic acid content ranging from 2.8% to 3.6%, which contributes to the fish's overall fat profile and is important for energy storage and cellular functions. In contrast, Kwetegyeka et al. (2008) found a slightly broader range for myristic acid, between 2.3% and 3.5%. Pentadecanoic acid, a less common saturated fatty acid, was found in substantial amounts by Masa et al. (2011), ranging from 14.7% to 17.1%, while Kwetegyeka et al. (2008) reported much lower values from 0.4% to 0.6%. This significant difference may be due to variations in the fish's diet and habitat conditions. Palmitic acid, a major saturated fatty acid, was found in the range of 8.9% to 9.9% by Masa et al. (2011) and 11.5% to 12.5% by Kwetegyeka et al. (2008). Stearic acid content varied from 0.5% to 0.7% in Masa et al. (2011) and from 9.7% to 11.1% in Kwetegyeka et al. (2008). Arachidic acid was only reported by Kwetegyeka et al. (2008), ranging from 0.2% to 0.4%. Therefore, the ranges for these saturated fatty acids in lungfish from Lake Victoria are: myristic acid (2.3% to 3.6%), pentadecanoic acid (0.4% to 17.1%), palmitic acid (8.9% to 12.5%), stearic acid (0.5% to 11.1%), and arachidic acid (0.2% to 0.4%).

Unsaturated fatty acids are critical for cardiovascular health and cognitive functions, and lungfish from Lake Victoria are rich in these beneficial fats. Masa et al. (2011) reported palmitoleic acid content ranging from 5.1% to 6.7%, which is important for lipid metabolism and cellular signaling. Kwetegyeka et al. (2008) found slightly lower values for palmitoleic acid, ranging from 3.6% to 4.6%. Oleic acid, a monounsaturated fatty acid known for its heart health benefits, ranged from 4.3% to 5.5% in Masa et al. (2011) and from 4.0% to 5.8% in Kwetegyeka et al. (2008). Linoleic acid, an essential omega-6 fatty acid, was reported by Kwetegyeka et al. (2008) to range from 0.9% to 1.1%, although Masa et al. (2011) did not report any values for this fatty acid. Alpha-linolenic acid, an omega-3 fatty acid important for anti-inflammatory processes, ranged from 3.1% to 3.9% in Masa et al. (2011) and from 0.39% to 0.47% in Kwetegyeka et al. (2008). Gamma-linolenic acid, another omega-6 fatty acid, was found to range from 1.8% to 3.0% in Masa et al. (2011) and from 0.05% to 0.11% in Kwetegyeka et al. (2008). Eicosapentaenoic acid (EPA), an important omega-3 fatty acid for heart health, ranged from 5.8% to 6.4% in Masa et al. (2011) and from 2.1% to 2.5% in Kwetegyeka et al. (2008). Docosahexaenoic acid (DHA), another critical omega-3 fatty acid, varied widely, from 11.9% to 14.5% in Masa et al. (2011) to 5.1% to 10.5% in Kwetegyeka et al. (2008). Docosapentaenoic acid (DPA), a lesser-known but important omega-3 fatty acid, ranged from 2.7% to 3.1% in Masa et al. (2011) and from 3.5% to 4.9% in Kwetegyeka et al. (2008). Therefore, the ranges for these unsaturated fatty acids in lungfish from Lake Victoria are: palmitoleic acid (3.6% to 6.7%), oleic acid (4.0% to 5.8%), linoleic acid (0.9% to 1.1%), alpha-linolenic acid (0.39% to 3.9%), gamma-linolenic acid (0.05% to 3.0%), eicosapentaenoic acid (2.1% to 6.4%), docosahexaenoic acid (5.1% to 14.5%), and docosapentaenoic acid (2.7% to 4.9%).

The total fatty acid composition of lungfish highlights its rich and balanced fatty acid profile. Masa et al. (2011) reported that the saturated fatty acids ranged from 27.7% to 32.5%, monounsaturated fatty acids (MUFA) from 21.4% to 26.4%, and polyunsaturated fatty acids (PUFA) from 35.2% to 42.6%. PUFA N-3, essential omega-3 fatty acids, ranged from 23.5% to 27.9%, and PUFA N-6, omega-6 fatty acids, ranged from 11.7% to 14.7%. Kwetegyeka et al. (2008) found saturated fatty acids ranging from 30.3% to 30.7%, MUFA from 20.8% to 21.4%, and PUFA from 47.6% to 49.2%. The PUFA N-3 ranged from 13.0% to 15.0%, and PUFA N-6 from 28.0% to 30.0%. These variations in fatty acid composition underscore the nutritional diversity of lungfish and its potential health benefits. The ranges for total fatty acids in lungfish from Lake Victoria are saturated fatty acids (27.7% to 32.5%), monounsaturated fatty acids (20.8% to 26.4%), polyunsaturated fatty acids (35.2% to 49.2%), PUFA N-3 (13.0% to 27.9%), and PUFA N-6 (11.7% to 30.0%). The nutritional value for lungfish based on the various studies has been summarized in Table 5.

Influence of environmental, dietary, biological, and methodological factors on the nutritive value of fish species in Lake Victoria Basin

Despite the clear nutritional benefits, it is important to acknowledge the limitations and variations in the reported nutrient levels across different studies. Several factors can significantly influence nutrient composition. For instance, environmental conditions play a crucial role in determining the nutritional profile of fish (Zhang et al., 2020). For instance, water temperature directly influences fish metabolic rates, thereby affecting lipids and protein accumulation. In warmer waters, fish tend to have increased metabolic rates, which can lead to higher fat content as they store more energy (Morash et al., 2021).

Table 5: Nutrient content ranges for lungfish from Lake Victoria

Saturated fatty acids	Ranges (%)	Reference
Myristic Acid (C14:0)	2.3-3.6	Masa et al. (2011); Kwetegyeka et al. (2008)
Pentadecanoic (C15:0)	0.4-17.1	
Palmitic Acid (C16:0)	8.9-12.5	
Stearic Acid (C18:0)	0.5-11.1	
Arachidic Acid (C20:0)	0.2-0.4	
Unsaturated fatty acids		
Palmitoleic Acid (C16:1n-7)	3.6-6.7	Masa et al. (2011); Kwetegyeka et al. (2008)
Oleic Acid (C18:1n-9)	4.0-5.8	
Linoleic Acid (C18:2n-6)	0.9-1.1	
Alpha-Linolenic Acid (C18:3n-3)	0.39-3.9	
Gamma-Linolenic Acid (C18:3)	0.05-3.0	
Eicosapentaenoic Acid (C20:5)	2.1-6.4	
Docosahexaenoic Acid (C22:6)	5.1-14.5	
Docosapentaenoic acid (DHA;C22:5n-3)	2.7-4.9	
Total fatty acids		
Saturated fatty acids (%)	27.7-32.5	Masa et al. (2011); Kwetegyeka et al. (2008).
Monounsaturated fatty acids (MUFA) (%)	20.8-26.4	
Polyunsaturated fatty acids (PUFA) (%)	35.2-49.2	
PUFA N-3 (%)	13.0-27.9	
PUFA N-6 (%)	11.7-30.0	

Conversely, the metabolic rate decreases in cooler waters, potentially resulting in lower lipid deposition. For example, Nile tilapia from Lake Victoria shows a lipid content ranging from 0.08% to 3.77% across different studies, indicating the influence of varying environmental conditions (Raymond et al., 2021; Muchiri et al., 2015; Abdulkarim et al., 2016). Water quality, including the presence of pollutants and nutrients, also significantly impacts fish health and nutrient composition. Fish living in cleaner, nutrient-rich waters are generally healthier and exhibit higher protein and mineral content (Thilsted et al., 2016). This can be attributed to better overall growth conditions and less metabolic stress compared to fish from polluted waters, where the presence of contaminants can lead to altered metabolic pathways and nutrient deficiencies.

Seasonal variations can also complicate the nutritional analysis of fish. Seasonal changes, such as temperature fluctuations and variations in food availability, can have profound effects on fish metabolism and nutrient storage (Costalago et al., 2020). During colder months, fish may accumulate more lipids to provide insulation against the cold, resulting in higher fat content (Brodte et al., 2008). For instance, African catfish showed lipid content ranging from 2.84% to 4.13% (Raymond et al., 2021), which might vary with seasonal changes. In contrast, warmer temperatures in other seasons can increase metabolic activity, leading to higher protein and moisture content.

Additionally, the seasonal availability of food sources impacts the diet of fish, subsequently affecting their nutrient composition. During times of food abundance, fish may consume a diet rich in nutrients, resulting in higher protein and fat content (de Souza et al., 2020). Conversely, nutrient content may decrease during lean seasons as fish rely on stored reserves, leading to fluctuations in their nutritional profiles. The reproductive cycle also plays a significant role, with nutrient levels in fish often changing during spawning seasons as nutrients are redirected towards gonad development, reducing their presence in muscle tissues (Singh et al., 2021).

Diet and feeding habits of the various species are also critical factors influencing the nutritional composition of fish (Ahmed et al., 2022). The natural diet of fish in Lake Victoria varies widely, affecting their nutrient profiles. Carnivorous fish typically have higher protein content due to their meat-based diet, while omnivorous species exhibit a more varied nutrient profile that reflects their diverse dietary intake (Jauralde et al., 2021). For example, protein content in Nile tilapia ranges from 16.40% to 23.47% (Raymond et al., 2021; Muchiri et al., 2015; Abdulkarim et al., 2016), highlighting the influence of diet on nutrient levels.

Biological factors, including genetic variation, age, size, and sex, also contribute to differences in nutrient composition among fish species (Ahmed et al., 2022). Genetic differences can lead to variations in metabolic efficiency and nutrient storage mechanisms, resulting in distinct nutrient profiles even within the same species. For instance, genetic variation in Nile tilapia collected in different sampling sites could explain the differences in protein content observed across different studies (Raymond et al., 2021; Muchiri et al., 2015; Abdulkarim et al., 2016). Age and size are important determinants as younger fish often have higher metabolic rates and different nutrient needs compared to older fish. Larger fish may also have more fat reserves, influencing their overall nutrient content. For example, lipid content in African catfish varies from 2.84% to 4.13%, possibly due to differences in age and size of fish sampled from the various studies (Raymond et al., 2021). Additionally, sex-related differences in nutrient composition are particularly evident during reproductive seasons when nutrient allocation varies between males and females, affecting the levels of certain nutrients in their tissues.

Methodological differences in how fish samples are collected, handled, and analyzed can introduce variability in the reported nutrient composition. Sampling methods, such as the time of day and location of fish capture, can significantly affect nutrient measurements. For instance, the study by Raymond et al. (2021) could have reported different moisture and lipid contents compared to Muchiri et al. (2015) and Abdulkarim et al. (2016) due to variations in sampling locations and times. Raymond et al. (2021) collected samples from vendors early in the morning, which may have affected freshness compared to fish captured directly from the wild in other studies.

Moreover, post-harvest handling, processing, and storage methods can lead to metabolic changes that alter nutrient composition (Ojelade et al., 2023). Common preservation techniques, such as drying and smoking, can alter the nutrient profile of fish. Drying, for instance, reduces moisture content and can concentrate other nutrients, while smoking can introduce additional compounds and affect the levels of certain nutrients. For example, the study by Namwanje et al. (2021) reported lower moisture and higher ash contents in dried silver cyprinid compared to fresh samples reported by Ogonda et al. (2014) and Abdulkarim et al. (2016). The conditions under which fish are stored, such as temperature and duration of storage, also influence nutrient stability. Lipids, in particular, are susceptible to oxidation, which can degrade their quality over time. Ogonda et al. (2014) ensured that fish were transported on ice and stored frozen until analysis, which could prevent nutrient degradation, whereas Okeyo et al. (2009) noted the influence of transportation duration and storage temperature on the lipid content of Nile perch, showing significant differences when samples were stored at 0-2°C compared to samples analyzed immediately.

Furthermore, variations in analytical techniques used by different laboratories can lead to discrepancies in reported values. Differences in sample preparation, such as drying and homogenizing, can also introduce variability, as can the specific methods used to measure nutrients, such as proximate analysis, gas chromatography, and spectrophotometry. For example, Namulawa et al. (2011) and Kwetegyeka et al. (2008) used different protocols for esterification and gas chromatography in analyzing fatty acids, leading to potential variations in reported fatty acid profiles. In Namulawa et al. (2011), samples were methanolysed and all fatty acids converted to their methyl esters in the methanolic solution, while Kwetegyeka et al. (2008) included a nitrogen flushing step and used a different gas chromatography setup, which could influence the detection and quantification of fatty acids. These methodological differences highlight the need for standardized procedures to ensure consistency and accuracy in nutritional analysis.

Implications on Community Nutritional Profile

The nutritional profile of economically valuable fish species in the Lake Victoria Basin holds substantial implications for the nutritional security of local communities. Species such as Nile perch and Nile tilapia, are rich sources of essential nutrients including omega-3 fatty acids, proteins, vitamins, and minerals, which are pivotal for brain development, cardiovascular health, and general wellness according to the FAO (2014). Fish is not only a staple in the diets of these communities but also a cornerstone of food security, providing a reliable and high-quality protein source as highlighted in the World Bank's 2016 report (Reference ?).

Economically, fishing is a lifeline for millions around Lake Victoria, with activities related to fishing, such as processing and trading, bolstering community livelihoods, enhancing welfare, and reducing poverty levels (Awange & Awange, 2021). Additionally, the cultural relevance of fish consumption is profound and ingrained in the local diet and practices, thus supporting community cohesion and traditional nutrition practices (Morgan et al., 2017). To fully realize Kenya's potential in aquaculture and enhance the country's food and nutrition status, deliberate efforts must be made to foster an environment that encourages both public and private investment in the industry.

However, these communities also face vulnerabilities due to overfishing and environmental changes that threaten the sustainability of these fish resources (FAO, 2022). The Cochrane et al. (2011) study emphasizes the necessity for sustainable fishing practices to ensure these resources can support future generations. This multifaceted impact underscores the critical role that the nutritional profile of local fish species plays in shaping the economic, cultural, and nutritional dimensions of communities in the Lake Victoria Basin.

Conclusion

The diverse fish species of economic importance in the Lake Victoria Basin, including Nile tilapia, Nile perch, silver cyprinid, African catfish, and lungfish, exhibit significant nutritional value, underscoring their vital role in the dietary needs and economic livelihoods of local communities. These fish provide high-quality protein, essential fatty acids, and key minerals, which contribute to overall health and well-being. The variability in nutrient content observed across different studies highlights the influence of environmental factors, diet, biological and methodological differences, underscoring the need for standardized analytical approaches to ensure accurate nutritional profiling. Given their rich nutritional profiles, promoting the sustainable management and consumption of these fish species can enhance food security, support public health, and drive socio-economic development in the region.

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Ethical approval

The authors declare that this study complies with research and publication ethics.

Informed consent

Not available

Data Availability

Data sharing does not apply to this article as no new data is created or analyzed in this study.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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RESEARCH PAPER

Marine Fish Drying in Major Drying Yards: An Explorative Study in the Bay of Bengal of Bangladesh

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Abstract

The study investigated detailed drying yard infrastructures, processing conditions, raw materials quality, spot quality defect point, packaging, storage, marketing, profit margin and production of commercially important marine fish species in major drying hubs of Cox's Bazar district. In Moheshkhali, Thakurtala (0.81 ha), Ghotibhanga (47.5 ha), and Sonadia yards (250 ha) identified 19±4, 71±3, and 250±11 active processors respectively. Shaporirdip (28.25±6.13 ha) and Shamlapur yards (21±5 ha) had 38±2 and 45±2 active processors respectively from Teknaf, and Chowfalldandi drying yards covered 97.5±13.23 ha, with 143±10 active processors from Cox`s Bazar sadar area. The Nazirertek area included two drying yards: Nazirertek, the largest at 2259.26 ha with 1328±75 active processors, and Nunierchara, a smaller yard (0.340±09 ha) with 3±0 active processors used for processing of dry fish. For 1 kg of finished dried products, the average quantity of raw fish required were 3.25±0.3 kg for pomfret, 3.7±0.25 kg for jewfish/croaker, 2.8±0.02 kg for mackerel, 4.5±0.2 kg for sardine, 4.01±0.2 kg for anchovy, 5.5±0.3 kg for Bombay duck, 3.9±0.2 kg for shrimp, 4.04±0.3 kg for skipjack tuna, 3.7±0.3 kg for sea catfish, 3.7±0.3 kg for shark, and 3.6±0.1 kg for other small pelagic species. The percentage of salt used ranged from 3% to 16%, and the average freshness quality defect point of raw material fish ranged between 1.38 to 3.3 depending on species. Dried fish processors used mostly traditional methods for raw material handling, processing, packaging, storage, and marketing of dried fish products. A total of 42,566 metric tons (MT) of marine dried fish production was recorded in the surveyed Cox's Bazar region. The average profit margins (%) of major sun-dried fish species were as follows: for pomfret 26 ±3, jewfish/croaker 25±1, mackerel 26±2, sardine 24±2, anchovy 25±5, bombay duck 28±3, ribbon fish 33±13, shrimp 14±0.3, shark 12±4 and for other species 11±6. The government and policymakers may find the results useful in planning and implementing the subsequent phases required for development and for the stakeholders in improving the quality, processing, storage, marketing and export of dried fish. Furthermore, this research may contribute to understanding the dynamics of Bangladesh's fish drying industry and its potential for sustainable development.

Introduction

Bangladesh possesses a wide variety of fisheries resources. The country ranks second in inland open-water capture production and fifth in global aquaculture production, making it one of the top fish producers in the world accounting for 4.91 million tonnes of fish production (FAO, 2024). Bangladesh produced 69866.52 MT of dried fish, accounting for approximately 15% of total fish production. Marine dried fish production contributed 59487 MT, with Cox's Bazar district accounting for 48285 MT. Bangladesh exported 2224.62 metric tonnes of dried fish, generated more than 48.72 core BDT in the 2022-2023 fiscal year (DoF, 2024).

Fish are preserved using conventional drying, smoking, and salting methods. The oldest traditional method of preserving fish was to expose it to the wind and sun for sundrying. Drying food is the world's oldest known preservation technology, and dried fish can be stored for many years (Doe and Olley, 2020). The method is cheap and effective in suitable climates; the fisherman and family can do the work, and the resulting product is easily transported to the market. It remains a core component of diets and cuisines across much of the world and is one of the main forms in which fish is sold and eaten in regions including Sub-Saharan Africa (e.g. Liverpool-Tasie et al., 2021) and Southeast Asia (Hortle, 2007). In Bangladesh, sun drying is the most common method of fish preservation.

The conventional sun drying procedure for fish takes 3-7 days, based on species, to completely dry (Balachandran, 2001). Dried fish is easy to transport, market, and store. These are often processed at cheap cost, are easily transportable, marketable, and storable, and have a high market demand (Nowsad, 2007, Nowsad, 2022). In Bangladesh, sun drying preserves a significant number of fresh fish from both freshwater and marine sources. It is a low-cost dietary protein source that is utilized as a substitute for fish when fresh fish is scarce in Bangladesh (Khan and Khan, 2001).

Cox’s Bazar of Bangladesh presents one of the most prominent marine fish drying in Bangladesh. Commercial fish drying mainly takes place in seven regions of Cox's Bazar District, as well as in Charfashion in Bhola, Alipur-Mohipur in Patuakhali, Rangabali, and the Dublarchar in the Sundarbans. Kutubdiapara and Nunierchara of Cox’s Bazar Sadar Upazila, Dhalghata-Matarbari, Ghotibhanga and Sonadia of Moheshkhali, and Shaporirdip and Zingira of Teknaf are the seven most important locations in Cox's Bazar (Nowsad, 2007). Traditional drying is still practiced in every coastal fishing town. Dhalghata-Matarbari in Moheshkhali and Kutubdiapara in Cox's Bazar Sadar are the two largest fish drying facilities. (Nowsad, 2004). The dried fish are then distributed throughout Bangladesh. It is also provided to overseas markets such as Singapore, Hong Kong, Malaysia, the United Kingdom, the United States of America, and the United Arab Emirates (Kleih et al., 2003).

Cox's Bazar has the longest coastline, roughly 120 kilometers. Fishing and drying are traditional practices in Cox's Bazar. The islands of Sonadia and Moheshkhali played an important role in drying this exportable commodity. Several drying industries have been created and operated in Sonadia, Moheshkhali, Cox's Bazar, and Teknaf (Nowsad, 2004)).

Several fish species such as Bombay duck (*Harpodon nehereus*), pomfret (*Stromateus chinensis* and *Parastromateus niger*), jewfish (*Johnius argenteus*, *Otolithoides argenteus* and *Otolithoides brunnes*), ribbon fish (*Trichiurus haumela*), anchovy (*Setipina taty*) and shrimp (*Penaeus spp*.) are used for commercial production of dried fish between October and March in the coastal districts of Bangladesh (Nowsad 2007; Amin et al. 2012).

Generally, dried fish and fishery products are marketed through many different channels and outlets in Bangladesh (Nowsad, 2022; Nayeem et al., 2010; Reza et al., 2005). Several studies on dried fish and its marketing system and profit margin in Bangladesh have been conducted by many researchers (Fersoushi et al., 2015; Amin et al., 2012; Monir et al., 2012; Flowra et al., 2012; Nayeem et al., 2010). Amin et al. (2012) found that the producers carried 70% of their dried fish to Asadganj market. Besides, some dried fish were also exported to the neighboring countries. Most dried fish producers market their products every 2-20 days, with 95% going to Chittagong and the rest of the other districts like Syedpur, and Dhaka (Al Mehedi et al., 2020). The seasonal income of the drying enterprise might vary from area to area. This variation was due to the raw material availability, size, and quality of the fish species, processing cost, and demand of the consumer (Marine, 2014; Purkait et al., 2018). But high-priced fish demanded high marketing costs resulting in higher marketing margins and profit compared to low-priced fish (Faruque et al., 2012; Haque et al., 2015). Many actors are involved in dried fish marketing such as beparies, arathdars, wholesalers, and retailers (Haque et al., 2016).

The current study was undertaken to assess the present condition of fish drying activities, including existing yard infrastructure, along with the activities at several marine fish landing sites, and commercially important dried fish processing sites in Cox's Bazar district. The study was conducted in three upazilas of the district: Moheshkhali, Teknaf, and Cox's Bazar Sadar. Nazirertek, Chowfalldandi, Khurushkul, and Nunierchara in Cox Bazar upazila; Thakurtala, Ghotibhanga, Sonadia in Mohakhali upazila; and Shaporirdip, Shamlapur in Teknaf upazila were targeted landing places and significant fish drying sites.

Materials and methods

Location

The survey was carried out in three upazilas of Cox's Bazar district and targeted specific fish landing places such as Nazirertek, Chowfalldandi, Khurushkul, Nunierchara (Cox Bazar Sadar upazila), Thakurtala, Ghotibhanga, Sonadia (Moheshkhali upazila), Shaporirdip, and Shamlapur (Teknaf upazila) (Figure 1).

Study time and target group

The data was collected in response to survey goals over six months in the year 2024, from January to June. The target groups were dried dish processors, entrepreneurs, fishermen, and other employees, both male and female, engaged in fish drying.

Sample size

About 500 data samples were recorded regarding fish drying yards, infrastructure, processing conditions, species, raw material quality, packaging, storage, marketing, profit margins, and production.

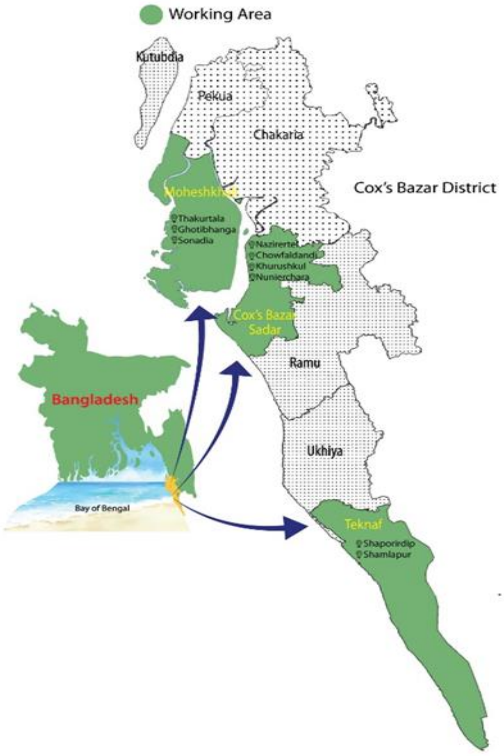

Figure 1. Location of the studied major marine fish drying yards and landing centers (drawn in Adobe illustrator, 2020 version)

Participatory Rural Appraisal (PRA)

For stakeholder involvement, semi-structured survey questionnaire and focus group discussions (FGDs) as PRA tool were used.

Key Informant Interview (KII)

Primary data generated by the survey and FGDs were varied with Key Informants Interviews with Department of Fisheries (DoF) officials, local government personnel, civil society men and Non-government Organization (NGO) personnels.

Questionnaire for data collection

Design and formulation of the questionnaire

A semi-structured questionnaire was designed to collect data from various drying sites and processing stakeholders depending on the study's objectives. Throughout the processes, the survey forms were checked, changed, and reviewed several times until a functional final form was achieved. The questionnaire was designed in such a way that stakeholders could answer it easily and logically once completed. Field data were acquired through face-to-face interviews.

Data collection methods

All data was collected in multiple stages to improve both reliability and coverage. First, questionnaires in structured and semi-structured forms were administered to the dried fish processors and employees. Secondly, FGDs were conducted with the intermediaries and other actors in the value chain to obtain qualitative data relating to practices, livelihoods and socio-economic factors. In the last step, these findings were validated through KIIs with district fisheries officer (DFO) and upazila fisheries officers (UFOs), assistant field officers, local leaders and members of NGOs.

Fish quality defect point (DP) analysis

Sensory quality defect points of raw material fish were determined by the fish freshness assessment method (Nowsad, 2014) with slight modification. Sensory analysis of raw materials for dry fish was evaluated by trained personnel using the sensory method (Table 1 and 2). Color, odor, texture, or muscle consistency of raw fish samples were also observed.

Data analysis

The data was collected and analyzed in descriptive statistics for accuracy. Tools were used in Microsoft Office 2019 for descriptive analysis; percentage, mean ($\overline{x}$) and standard deviation (SD).

Table 1. Determination of defect points for freshness test of raw fish

Characteristics	Defects	Defect points	Grade
Odour of broken neck	a) Natural odour b) Faint or sour odour	1 5	Acceptable Rejected
Odour of gills	a) Natural odour b) Faint sour odour c) Slight moderate sour odour d) moderate to strong sour odour	1 2 3 5	Excellent Acceptable Acceptable Rejected
Colour of gills	a) Slight pinkish red b) Pinkish red to brownish c) Brown or grey d) Bleached colour, thick yellow slime	1 2 3 5	Excellent Acceptable Acceptable Rejected
General appearance	a) Full bloom, bright, shining, iridescent b) Slight dullness and loss of bloom c) Definite dullness and loss of bloom d) Reddish lateral line, dull, no bloom	1 2 3 5	Excellent Acceptable Acceptable Rejected
Slime	a) Usually clear, transparent and uniformly spread b) Becoming turbid, opaque and milky c) Thick sticky, yellowish or green colour	1 2 5	Excellent Acceptable Rejected
Eye	a) Bulging with protruding lens, transparent eye cap b) Slight cloudy of lens and sunken c) Dull, sunken, cloudy d) Sunken eyes covered with yellow slime	1 2 3 5	Excellent Acceptable Acceptable Rejected
Consistency of flesh	a) Firm and elastic b) Moderately soft and some loss of elasticity c) Some softening d) Limp and floppy	1 2 3 5	Excellent Acceptable Acceptable Rejected

Table 2. Grading of fish with grade points

Grade	Points	Comments
A	< 2	Excellent/ Acceptable
B	2 to < 4	Good / Acceptable
C	4 to 5	Bad / Rejected

Results

Fish drying activity

Fish drying yard

Dried fish processors employed sun drying for two main reasons: demand for consumption, which was primarily driven by the demands of businesses and household consumption, as documented from the study data. In Moheshkhali, around 340 fish processors with an area covered 298.31 hectares (ha) in three fish drying yards; in Teknaf, 83 fish processors with an area covered 49.5 ha in two drying yards; at Chowfalldandi, 143 processors with an area covered 97.5 ha and in Nazirertek, found 1331 processors with the area covered of 225.34 ha recorded in two drying yards used as processing of dried fish (Table 3).

These findings revealed a variety of sizes of drying yards, all are privately operated and situated on the seashore except for Nazirertek's yard, with significant variation in the number of active processors between locations (Table 3).

Table 3. Existing fish drying yards under different landing centers in Cox's Bazar

Sl. no.	LC	Drying yards	Area (ha)	Type of yard	No. of active processor	Managed by
1	Moheshkhali	TT	0.81±0	Onshore	19±4	Private
		Gbh	47.5±5		71±3	Private
		Sd	250±0		250±11	Private
2	Teknaf	Slp	28.25±6.13	Onshore	38±2	Private
		Spd	21±5		45±2	Private
3	BFDC	Cd	97.5±13.23	Onshore	143±10	Private
4	Nazirertek	Nt	225±9.26	Approved & organized*, onshore	1328±75	Private
		Nc	0.34±0.09		3±0	Private

LC-Landing Center, TT-Thakurtala, Gbh- Ghotibhanga, Sd-Sonadia; Slp- Shamlapur, Spd- Shaporirdip; Cd-Chowfalldandi; Nt-Nazirertek, Nc-Nunierchara.
* Only one drying center in Nunierchara named Sagar Fish Exports and it is FDA-approved and certified.

Infrastructures of sun-drying yard

The present infrastructure and facilities in sun-drying yards of various landing centers are depicted in Table 4. Sun drying in the Cox's Bazar district was carried out by bamboo-fenced, elevated bamboo rack or pole-based fish drying yards called as "*killa" or "basha*". The quantity of fish in killa was difficult to assess because it varied depending on the availability of raw material quantity and the specific fish drying procedures prevalent in that geographical area. However, some important features were noticed.

Thakurtala, Ghotibhanga, and Sonadia Island were the most widespread sun-drying regions in Moheshkhali upazila. Out of 459 killas, 410 have sheds to keep dry fish, and 448 have tube wells for washing and drinking. Split bamboo mats were used to elevate 1,361 drying racks, while 691 were covered by black polythene sheets. During the course of the study, the author did not come across any yards that used mosquito netting, mechanical solar dryers with exhaust fans, electric dryers, ice boxes, huge sheds, particularly during wet or foggy weather, hoover packaging, or covered plastic buckets. However, all processors used bamboo parallel or vertical drying poles, split-bamboo elevated racks for processing and polythene sacks for packaging. The drying yards have electricity and Pucca road connections except for Sonadia Island, although there was one ice factory existing but other one was under construction at Ghotibhanga.

Sun-drying places in the Teknaf upazila included Shaporirdip and Shamlapur, having a total of 95 killas. There were 94 storage sheds and 66 tube wells. The total numbers of drying racks identified were 369 with bamboo mats and 187 with black polythene sheets. The survey found no mosquito nets, electric dryers, ice boxes, or huge sheds in Shamlapur, however, there were 22 mechanical sun dryers with exhaust fans. Where processors used drying bamboo poles and polythene sacks for storage with good electricity and road networks were provided. There were two ice factories nearby (Table 4).

A total of 165 killas were detected in Khurushkul and Chowfalldandi of Cox's Bazar sadar upazila, of which 143 had the capacity for storage sheds and 14 had the capacity for tube wells. Black polythene sheets were found on 295 drying racks, but bamboo mats were present on 598 of them in 165 killas. This indicates that no evidence of the use of improved facilities such as electric dryers, ice boxes, mosquito netting, or other advanced methods for preparing and storing dried fish was found. However, all processors have access to a good road, electricity, drying poles and elevated racks, and polythene sacks for the processing and storage. About 22 ice factories were located in the region.

With 2,681 killa, Nazirertek is the largest sun-drying site in Cox's Bazar area. There are 572 tube wells, and 2,719 storage structures have existed at the site. There were 2,599 drying racks that were wrapped in black polythene sheets and 5,223 drying racks with bamboo mats. In addition, 210 large open shelters are found to protect fish from inclement weather, thirteen fish-drying yards used mosquito nets, thirteen mechanical sun dryers, one electric dryer, one vacuum packing equipment, and four basic sealer machines. There was no covered plastic storage container, no ice plant nearby, and no ice box for transporting raw materials. The processors utilized drying poles and polythene sacks as a last resort. The killas were connected to the electricity grid, but the road to Nazirertek was still under construction, they could still find it difficult to reach the yard for raw material collection and processed product transportation (Table 4)

Table 4. Infrastructures and facilities in sun-drying yards of different landing centers

Sl.no.	Infrastructure	Number ($\bar{x}$ ±SD)			
		Moheshkhali	Teknaf	BFDC	Nazirertek
1	Fish drying establishments (killa/basha)	459±16	95±5	165±13	2681±129
2	Raised drying rack wrapped with split bamboo mat	1361±50	369±24	598±17	5223±285
3	Raised drying rack wrapped by black polythene sheet	691±37	187±11	295±13	2599±71
4	Fish drying yards covered with mosquito net	-	-	-	13±2
5	Mechanical solar dryer with exhauster fan	-	22±3***	2±0	13±3
6	Electric fish dryer	-	-	-	1±0
7	Vacuum packaging machine	-	-	-	1±0
8	Traditional polythene sac to store dry fish (%)	100	100	100	100
9	Connection to Pucca Road (%)	100	100	100	100**
10	Municipal water supply	-	-	-	-
11	Ice factory in the vicinity	1±0	2±0	22±1	-
12	Shed in killa for storage of dry fish	410±18	94±4	143±10	2719±79
13	Large open shed for drying during rainy/foggy weather	--	--	--	210±10
15	Uprisen drying poles/bars (%)	100	100	100	100
16	Simple sealer packaging machine	-	-	-	4±1
17	Covered plastic container to store	-	--	-	--
18	Electricity supply (%)	100	100	100	100
19	Tube well	448±15	66±2	14±2	572±58
20	Icebox	-	-	-	-

*1±0 means have a connection to the pucca road and electricity supply except Sonadia drying yard of Moheshkhali.
** Only Nunierchara is present and Nazirertek is under construction. *** Present in Shamlapur

Processing conditions of fish drying

The processing condition of fish drying at different landing centers is shown in Table 5. Drying methods were varied with the type or size of fish to be dried. Both bamboo-made racks (0.40 – 0.90 m above ground)) and mats were used for spreading fish. In most places, fish spread on the mat directly on the earth without using any bamboo rack. Each entrepreneur had a well-marked territory, fenced by bamboo with elevated bamboo racks, poles, and bars where the fish is dried. The present study was carried out to know the % of the compliance of processing conditions of fish drying at different landing centers. The study included parameters for processing and method of fish drying at the studied place and found results that are shown in Table 5. The landing center's processors used an elevated drying rack, a mosquito net-covered elevated rack, an exhaust fan-covered fish drying room, potable water for washing raw materials, ice or re-ice fish while sorting, traditional polythene sac storage, covered containers for storage, receiving raw materials with ice in an ice box, sorting/grading raw fish before washing/drying, washing raw fish before spreading, handling fish with bamboo baskets, using salt before sorting and using salt in fish before spreading for the production of dried fish.

Table 5. Processing condition of fish drying of different landing centers

Sl. no.	Parameters	% Compliance ($\bar{x}$ ±SD)							
		Moheshkhali			Teknaf		BFDC	Nazirertek	
		TT	Gbh	Sd	Slp	Spd	Cd	Nt	Nc
1	Elevated drying rack	100	38±3	100	77±5	22.4±3	66±5	100	100
2	Having an elevated rack covered by mosquito net	-	26±5	-	22±2	-	-	22±4	100
3	Mosquito net-covered fish drying room with exhaust fanning	-	-	-	4±1	-	1.4±0.1	3±1	100
4	Using potable water for raw material washing	100	100	100	84±4	47±3	7±0.2	94±4	100
5	Ice or re-ice fish while sorting	-	-	-	-	-	-	-	-
6	Using traditional polythene sac storage	100	100	100	100	100	100	100	-
7	Using a covered container for storage	-	-	-	-	-	-	-	-
8	Receiving raw material in ice condition in the ice box	-	-	-	--	-	-	-	-
9	Sorting/grading raw fish before washing/drying	100	100	100	100	100	100	100	100
10	Washing raw fish before spreading	-	-	-	-	-	-	-	84±4
11	Using canal/ditch water for fish washing	41±5	35±1	-	-	46±4	93±3	-	-
12	Using bamboo baskets while handling	36±6	26±6	18±4	66±3	78±3	26±4	90±6	47±6
13	Using salt in fish before sorting	--	-	-	-	-	-	-	83±6
14	Using salt in fish before spreading	100	100	100	100	100	100	100	100

TT-Thakurtala, Gbh- Ghotibhanga, Sd-Sonadia; Slp- Shamlapur, Spd- Shaporirdip; Cd-Chowfalldandi; Nt-Nazirertek, Nc-Nunierchara. *Compliance means following a rule or order.

Raw materials quality

The study area was recognized to harbor many species of marine fish. Monthly availability of species during different seasons was also well recorded. The winter season has more variation in terms of species availability compared to the summer or other seasons. In Cox's Bazar cost, due to relative abundance in landing, a variety of fish species, including pomfret (*Stromateus chinensis* and *Parastromateus niger*), jewfish/croaker (*Johnius argenteus, Johnius belangerii, J. elongates, J. dussumieri and Otolithes cuvieri*), mackerel (*Scomber australasicus* and *Rastrelliger brachysoma*), tuna (*Thunnus albacares* and *Euthynnus affinis*), sea catfish (*Tachysurus thalassinus* and *Rita rita*), sardine (*Sardinella* *longiceps*), anchovy(*Setipina taty*, *Coilia ramcarati* and *Setipinna phasa*), bombay duck (*Harpodon nehereus*), ribbon fish (*Trichiurus haumela*), small shrimp (*Peneaeus indicus*, Mixed shrimp), and others species (Spotted sea fish- *Scomberomorus guttatus*, Four thread tassel fish- *Eleutheronema tetradactylum*, Pale edged stingray- *Himantura bleekeri*, Indian River shad- *Gudusia chapra*, Yellowtail mullet-*Sicamugil cascasia*, Indian salmon- *Polynemus tetradactylum* and so on) are used for the commercial production of dried fish during October and April.

Spot quality defect points of raw materials

The raw material (species) used during the current study were subjected to organoleptic testing and sensory evaluation to determine the freshness quality.

The study found that the average quality defect points for pomfret, jewfish/croaker, mackerel, tuna, sea catfish, sardine, anchovy, bombay duck, ribbon fish, mola, small shrimp, and others species of raw materials were 2.25±0.3, 2.06±0.09, 2.1±0.03, 2.06±0.21, 2.4±0.19, 2.13±0.59, 2.08±0.19, 2.14±0.03, 2.13±0.77, 2.37±0, 2.22±0.18, 1.96±0.07 at Moheshkhali area, 2.5±0.46, 2.06±0.09, 2.1±0.03, 1.73 ±0.27, 2.4±0.53, 2.19±0.27, 2.13±0.27, 1.38±0.53, 1.67±0.34, 2.21±0.31, 2.02±0.03, 2.67±0.14 in Teknaf, 2.6±0.3, 2.5±0.1, 2.5±0.05, 2.56±0.4, 2.83±0.3, 2.9±0.1, 3.3±0.4, 2.97±0.5, 2.5±0.5, 2.7±0.2, 2.4±0.14, 2.5±0.2 in BFDC landing site area, and 2.18±0.34, 2.06±0.08, 2.10±.03, 2.15±0.08, 2.20±0.32, 2.10±0.30, 2.20±0.5, 1.81±0.14, 2.14±0.03, 2.7±0.19, 2.02±0.03, 2.7±0.14 in Nazirertek respectively (Figure 2). The quality of all the raw fish remained an acceptable range (within grade A to B). Anchovy was highest in terms of quality defect point recorded in BFDC.

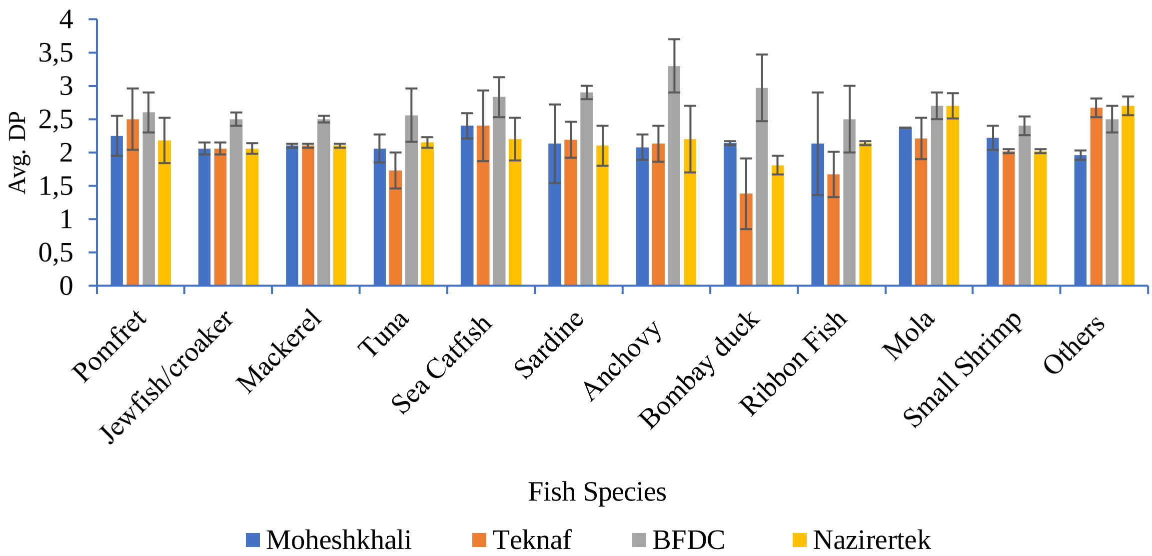

Figure 2. On-spot quality defect points of sampled raw materials fish for drying

Quantity of raw materials for each kg dry fish drying

The present study calculated raw materials required for 1kg production of dried pomfret, jewfish/croaker, mackerel, sardine, anchovy, Bombay duck, ribbon fish, shrimp, tuna, sea catfish, shark, and others mixed species were 3.25±0.3, 3.7±0.25, 2.8±0.02, 4.5±0.2, 4.01±0.2, 5.5±0.3, 3.2±0.08, 3.9±0.2, 4.04±0.3, 3.7 ±0.3, 3.6±0.1, 3.6±0.3kg at Moheshkhali's drying yards; 3.5±0.5, 3.02±0.3, 2.7±0.3, 3.5±0.6, 3.2±0.2, 6.1±0.1, 2.9±0.4, 3.9±0.5, 3.6±0.6, 3.5±0.5, 2.6±0.25, 3.3±0.2kg at Teknaf's fish drying yards; 3.5±0.6, 3±0.7, 2.75±0.3, 4±0.2, 3.4±0.5, 4.6±0.7, 3.75±0.5, 3.5±0.9, 3.25±0.3, 4.13±0.3, 3.5±0.6, 3.4±0.5 in BFDC landing site's drying yards and 3.45±0.01, 3.4±0.3, 2.65±0.02, 3.8±0.5, 3.42±0.7, 6.4±0.1, 2.9±0.4, 4.12±0.5, 3.6±0.02, 3.6±0.06, 3.4±0. 3, 2.8±0.3kg at Nazirertek fish drying yards respectively (Figure 3). Highest raw material needed to prepare 1 kg dry fish was Bombay duck in Nazirertek.

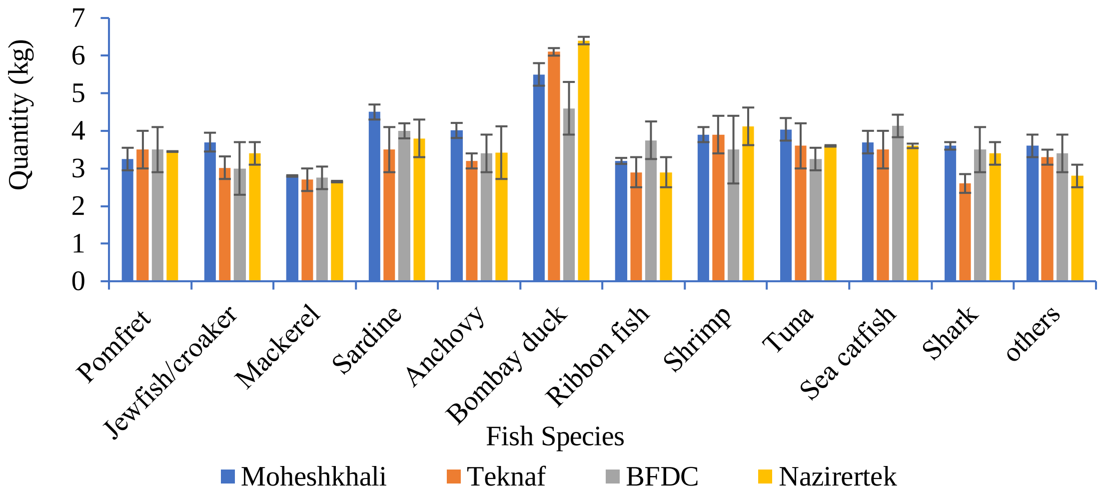

Figure 3. Raw fish used/kg for dried fish production of different landing centers

Salt use with raw fish for salted fish drying

Table 4 displays the percentage of salt used for the major species of fish dried in the study areas. It was found that fish farmers in the locations under study used salt with raw fish before drying, but they did not keep fish and salt at a set ratio.

In Moheshkhali Upazila fish drying centers, the study found that the percentage of salt used varied from yard to yard and species to species. Here the salt used ranged as follows: pomfret was only found with 3%, jewfish/croaker with 8-13%, mackerel with 3-6%, sardine with 4-7%, anchovy with 3-9%, bombay duck with 5-10% and ribbon fish with 4-23%, sharks being with 2-4%, shrimp with 5-6%, and others mixed species with 4-13%. Salt used in Teknaf was: pomfret 3–4%, jewfish/croaker 8–15%, mackerel 3–8%, sardine 5–8%, anchovy 3–10%, bombay duck 5–13%, ribbon fish 6–23%, shark 2–4%, shrimp 5–6%, and others 4–13%. At Chowfalldandi (BFDC ghat area) fish drying yards the percentage of salt used was found for pomfret, jewfish/croaker, mackerel, sardine, anchovy, bombay duck, ribbon fish, shark, shrimp, and other species were 4,15, 8, 8, 10, 13, 6, 4, 5 and 10% respectively. In Nazirertek fish drying yards, the percentage of salt used depended on the production capacity and target of marketing. The study found the salt used was: for pomfret- 3%, jewfish/croaker- 6.5-33%, mackerel- 4.5-7%, sardines- 4-5%, anchovy- 6-7%, Bombay duck- 7-16%, ribbon fish- 4-7%, shark- 2%, shrimps- 4.5% and other fish- 10-16% (Table-6).

Table 6. % of salt used in fish drying operation of different landing centers

Sl. no.	Species	% of salt used in fish before drying ($\overline{x}$ ±SD)							
		Moheshkhali			Teknaf		BFDC	Nazirertek	
		TT	Gbh	Sd	Slp	Spd	Cd	Nt	Nc
1	Pomfret	3±1	3±1	3±1	3±1	-	4±1	3±0.35	3±1
2	Jewfish/ croaker	11±1	13±2	8±1	13±1	13±1	15±1	6.5±2	25±8
3	Mackerel	6±1	5±1	3±1	5±.1	5±1	8±2	4.5±1	-
4	Sardine	4±1	7±1	5±.1	6±1	5±1	8±0.1	4±1	-
5	Anchovy	7±1	9±1.3	3±0.1	10±2	8±1	10±2	6±1	7±1
6	Bombay duck	9±2	10±1	5±1	4±02	4±2	13±1	7±1	5±1
7	Ribbon fish	4±1	6±2	3±0.3	4±1	3±1	6±1	4±1.6	7±1
8	Shark	3±0.3	2±1	2±1	2±1	6±2	4±2	2±1	--
9	Shrimp	6±1.	5±2	5±1	4±1	6±1	5±1	4.5±1	-
10	Others	8±4	13±7	4±1	8±3	7±1	10±3	10±4	16±2

TT-Thakurtala, Gbh- Ghotibhanga, Sd-Sonadia; Slp- Shamlapur, Spd- Shaporirdip; Cd-Chowfalldandi; Nt-Nazirertek, Nc-Nunierchara.

Packaging of dry fish

Upon sorting, the dried fish were placed in jute and plastic bags for convenience of handling. Bamboo baskets were occasionally employed for the same function. The size varied according to the volume of product to be stored. The processors in Moheshkhali, Teknaf, and the BFDC landing site area used traditional gunny sacks or baskets for packaging. In Nazirertek, 87% of the processors used gunny sacks, 10% used simple sealing in plastic pouches, and 3% utilized HDPE pouches. In Nazirertek, there was no vacuum packaging, whereas, in Nunierchara, only 10% to 15% of dried fish were vacuum packaged (Figure 4).

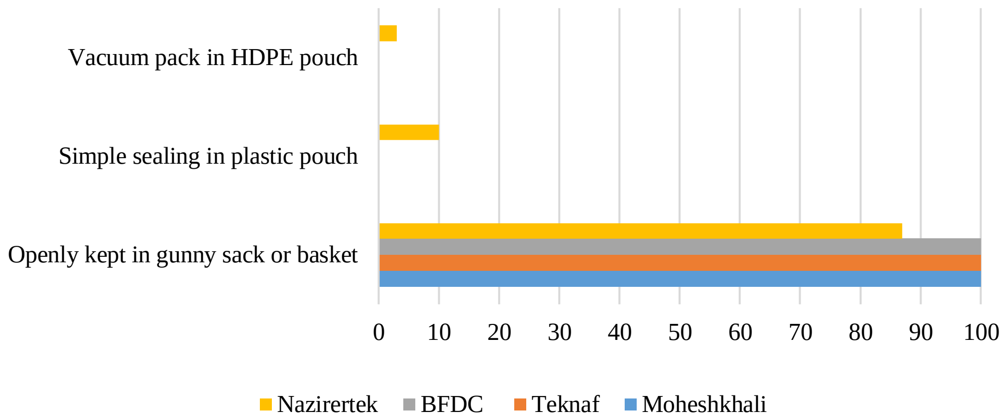

Figure 4. Compliance packaging (%) condition of different landing centers

Storage of dry fish

In Moheshkhali, dried fish openly kept in the sack on the floor or rack was about 72.73%, sealed in a plastic pouch and kept on rack was 27.27%, while in the drying yards of the BFDC landing site, processed dried fish openly kept in a sack on the floor or rack was 47.62%, sealed in a plastic pouch and kept on rack was 52.58%. These findings are consistent with the findings of the current study on the storage percentage of dried fish in other locations. Vacuum packed in cardboard carton was 14.28% (only at Nunierchara) at Nazirertek; openly kept in a sack on the floor or rack was 57.14%; sealed in a plastic pouch and kept on rack was 42.86%; and openly kept in the sack on the floor or rack was 57.15%; sealed in a plastic pouch and kept on rack was 28.57% (Figure-5).

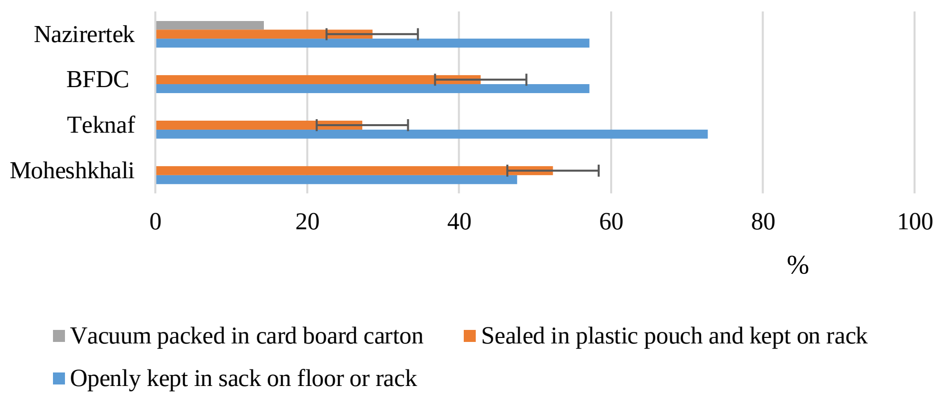

Figure 5. Storage of dry fish (%) in drying yards under different landing centers

Marketing of dry fish

The dried fish from Moheshkhali was marketed by 42.1% as retail and 57.89% as wholesale; at Teknaf 27.27 % retail and 72.73% wholesale; at BFDC landing site's drying yards - 50 % retail and 50% wholesale while in Nazirertek 23.1% retail and 76.92% wholesale (Figure-6). Highest wholesale marketing was recorded in Nazirertek and lowest in BFDC, whereas retail marketing was found highest in BFDC and lowest in Teknaf.

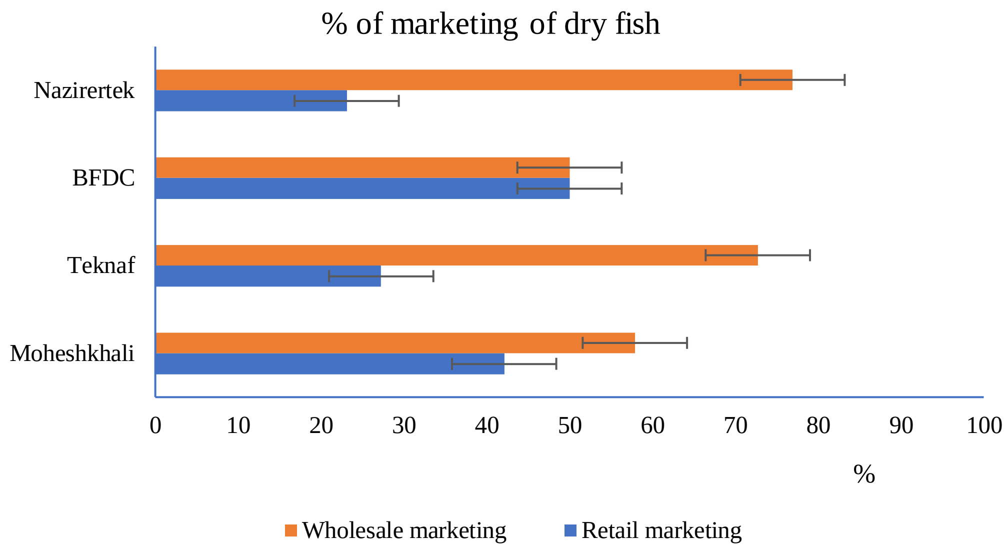

Figure 6. % Marketing of dry fish in drying yards under different landing centers

Profit margin

Species often to determine the profit margin for a fish-drying business. During the present investigation, key processors' profit margin data was obtained based on their quantity of dried fish operation. The percentage of profit margin for pomfret, jewfish/croaker, mackerel, tuna, sea catfish, sardine, anchovy, bombay duck, ribbon fish, mola, small shrimp, and other mixed species were 26 ±3, 25±1, 26.±2, 24±2, 25±5, 28±3, 33±13, 14±0.3, 12±4, 11±6 at Moheshkhali yards, 26±1, 19±2, 20±5, 26±2, 24±2, 21±3, 26±2, 15±4, 15±2, 15±2 in Teknaf yards, 24±1, 25±7, 25±5, 23±4, 22±2, 25±6, 21±14, 14±3, 12±2, 12±1 in BFDC landing site yards, and 27±4, 32±3, 23±3, 25±5, 23±5, 22±3, 23±3, 14±2, 11±2, 16±2 in Nazirertek yards, respectively. Figure 7 illustrates the profit margins of sun-dried major fish species in the study area. Jewfish/croaker earned highest profit from Nazirertek compare to other drying sites.

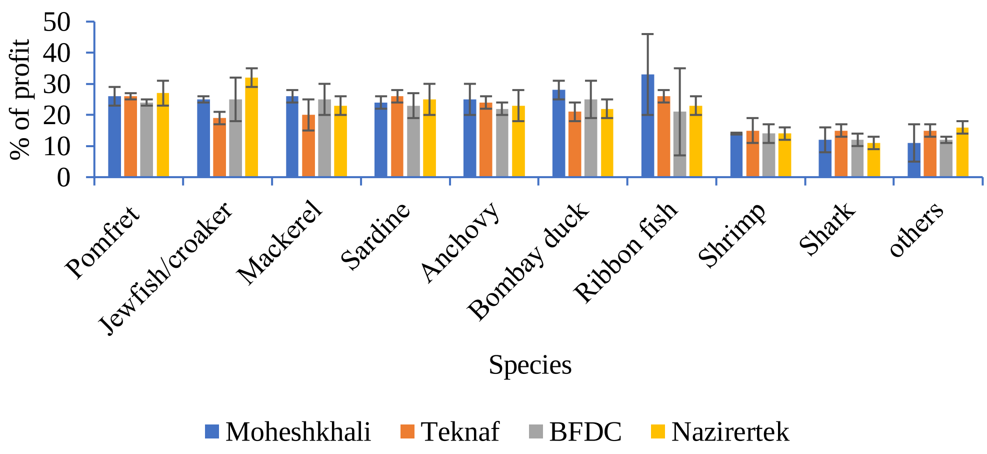

Figure 7. Profit margin (%) of dried fish of different landing centres

Quantity of sun-dried fish (MT) by species

The total marine dried fish production at Cox's Bazar drying area under the study period was 42566 MT (Table-5). While in the Moheshkhali area, total production was 3875.8±36.9 MT, in Teknaf 2422.2±81.3 MT, in BFDC landing yard 2376.3±121.1MT and Nazirertek yards 33892.5±34 MT. The production of dried fish by major species is shown in Table 7.

Table- 7. Quantity of sun-dried fish (MT) by species of drying yards under different landing centers

Sl. no.	Name of species	Quantity of sun-dried fish ($\overline{x}$ ±SD)			
		Moheshkhali	Teknaf	BFDC	Nazirertek
1	Pomfret	214.5±3	33±3	46.2±1.5	9.9±1.5
2	Jewfish/croaker	40±3	230±3	20±1.2	3430±30
3	Mackerel	77±0.6	80.5±6	24.5±3	80.5±6
4	Tuna	90±1.5	33±3	30±3	57±4
4	Sea catfish	24.2±1.6	94.6±3	8.8±3	81.4±6
5	Sardine	105±6	122.5±7	63±7	465.5±21
6	Anchovy	246.4±9	294.4±21	268.8±6	8968±24
7	Bombay duck	1155±41	445.5±16	561±4	9075±32
8	Ribbon fish	1310.4±34	603.2±15	780±11	9937.2±32
9	Shark	80.5±3	25.3±3	41.4±4	18.4±3
10	Brown shrimp	82.8±3	205.2±13	57.6±3	543.6±10
11	other	450±21	255±6	475±8	1225±18
Subtotal		3875.8±36.9	2422.2±81.3	2376.3±121.1	33892.5±34
Total		42566			

Discussion

Fish drying activity

Fish drying yard

The majority of fish species in Cox's Bazar were produced in dried form and sold for both domestic and commercial purposes. All of these major fish drying yards are located in different landing centers of Cox's Bazar district: in Cox's Bazar upazila, mostly Nazirertek, Chowfalldandi, Khurushkul, and Nunierchara; in Moheshkhali upazila, in Thakurtala, Ghotibhanga, and Sonadia; and finally, and in Teknaf upazila, in Shaporirdip and Shamlapur. New drying entrepreneurs have emerged, and some of them are operating in Nazirertek, Sonadia, Moheshkhali, Cox's Bazar, and Teknaf. Nowsad (2004) and Hossain et al. (2015) identified large-scale commercial marine fish drying yards were in Nazirartek, Chowfalldandi, Khurushkul, Moheshkhali, and Teknaf area. According to Hossain et al. (2015), Nazirertek covered 682 acres (276 ha) and 2,200 Khola while 784 acres (317 ha) were recognized by Belton et al. (2018). Hossain et al. (2022) highlighted that Nazirartek, the largest fish drying centre, has an increased number of Khola, while Teknaf dry fish yards have declined in the past 4–5 years. Our study findings recorded more than 220 ha area for drying yards at Nazirertek.

Infrastructures of sun-drying yard

Sun drying in Cox’s Bazar was done in killa or basha (fish drying yards) and these yards had different structures in different areas. The study found raised drying rack wrapped in split bamboo mats, a raised drying rack wrapped by black polythene sheet, fish drying yards covered with mosquito net, mechanical solar dryer with an exhauster fan (Nazirertek), an electric fish dryer (Nazirertek), vacuum packaging machine, traditional polythene sac to store dry fish (%), connection to pucca road (%), ice factory in the vicinity, shed in killa for storage of dry fish, large open shed for drying during rainy/foggy weather, up risen drying poles/bars (%), simple sealer packaging machine (in Nazirertek), electricity supply (%) and tube well in fish drying establishments (killa/basha) in the study area. Most of the sites have poor-quality equipment. Few have advanced ones; actually, most of them don't had mosquito nets, ice boxes, vacuum packets, etc., they were so traditionally oriented. This result also agreed with studies by Nahiduzzaman et al. (2020), Kubra et al. (2020), Rahman et al. (2017), and Nowsad (2004), which stated that sun drying for commercial purposes is typically done on an elevated bamboo rack constructed of splits and poles, for domestic use is done on a smaller scale using bamboo baskets and hanging small earthen pots. Paul et al. (2018) and Al Mehedi et al. (2020) reported that marine fish were dried by hanging over bamboo bars and hung similarly over bamboo poles. Hamja et al. (2024) suggested the establishment of ice plants, tube well facilities, improved technology and equipment that should be used for drying.

Processing conditions fish drying

The study found that elevated drying rack, using potable water for raw material washing, using traditional polythene sac storage, sorting/grading raw fish before washing/drying, using bamboo baskets while handling and using salt in fish before spreading for processing in all drying sites.

An elevated rack covered by a mosquito net was found in Ghotibhanga, Shamlapur and Nazirertek area, mosquito net-covered fish drying room with exhaust fanning was found in Shamlapur, Nazirertek and Chowfalldandi. washing raw fish before spreading and using salt in fish before sorting practice only in Nunierchara and canal water was utilized for washing purposes in Moheshkhali, BFDC and Teknaf. Ice or re-ice fish while sorting, using a covered container for storage and receiving raw material in ice condition in ice boxes were not found at any of the drying sites. All in all, a high level of compliance was not uniform across the regions, especially in the areas of infrastructure and processing. Reza et al. (2005) reported on the traditional fish drying system in Cox's Bazar, Bangladesh, where fish is dried on bamboo mats, concrete floors, raised platforms, or poles. The result aligned with other studies: Paul et al. (2018), Rahman et al. (2017), and Hossain et al. (2015), who reported bamboo mats or racks for dry fish. Samad et al. (2009) and Shamim et al. (2014) reported similar sun-drying methods, though Soegiyono (1994) added that fish was put on trays for sun drying.

Raw materials used for drying

The current study was discussed with 10 major species that were used for sun-drying. Hossain (2015) identified the ten primary species used in dry fish production by volume and abundance, including Bombay duck, ribbon fish, croaker, white sardine, anchovy, shrimp, pomfret, river shad, flatfish, and rays. Payra et al. (2016) reported 19 species, with 16 finfish and the rest were shellfish. Shuchi et al. (2022) documented 23 dry fish species and one shrimp species, while Al Mehedi et al. (2020) identified 21 species, categorizing them into major species (80% of total dried fish, e.g., Loittya, Faissa, Churi) and minor species (20%, e.g., Shapla pata, Poa, Chingri, Koral, Ramsos, Rupchanda, Lakkha, Rupsha, Bhata).

Spot quality defect points of raw materials

Quality defect points (DP) were studied for different fish species across four locations. The average DP was 1.38 to 3.3: These defects point values indicate that all raw materials are good and acceptable. The raw material quality was excellent as those were freshly landed. Raw fish are processed quickly by yard area temperature at Sonadia Island's sandy beach yard. Bulk harvests of large boats are unloaded on a mat of split bamboo kept on sand. Proper icing is not done after the landing of the raw fish. Overall, the study found that the raw materials quality' an average of 2-3 DP. The present study results coincided with both the study of Nowsad (2004) and Reza et al. (2005). However, it was well documented that the quality of raw material used for traditional drying was of poor quality primarily due to insufficient icing during harvest (Nowsad, 2007; Al Mehedi et al., 2020).

Quantity of raw materials for each kg dry fish drying

The quantity of raw materials for each kg of dry fish drying varies according to the different species under study. The average quantity of raw materials for each kg of dry fish was found to be 2.6 to 6.5 kg. It also varies in raw fish quality, temperature rate, fish drying process practice and so many factors related to fish drying. According to Hossain et al. (2015), to produce 1 kg of dried lotya, ichhiri, small chhuri, pata, large chhuri, tak chanda, phaisa, poa and olua - 5.97, 4.24, 3.17, 3.06, 3.00, 2.69, 2.68, 2.17 and 1.92 kg fresh fish was needed. Normally, dry fish producers get 30-35 kg of dry fish from 100 kg of raw fish (Al Mehedi et al., 2020). Current studied findings more or less similar with above author's results.

Salt use with raw fish for salted fish drying

The present study revealed that on average, the percentage of salt used in the fish drying yards at Cox's Bazar area were- 3-5% for pomfret, 7-13% for jewfish/croaker, 3-8% for mackerel, 4-8% for sardine, 7-8% for anchovies, 5-8% for bombay duck, 3-7% for ribbon fish, 3-6% for shark, 4-6% for shrimp and a range of 5-16% for other species (table-4). All the fish farmers used non-branded commercial salt for this purpose. According to Nowsad (2004), the fish undergoes salt preparation before being sun-dried. However, the salt content of the uncooked fish does not go above 3-4%. according to Sugathapala et al. (2012) consumers like goods with minimal or no salt content. However, fish needs to be salted by 10–15% on overcast or wet days. Fish were carefully cleaned and salted at a ratio of 1:3 (salt: fish) after dressing. Nahiduzzaman et al. (2020) and Rahman et al. (2017) discovered that processors blended 1 kg of salt for every 20 kg of raw fish.

Packaging of dry fish

The study found that at Moheshkhali, Teknaf, and BFDC landing site areas, processors completely use traditional gunny sacks or baskets for packaging dried fish. But at Nazirertek, 87% of processors use gunny sacks, 10% use simple sealing in plastic pouches, and 3% use vacuum packs in HDPE pouches (Nunierchara) only for packaging dried fish. Nahiduzzaman et al. (2020), Al Mehedi et al. (2020), Islam et al. (2020), Paul et al. (2018) and Rahman et al. (2017) reported that after sorting, the dried fish were packed into plastic and jute bags for easy handling. Sometimes bamboo baskets are also used for this purpose. Hossain et al. (2015) reported that almost 85-90% of dried products were simply packed in a plastic pouch and exported to Hong Kong or other countries. The study also relevant to Chattopadhyay et al. (2024), also claimed the main goal of packaging innovations is to maintain the traditional essence of dry fish.

Storage of dry fish

The study found the following storage methods for dried fish: Moheshkhali used open sack 47.62% and sealed pouch 52.58%; Teknaf open sack 72.73% and sealed pouch 27.27%; Khurushkul open sack 57.14% and sealed pouch 42.86% and vacuum packed 14.28% and Nazirertek open sack 57.15% sealed pouch 28.57%. Nahiduzzaman et al. (2020), Rahman et al. (2017), and Samad et al. (2009) reported that well storage is a system prerequisite for quality products and also for shelf life. Storage of dried fish is found to be done in a tent made of thin plastic sheets and bamboo split for temporary storage until sold or sold. Packed dried fish were kept in these tents for temporary storage until marketing or selling. (Nowsad, 2007; Al Mehedi et al., 2020).

Marketing of dry fish

The study showed dried fish marketing distribution in Bangladesh: Moheshkhali (42.1% retail, 57.89% wholesale), Teknaf (27.27% retail, 72.73% wholesale), Khurushkul (50% retail, 50% wholesale), and Nazirertek (23.1% retail, 76.92% wholesale). Generally, dry fish and fishery products are marketed through many different channels and outlets in Bangladesh (Paul et al., 2018; Reza et al., 2005 Nayeem et al., 2010). The marketing channel for dry fish starts with the producer and then goes to the reader, wholesalers, and retailers and finally up to consumers or from the producer to the retailer and finally up to consumers. The present result is similar to Samad et al. (2009) and more or less similar findings were also found by Flowra et al. (2012), Marine et al. (2014), Shamim et al. (2011), and Al Mehedi et al., (2020). In domestic marketing, marine dry fish producers sell fish mainly to beparis (69%) via aratdar, 19% to Faria, and 12% to inter-district aratdar agents. On the other hand, especially for export marketing, marine dry fish producers sell the entire amount (100%) to fish-drying factories/ processing plants (Haque et al., 2016).

Profit margin

The study identified that there were profit differences in dried fish between four drying centers (Moheshkhali, Teknaf, BFDC and Nazirertek) based on species. The maximum profit percentages were achieved for ribbon fish

(33%), bombay duck (28%), and pomfret (27%), and finally, the minimum values of 12% for shark and 14% for shrimp were observed for two species. There were also great differences in profit margins in different regions, and they were generally higher in Moheshkhali. Net profits per species varied between 11% and 33%, with ribbon fish and Bombay duck having the highest percent margin. The profit margin of processors for dried pomfret, Indian salmon, Bombay duck, ribbon fish (small size), Indian piker, Spanish mackerel, and big eye croaker was 10.52 %,17.33 %, 11.83 %, 11.83 %, 13.15 %, 12.27 %, and 5.23 % respectively reported by Amin et al. (2012) and Haque et al., (2016). More or less similar profit margins were reported by Ahsan et al. (2016), Faruque et al. (2012), and Biswas et al. (2006), which showed 35% and 19% marketing margins respectively, for dried products of bombay duck and ribbon fish in Cox's Bazar. The highest estimated net profit was recorded for dry Churi (large) at $0.57 per kg (Dey et al., 2024).

Quantity of sun-dried fish (MT) by species

The survey observed that Cox's Bazar dried fish production was 42,566 MT in the four major study locations. In 2022-2023, a total of 69,866.52 MT of dried fish were processed out of which Cox's Bazar produced 48,285 MT (FRSS, 2023). The studied findings from major drying locations are more or less like FRSS (2023). Bangladesh exported dried fish, 2224.62 MT, and earned more than 48.72 crore taka or USD 6,52,000 per annum (FRSS, 2023). Hossain et al. (2015) observed that 204,000 MT of marine and 36,000 MT of freshwater fish were required to produce 51,000 MT of marine and 9,000 MT of freshwater dried fish. According to the studied findings the highest dry fish production was recorded in Nazirertek and lowest in Teknaf. Nazirertek is the largest marine fish drying facilities of the country noted by Hossain et al. (2022). In terms of species production, Ribbon fish was recorded the highest and shark was the lowest. Matching to FRSS (2023) shark was the lowest in species-wise annual production of Bangladesh.

Conclusion

The article highlighted the significance of marine dried fish production and trade in Cox's Bazar district, which plays a crucial role in the economy through food production, employment, and product diversification. Key fish drying centers in Cox's Bazar sadar upazila include Nazirertek, Chowfalldandi, Khurushkul, and Nunierchara, while other centers are in Moheskkhali and Teknaf Upazila. The dry fish industry in Cox's Bazar holds significant economic and cultural importance, providing livelihoods to thousands of coastal communities and contributing to the region's economy. Despite its potential, the industry faces challenges such as outdated processing methods, poor infrastructure, market inefficiencies, and environmental concerns. Addressing these issues through modernization of drying techniques, improving supply chain management, sanitary and epidemiological standards, organizing joint product storage, and sale and ensuring environmental sustainability can greatly enhance production quality and market competitiveness. Additionally, government and private organization support, proper regulations, and community engagement are crucial for transforming the dry fish sector into a more profitable and sustainable industry, ultimately boosting local employment and contributing to national economic growth.

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Ethical approval

The study was done following the ethical guidelines of the Department of Fisheries Technology of Bangladesh Agricultural University.

Informed consent

Not available.

Conflicts of interest

The authors declare no conflicts of interest.

Data availability statement

The data presented in this study are available in the article.

Author contribution

Author 1: Field data curation and analysis and thesis/report writing
Author 2: Conceptualization, planning, supervising, writing, and revising the original manuscript
Author 3: Field data curation and analysis, writing original manuscript and corresponding author

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RESEARCH PAPER

Marmara Lake (Manisa-Türkiye)'s Final Waters: Assessment of Water Quality Parameters and Trophic Status Before Near-Total Drying

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Abstract

This study was carried out at 3 different stations in Marmara Lake, in Western Anatolia in Türkiye, and focused on variations in water quality parameters based on months. Water samples collected from the surface of the lake were analyzed monthly in terms of total suspended solids (TSS), volatile suspended solids (VSS), fixed suspended solids (FSS), ammonium nitrogen (NH_4^+-N), nitrite nitrogen (NO_2^--N), nitrate nitrogen (NO_3^--N), phosphate phosphorus (PO_4^{-3}-P), silica (SiO_2) and chlorophyll-*a* (Chl-*a*) parameters. As a result of this study, according to Inland Water Quality Standards defined in Surface Water Quality Management Regulations (SWQMR), Marmara Lake can be considered the Class-I quality by the measured ammonium nitrogen and nitrate nitrogen and the Class-II by the measured nitrite nitrogen and phosphate phosphorus. Moreover, it was evaluated that the lake is in a eutrophic status according to its Carlson's trophic state index (TSI) scores based on the phosphate phosphorus values, and in a hypereutrophic status based on the chlorophyll-*a* values. This study presented the latest scientific research evaluating the surface water quality parameters and trophic levels of Marmara Lake before its complete drying. In this respect, the study has historical importance in documenting the lake's final ecological state and will be able to create a critical reference point for potential restoration efforts.

Introduction

Lakes are valuable wetlands that play an important role in the world hydrological cycle, biodiversity support, regulation of carbon cycling and climate, and also provide various ecosystem services (Zedler et al., 2005; Dudgeon et al., 2006; Tranvik et al., 2009). However, due to global climate change and human activities, lakes or wetlands in many parts of the world face serious threats, including eutrophication, pollution, lowering of water levels, and even complete drying. (Moss et al., 2011; Jeppesen et al., 2014; Tussupova et al., 2020). Of these, the drying not only disrupts the ecological balance but also causes wide-ranging impacts on regional water resource management, biodiversity conservation, and the socioeconomic structure of local human populations (Čížková et al., 2013; Alaniz et al., 2019). According to the Global Wetland Outlook data published by the Ramsar Secretariat in 2018, 87% of the world's wetlands have been lost in the last 300 years due to various problems such as construction, pollution, drying, and overuse. (Gardner & Finlayson, 2018) According to WWF's Living Planet Reports (WWF, 2024), the greatest decrease in vertebrate populations between 1970 and 2012 occurred in wetland species with 81%, and 25% of these are currently at risk of extinction. There are 131 wetlands in Türkiye, including natural lakes. 14 of them are the Ramsar Sites, 59 are Wetlands of National Importance and 58 are Wetlands of Local Importance, apart from these, there are 6 more lakes declared as National Parks, the highest environmental conservation status in Türkiye (DKMP, 2024). Marmara Lake (Manisa-Türkiye) was also included in the wetland category in 2002 and registered as a Wetland of National Importance in 2017. Despite all these protected statuses, the lake, once covering an area of almost 6000 hectares (too variable periodically), is now completely dry due to faulty water basin management choices and drought caused by global climate change (Körbalta, 2019). Before its drying or this ecological catastrophe, the lake was a biodiversity hotspot, hosting 144 bird species—56 of which were breeding there (Gül, 2008); at least 15 fish species (İlhan & Sarı, 2011), emergent or submergent wetland plants (Seçmen & Leblebici, 1982), numerous aquatic macro-microorganisms (Cirik, 1980; Ustaoğlu, 1989) making it an ecosystem of remarkable ecological value. The lake also supported fisheries activities that significantly contributed to the regional economy, providing livelihoods for many local populations in the past.

Nowadays, the restoration of Marmara Lake is on the agenda through the joint efforts of water-related environmental activists and also the probable contribution of local water management authorities (personal communication). These kinds of restoration efforts will be able to aim not only to save an ecological system that is an important water resource and biodiversity center for the region and a vibrant ecosystem with diverse birds, fishes, and other aquatic species, but also to regain fisheries activities that were once supported by the lake. Water quality parameters are considered important indicators for understanding changes occurring in lake ecosystems (Wetzel, 2001). This study aims to present the latest scientific research evaluating the surface water quality parameters and trophic levels of Marmara Lake before its complete drying. In this respect, it has historical importance in documenting the lake's final ecological state and will be able to create a critical reference point for potential restoration efforts.

Materials and Methods

The research area, Marmara Lake, is an alluvial dam lake at an altitude of 75 m above sea level. Located in the Gediz River basin, the second largest river flowing into the Aegean Sea, the lake covers an area of approximately 70 km^2, 6 km from north to south and 12 km from east to west. Originally a seasonal, slightly salty lake in a closed basin, fed by small streams and groundwater, it was converted into an irrigation reservoir in 1953 (Bulkan, 2009). With the arrangements made, streams such as Kum Stream and Gediz River were added to the sources feeding the lake. The excess water of the lake was released to the Gediz River again through a canal (Arı & Derinöz, 2011).

This study was carried out monthly at 3 different stations in Marmara Lake between January and December 2016 (Figure 1). A Hach Lange DR 6000 brand spectrophotometer was used for measurements. Total suspended solids (TSS), volatile suspended solids (VSS) and fixed suspended solids (FSS) were analyzed with gravimetric methods (Stirling, 1985). Analyses of ammonium nitrogen (NH_4^+-N), nitrite nitrogen (NO_2^--N), nitrate nitrogen (NO_3^--N), phosphate phosphorus (PO_4^{-3}-P), silica (SiO_2) and chlorophyll-*a* (Chl-*a*) have been performed using a spectrophotometer (Strickland & Parsons, 1972; Wood, 1975; Parsons et al., 1984; Egemen & Sunlu, 2003). Alkalinity ($CaCO_3$) was analyzed with the titrimetric method (APHA, AWWA, WPCF, 2005). Water quality of the Marmara Lake has been determined referring to the Inland Water Quality Standards (SWQMR, 2015).

The Carlson's Trophic State Index (TSI) was calculated using chlorophyll-a (Chl-*a*) and total phosphorus (TP/PO_4^{-3}-P) concentrations in µg/L, with the formulas TSI (Chl-*a*) = 9.81 ln(Chl-*a*) + 30.6 for chlorophyll-a and TSI(TP) = 14.42 ln(TP) + 4.15 for total phosphorus, respectively (Carlson & Simpson, 1996). Based on the calculated TSI scores, the trophic state of the lake was evaluated as oligotroph (TSI < 40), mesotroph (40 ≤ TSI < 50), eutroph (50 ≤ TSI < 70), or hypertroph (TSI ≥ 70).

Figure 1. The study area and Marmara Lake's total drying chronology (*: stations)

In the study, the data were classified according to months and stations, checked in terms of their normality and homogeneity and then their average values and standard errors (± se) were calculated. Instead of focusing on stations, the study focused variations in water quality parameters based on months. Statistical analyses were all performed using Past v5.1 software program. Non-parametric several samples variance test (ANOVA followed by Kruskal-Wallis) was used to determine significant differences among months (Hammer et al., 2001).

Results and Discussion

Figure 2 shows the fluctuations in the water quality parameters detected in the monthly study in the surface water of Marmara Lake during a one-year study period. The differences between months were found statistically significant in all parameters ($p < 0.001$). The overall average values of water quality parameters were calculated as 161.5± 10.03 mg/L for alkalinity ($CaCO_3$), 22.53±4.71 mg/L for TSS, 6.52± 1.47 mg/L for VSS, 16.01± 3.81 mg/L for FSS, 3.65±0.602 mg/L for SiO_2, 0.044± 0.008 mg/L for NH_4^+-N, 0.009± 0.001 mg/L for NO_2^--N, 0.011± 0.006 mg/L for NO_3^--N, 0.036± 0.008 mg/L for PO_4^{-3}-P, 26.69± 6.76 µg/L for chlorophyll-*a* . Additionally, a comparison of Marmara Lake with several lakes and reservoirs in Türkiye according to water quality parameters is presented in Table 1.

In most waters, alkalinity ($CaCO_3$) is much more important than total hardness. Waters with total hardness greater than 20 mg/L $CaCO_3$ are considered safe for pond production. Such waters can be useful in protecting fish against the harmful effects of metal ions and pH changes. $CaCO_3$ corresponds to the acid-accepting capacity of water and the concentration of basic compounds in the structure of water. Low-alkalinity waters have low buffering capacity, and as a result, these waters are sensitive to changes in pH. Such changes can directly harm fish populations. Low-alkalinity ponds are less productive than high-alkalinity ponds. Lakes with high alkalinity (< 300 mg/L $CaCO_3$) are unproductive because they contain high levels of CO_2. The ideal range for alkalinity is 20-300 mg/L $CaCO_3$ (Egemen & Sunlu, 2003). The average total alkalinity value determined in the study was determined as 161.5 mg/L± 10.03. This result is among the ideal alkalinity values stated by Egemen & Sunlu (2003). The average alkalinity value determined by Mutlu et al., (2013), Turan & Aldemir (2023) is that value is higher than the alkalinity value we determined.

TSS is a parameter that, if higher than a certain threshold concentration, usually causes physically negative effects in water column, turbidity, condensation, and toxicity, as well as threats aquatic organisms health by decreasing the water transparency and dissolved oxygen concentration (Uslu & Türkman, 1987). The determined TSS ranged from 2.2 (April) to 45.1 (June), VSS ranged from 17.5 (November) to 1.6 (April) and

Table1. Comparison of water quality parameter values (mg/L) of Marmara Lake with different lakes or reservoirs

Lakes	(NH^+_4-N)	(NO^-_2-N)	(NO^-_3-N)	(PO^{3-}_4-P)	(SiO_2)	Chl-*a* (µg/l)	Alkalinity	Ref.
Kalecik	0.23	-	0.27	0.1	-	-	-	1
Çip	0.03	-	1.25	0.05	-	-	-	1
Işıktepe	0.002-0.14	-	0.929	0.06	-	-	98-148	2
Almus	0.29	0.011	0.18	0.03	-	-	-	3
Yamula	0.46	0.083	0.69	0.04	-	-	-	4
Dicle	-	-	-	-	-	-	-	5
Van	0.04-2.62	0.04-17.56	16.79-64.63	7.38-9.13	-	-	7630-7879	6
Derbent	0.18	0.05	0.96	0.05	-	-	163.8	7
Afşar	0.13-1.35	0-0.025	0-1.8	0-1.16	-	0.2-49.5	-	8
Mogan	1.8-2.3			0.1-0.23	-	<50	-	9
Selevir	0.063	0.02	0.006	0.17	-	-	-	10
Uluabat	0.19	0.043	0.99	0.42	-	-	-	11
Karagöl	0.01-0.51	0.00-0.02	0.48-5.96	0.12-0.36	-	-	224.6-304.3	12
Karagöl	0.002-0.64	0.0006-0.154 (Σ)		0.003-0.112	0.80-10.90	0.9-9.3	-	13
Demirköprü	0.08-1.736	0.002-0.074	0-0.154	0.018-0.262	3.29-9.69	1-162	26.8	14
Wadi Al- Arab	-	-	0.7-30.4	0.73-1.02	2.33-1.46	-	-	15
Marmara Lake	0.019-0.121 0.044±0.008	0.004-0.019 0.009±0.001	0-0.06 0.011±0.006	0.003-0.089 0.036±0.008	0.2-6.5 3.65±0.602	2.5-79.2 26.69±6.76	101-197 161.5±10.0	16

Reference: 1. Alpaslan et al., 2015; 2. Küçükyılmaz et al., 2014; 3. Buhan et al., 2010; 4. Çevik & Elibol, 2009; 5. Varol, 2015; 6. Turan & Aldemir, 2023; 7. Taş, 2006; 8. Ayvaz et al., 2011; 9. Ozdemir, et al., 2024; 10. Bulut et al., 2011; 11. Iscen et. al., 2008; 12. Mutlu et al., 2013; 13. Sömek & Balık, 2009; 14. Türk Çulha & Erdoğuş, 2018; 15. Saadoun et al., 2010; 16. This study.

FSS ranged from 40.1 (June) to 0.5 (April) mg/L. According to SWQMR (2015), the required TSS value for the eutrophication limit of lakes is 5 mg/l. The average values of water quality parameters were detected in Marmara Lake as; 22.53±4.71 mg/L for TSS, 6.52± 1.47 mg/L for VSS, 16.01± 3.81 mg/L for FSS (Figure 2). It is evaluated that the TSS and FSS values are high due to the increase of phytoplankton biomass and the terrestrial inputs transferred by rainwater and snowmelt. This result is considerably higher than the Demirköprü Dam Lake (5.41 mg/L) and Dicle Dam Lake (3.15 mg/L) TSS values (Türk Çulha & Erdoğuş, 2018; Varol, 2015). The TSS result in Marmara Lake shows that the lake is in the polluted water category.

The average SiO_2 value determined in Marmara Lake was determined as 3.65±0.602 mg/L. Similar to these values, Sömek & Balık (2009) reported the SiO_2 values from the Karagöl Lake, Saadoun et al., (2010) reported the SiO2 value to be between 2.33-7.60 mg/L in the Wadi Al-Arab Dam in Bulgaria, and Türk Çulha & Erdoğuş (2018) reported it to be 3.29-9.69 mg/L in the Demirköprü Dam Lake. Egemen & Sunlu (1996) assessed that the SiO_2 concentrations were very low in the spring season when the growth of diatoms was rising and high in the winter season when phytoplankton activity was poor. However, in this study, the main source of SiO_2, which is at its maximum level in the autumn months, is thought to be from terrestrial inputs due to precipitation.

In this study, The NH_4^+-N ranged from 0.121 (January) to 0.019 (May). It is thought that the reason for the relatively low NH_4^+-N values in the spring season in Marmara Lake is the consumption of increased phytoplankton biomass as food and the conversion of ammonium to ammonia with increasing pH during this period. The average NH_4^+-N value determined in the study was found to be lower than the value determined for the Yamula Dam Lake by Çevik & Elibol (2009) (0.46 mg/L), while it was found to be higher than the data of other lentic water bodies listed in Table 1. The overall average value of NH_4^+-N is in the Class I category according to SWQMR (2015). Sarıyıldız et al. (2008) reported that the NH_4^+-N value in their study conducted with samples taken from the region where the Gediz River enters the same lake fell into the Class IV category according to SWQMR (2015).

NO_2^--N is an unstable nitrogen form that occurs as a result of the oxidation of ammonia or the reduction reaction of ammonia to nitrate and rarely accumulates in the water column (at the anoxia); additionally, it was able to originate from the decomposition of various organic proteins (Boyd & Tucker, 1998). The mean NO_2^--N value in this study is 0.009±0.001 mg/L. Buhan et al., (2010) reported no pollution due to NO_2^--N (0.011 mg/L) values in the Almus Dam Lake. Türk Çulha & Erdoğuş (2018) stated that nitrite in Demirköprü dam lake was higher in summer than in other months. According to the SWQMR (2015) water quality parameters, the values of NO_2^--N are in the Class II water category. In Marmara Lake, the highest nitrite value was determined in the months representing the autumn period. This result was assumed to be due to the high temperature and low oxygen conditions occurring in the summer and autumn months in Lake Marmara, which was quite shallow and under the influence of possible fertilization due to intensive agricultural activities in its surroundings before it dried out completely, causing disruptions in the nitrogen cycle processes in both the water column and the sediment. Previous research has shown that this cycle in lakes can be impacted by environmental factors like temperature, N availability, dissolved oxygen, and microbial diversity and abundance (Yoshinaga et al., 2011; Xu et al., 2012; Wu et al., 2012; Zhu et al., 2015).

The average NO_3^--N value determined in the study is 0.011±0.006 mg/L. These data are considerably lower than the other nitrate values given in Table 1. When the monthly distribution of nitrate is examined, the value is determined only in January and March. When the average NO^{3-}-N values determined in Marmara Lake are compared with the water quality parameter values specified by SWQMR (2015), it is determined that they fall into the Class I category. Again, the NO^{3-}-N values determined in Selevir and Demirköprü dam lakes fall into the Class I category (Bulut et al., 2011; Türk Çulha & Erdoğuş, 2018).

PO_4^{-3}-P is measured in relatively limited concentration in uncontaminated natural waters by the pollutants and determines the productivity of lakes (Tepe & Boyd, 2003). Unlike nitrogen, which has many forms in lake systems, the most obvious inorganic phosphorus forms are ortho-phosphate or phosphate phosphorus, and more than 90% of the phosphorus detected in freshwater is found in the cells of living aquatic organisms as organic phosphate (Wetzel, 1983). The basis of all organic phosphorus compounds are the ortho-phosphate anions (Uslu & Türkman 1987). The average PO_4^{-3}-P value determined in Marmara Lake is 0.036±0.008 mg/L. PO_4^{-3}-P values were determined to be higher in the autumn months. This increase is thought to be due to, during the rainy period, the surface waters coming from terrestrial environments mixing with rainwater due to the slope of the land where the lake is located, nutrients coming from the agricultural areas, and the geological structure of the lake. Similar results were determined in Demirköprü Dam Lake (Türk Çulha & Erdoğuş, 2018). When compared with the study data in Table 1, it has a lower phosphorus value than Afşar, Uzunçayır, Selevir, Hirfanlı, Demirköprü Van, Uluabat and Wadi Al-Arab lakes. When compared with the water quality parameter values specified by SWQMR (2015), the PO_4^{-3}-P values determined in Marmara Lake fall into the Class II category. Chlorophyll-*a* is a dominate photosynthetic pigment in all phytoplanktonic organisms to carried out the primer production of nutrients and these organisms constitute the first link of the food chain in a freshwater ecosystem, with aquatic macrophytes. Therefore, the concentration of chlorophyll-a is the most important indicator to estimate phytoplankton biomass and trophy levels in a lake (Vollenweider & Kerekes, 1982). Chlorophyll-*a* values determined in Marmara Lake having 6 m of the deepest point, were inversely proportional with nutrient elements, reaching high values in autumn months, while lower values were determined in spring season when production is lower. In this study, the average chlorophyll-a amount was measured as 26.69±6.76 µg/L. This value is higher than the values of Borçka and Hirfanlı dam lakes given in Table 1, but lower than the values of other lakes. The average chlorophyll-*a* amount determined in Lake Marmara is in the hypereutrophic level according to SWQMR (2015). Furthermore, the excessive developments of macrophytes in surface water during the study periods is another indicator of eutrophication.

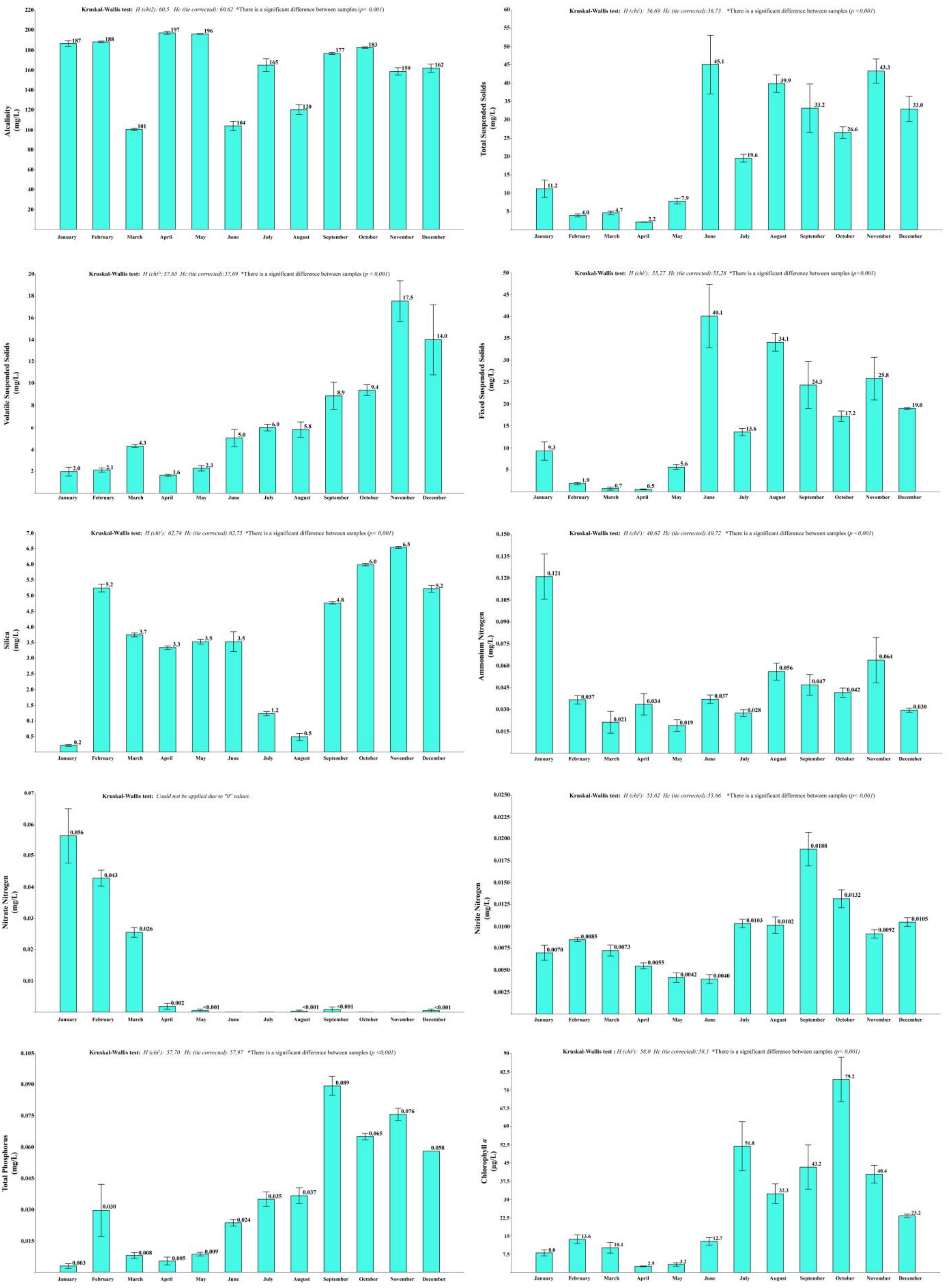

Figure 2. Monthly variations of water quality mean values (with ± se) in the Marmara Lake

The overall average TSI scores were calculated 47.9±5.1 for TSI(TP) and 57.8± for TSI(Chl-*a*). The TSI (TP) scores ranged from 19.7 (April) to 68.6 (September), TSI (Chl-*a*) scores ranged from 39.4 (April) to 73.1 (October). Based on the calculated TSI scores, the trophic state of the lake is classified into one of four categories: oligotrophic (TSI < 40), mesotrophic (40 ≤ TSI < 50), eutrophic (50 ≤ TSI < 70), or hypertrophic (TSI ≥ 70). According to these trophy classification, Marmara Lake was eutrophic by the TSI (TP) and was hypertrophic by TSI (Chl-*a*) in the summer and autumn months (Figure 3).

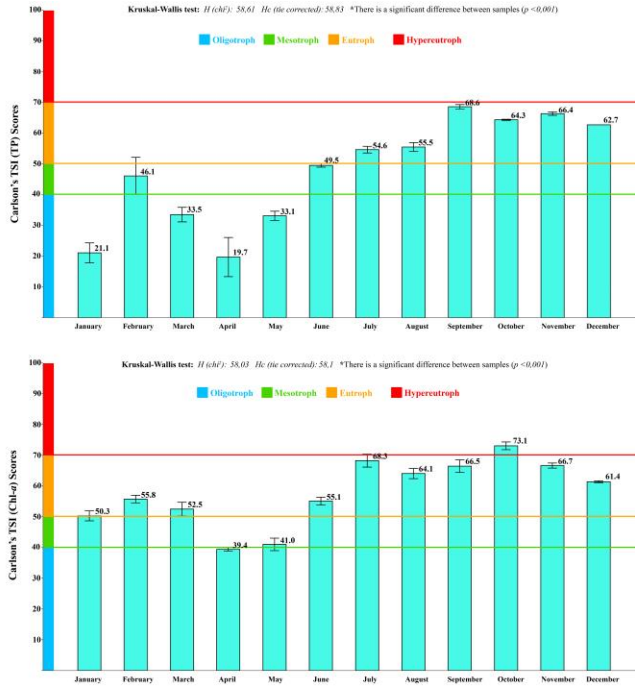

Figure 3. Monthly variations of mean Carlson's TSI scores (with ± se) in the Marmara Lake

A potential wetland restoration will be able to save a regional biodiversity center and a living ecosystem with diverse birds, fishes, and other aquatic species, but also to regain fisheries activities that were once supported by the lake. Following the restoration project in the future, it can be concluded that the lake area, which is currently used for agriculture, may have high nutritional value as a result of fertilization. The authors recommend that eutrophication control and ecological quality monitoring strategies should be developed, and measures should be taken to prevent fertilizers and other nutrients from agricultural areas from being carried into the lake. Additionally, it is thought that other pollution factors (metal, pesticides, etc.) should also be examined before restoration is carried out.

Conclusions

According to the data obtained from this study, which was carried out before the Marmara Lake dried up, the lake was determined to fall into the Class I category in terms of ammonium and nitrate nitrogen and the Class II category in terms of nitrite nitrogen and phosphate phosphorus values, according to SWQMR (2015). SMM values were determined to be higher than the SSM value of 5 mg/L required for the control of eutrophication in dam lakes by SWQMR (2015). Moreover, it was evaluated that the lake is in a eutrophic status according to its trophic state index scores and phosphate phosphorus, and in a hypereutrophic status according to its chlorophyll-a value.

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Ethical approval

The author declares that this study complies with research and publication ethics.

Informed consent

Not available.

Conflicts of interest

There is no conflict of interests for publishing of this study

Data availability statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Author contribution

Saniye Türk Çulha: Writing original draft, Conceptualization, Data curation, Formal analysis, Review and editing, Visualization, Supervision. Haşim Sömek: Data entry, Conceptualization, Methodology, Illustrations, Data improvement, Statistical analysis, Writing – Original draft. Hakkı Dereli: Examples, Supervision, Validation, Visualization, Editing, Resources, Review.

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RESEARCH PAPER

Antibiofilm Activity and Chemical Profiling of Biomolecule Extracts from Marine Sediment Bacteria

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Abstract

Some of the secondary metabolites in the marine ecosystem control the adhesion of microfouling microorganisms to surfaces, thereby exhibiting antibiofilm properties. The main objective of this research was to understand the antibiofilm and antibacterial activity of biomolecule extracts of bacteria from marine sediments. Each complex and pure biomolecule was evaluated for inhibition effects against two marine biofilm bacteria using the antibiofilm activity assay. The maximum activity of the biomolecules in preventing bacterial adhesion was determined to range between 68.59 percent and 91.84 percent for *Pseudoalteromonas agarivorans* and between 15 percent and 65.68 percent for *Exiguobacterium homiense*. Additionally, the antibacterial activity of biomolecule extracts against four marine biofilm bacteria was tested by the minimum inhibitory concentration method. The strongest minimum inhibitory activity of pure extract (0.78 mg/mL) from *Bacillus simplex* was recorded against *Alteromonas genoviensis*. Research has also focused on the determination of compounds such as alkaloids, phenolics and flavonoids in the structure of biomolecular extracts using spectrophotometric analysis. It was concluded that the pure biomolecules isolated from sediment bacteria are predominantly composed of alkaloids. These novel microbial biomolecule extracts could be used as sources to produce antibiofilm and antifouling products.

Introduction

Biofouling in marine environments is a progressive process initiated by microfouling and subsequently progressing to macrofouling (Adnan et al., 2018). The initial phase of microfouling is defined as the development of microbial biofilm (Caruso, 2020). The microfouling stage is developed by the rapidly production of extracellular polymeric substances (EPS) after biofilm bacteria attach to underwater surfaces (Abdulrahman et al., 2022). α-, γ-Proteobacteria, and Cytophaga-Flavobacterium-Bacteroides bacteria are dominant groups in marine environments. Members of γ-proteobacteria such as *Pseudoalteromonas* and *Alteromonas* are most frequently isolated from seawater, and there are also studies focused on their EPS production and biofilm formation mechanisms (Nichols et al., 2004; Nandakumar et al., 2004).

Bacterial EPS attach to underwater structures and living organism surfaces, colonize their environment, and provide a background for the main fouling marine organisms (Patil and Anil, 2005; Khandeparker et al., 2006; Cavalcanti et al., 2020). These extracellular polymeric structures from bacteria facilitate their access to underwater surfaces and preserve them from unfavorable conditions and detrimental risks (Zeng et al., 2020). The physical properties and morphology of bacteria as colloidal particles, such as their dimensions, range of growth ratios, and common negative charge, simplify their incursion into diverse habitats (De Carvalho, 2018; Patra et al., 2022).

The negative impacts of marine fouling and its economic penalties on marine transport and industries are notable (Bekiari et al., 2015; Dang and Lovell, 2016). Additionally, it is well-known that biofouling is the reason for the destruction of metallic structures by significant corrosion. Many attempts have been made to reduce fouling with the use of physical, chemical, and biological substances. However, the greatest success has been achieved with the use of marine coatings (Adnan et al.,2018; Cao et al., 2011; Iorhemen et al., 2016; Lade et al., 2014). Repressing prior surface colonizers of marine biofilm bacteria is an effective strategy for controlling biofouling on underwater surfaces (Abdulrahman et al., 2022). The application of damaging antifoulants and their relations with environmental situations have increased the progress of environmentally friendly choices (Callow and Callow, 2011; Nurioglu et al., 2015). From this point of view, research concerning marine bacteria's chemical defenses in the prevention of biofouling has significant expectations. A great deal of research has been carried out to shed light on antifoulants derived from bioactive molecules as replacements for environmentally unfriendly marine coatings (Ciriminna et al., 2015; Omae, 2003; Qian et al., 2009; Wang et al., 2017). The application of ecologically friendly biocides as replacements for synthetic chemicals has recently appeared because the only aim of chemistry is to produce or discover novel and effective chemical products that are reliable for use with expanded prolificacy (Adnan et al.,2018). Therefore, recently developed technologies with alternative resolutions are being discovered to inhibit this marine biofilm (Patra et al., 2022).

The extreme conditions of marine environments have caused microorganisms to synthesize different biomolecules to adjust to the conditions for survival (De Carvalho and Fernandes, 2010). Over the past five decades, researchers have identified over 20,000 naturally occurring marine biomolecules with potential biotechnological significance (Gallimore, 2017). New biomolecules capable of preventing biofouling were also explored by extraction from marine bacteria because of their secondary metabolism (antibiofilm, antibacterial, antilarval, and antialgal) (Aguila-Ramírez et al., 2014; Vimala, 2016). The secondary metabolites in the marine environment control the attachment of microfouling organisms to any surface, which is the cause of antifouling surfaces (Engel et al., 2002; Sjogren et al., 2004). The various molecules with notable antibiofilm activity may prohibit biofouling formation based on the role of the biofilm bacteria (Abdulrahman et al., 2022). As a matter of course, biomolecules produced by marine bacteria can induce deterioration in biofilm formation (Ganapiriya et al., 2012), so they can be functional in improving ecologically friendly metabolites to prevent biofouling (Holmstro¨m and Kjelleberg, 1999). When compared with the bioactive antibiofilm molecules from macro-organisms (polychetes, tunicates, bryozoans, molluscs, sponges, etc.), scarce data are present from marine bacteria (Fusetani, 2004; Adnan et al.,2018).

After years of intense research on terrestrial bacteria, the focus has shifted to marine ecosystems (WHO, 2015; Böhringer et al., 2017; Choudhary et al., 2017). Antibiofilm contents that are secondary metabolites of marine bacteria fascinate many researchers due to their superior antibacterial potential. These metabolites are exposed to broad research conducted on the chemistry of marine microbial biomolecules, which has been intensively developing recently. Due to their unique possessions, they have become one of the precedents for marine biotechnology (Andryukov et al., 2019). Marine bacteria are a plentiful source of various categories of protein derivatives of secondary metabolites (Andryukov et al., 2019). For example, hydrolase enzymes (Chen et al., 2013; Aykin et al., 2019) and biomolecules such as alkaloids, terpenoids, polyketides, peptides, etc. (Satheesh et al., 2016; Chen et al., 2018) from marine bacteria exhibit important antibiofilm activity. Many of the isolated antimicrobial-based secondary metabolites are capable of rapidly killing biofilm bacteria (Andryukov et al., 2019). With the increasing interest in discovering marine-derived biomolecules, the biotechnological potential of marine alkaloids has arisen as a rising class of bioactive metabolites. The number of these bioactive metabolites that can be isolated is very limited. Researchers should consider studying the pure and complex chemical structures of these biomolecules and the various biological activities of marine alkaloid molecules. These alkaloids are natural biomolecules that contain nitrogen and have important activities (Rodrigues et al., 2016; Zhou and Huang, 2020).

The main objective of present research was to understand the antibiofilm and antibacterial activity of marine sediment bacteria. It is hypothesized that the biomolecule extracts of bacteria isolated from marine sediments were a feature in antibiofilm activity. Based on experimental analysis and our previous research, the study was designed to understand the differences in antibiofilm activity of pure and complex biomolecule extracts obtained from sediment bacteria.

Materials and Methods

Pure and Complex Biomolecule Extracts from Marine Sediment Bacteria

The seven complex extracts were obtained from Turkish marine sediment bacteria, including *Bacillus simplex* KJ161411, *Alkalihalobacillus macyae* MW559742, *Kocuria rosea* MW559735, *Lacisediminihabitans profunda* MW559737, *Bacillus safensis* MW559602, *Bacillus vietnamensis* MW559607, and *Bacillus baekryungensis* KJ161399, using methanol with ion exchange chromatography (Diaion-HP20) (Omuzbuken et al., 2022). On the other hand, Silica gel SiliaFlash column resin was used for the purification process of complex extracts of *Kocuria rosea*, *Alkalihalobacillus macyae*, and *Bacillus simplex*. 61 : 32 : 7 chloroform : methanol : water, 64 : 50 : 10 chloroform : methanol : water, methanol, 40 : 10 : 50 butanol : acetic acid : water and water were passed through the columns, respectively. After the purification process, three pure extracts were obtained.

The Biofilm Bacteria Tested

The biofilm bacteria *Pseudoalteromonas agarivorans* FJ040188, *Vibrio lentus* FJ200649, *Alteromonas genoviensis* FJ040186, and *Exiguobacterium homiense* FJ200653 were isolated from Izmir Bay (Eastern Aegean Sea, Turkey) (Kacar et al., 2009). The biofilm bacteria were grown overnight on Zobell Marine Broth (HiMedia) at 26 °C (OD600 value of 2).

Testing Biomolecule Extracts for Antibacterial Activity: Minimum Inhibitory Concentration

The minimum inhibitory concentration (MIC) was determined by the microdilution method described by Zgoda and Porter (2001), with some modifications against *V. lentus*, *P. agarivorans*, *A. genoviensis* and *E. homiense* (Kacar et al., 2018). Briefly, a series of dilutions of the pure and complex biomolecule extracts was provided, ranging from 0.78 mg/mL to 25 mg/mL. This was followed by a series of dilutions of biomolecule extracts transferred to the broth in transparent 96–well microtiter plates. The transparent 96–well microtiter plates were incubated for 24 h at 26 °C. The results were obtained using 1% triphenyl tetrazolium chloride (Sigma USA), which may be bacterial growth positive when a red color, indicating the formation of triphenyl formazan, was recorded. The biofilm bacteria without biomolecule extracts were tested as a positive control in the analyses. The minimum inhibitory concentration experiments on the antibacterial activity of biomolecule extracts were performed in duplicate.

Screening of Biomolecule Extracts for Antibiofilm Activity

The prevention of bacterial attachment testing for a change in the percentage of bacterial adhesion (intense biofilm producer isolates; *P. agarivorans* and *E. homiense*) on the surface of black polystyrene microplates (Greiner Bio-One, Austria) in seawater was performed with sterile conditions at 20 °C, as described and modified by Aykin et al. 2019 and Leroy et al. (2008). Briefly, the biomolecule extracts were analyzed for inhibition of bacterial attachment. The biomolecule extracts were diluted at different concentrations (0.15 to 25 mg/ml) and spotted 1 h before introducing the bacterial suspension. After the incubation at 20 °C for 24 h using orbital shaking (120 rpm), three washes, and fixing for 1.5 h at 4 °C with 2.5% formaldehyde, the samples were stained with 200 µL DAPI (4 g/ml) for 20 min. Microplates were measured using a Synergy HTX multimode reader (Biotek, USA) at 350 nm light excitation and 510 nm light emission wavelengths. Sterile seawater was used as a control with the bacterial suspension. All experiments on the antibiofilm activity of biomolecule extracts were performed in duplicate.

The change in bacterial attachment was measured as the percentage reduction (CR) by comparing the fluorescence of the blank (FB: without bacteria, negative control), the fluorescence of the control (FC: bacteria without biomolecule extracts, positive control), and the fluorescence of the sample (FS: bacteria with biomolecule extracts).

$$CR = \{[(FC-FB) – (FS-FB)]/ (FC-FB)\} \times 100$$

Chemical Profiles of Biomolecule Extracts

The chemical profiles of biomolecule extracts were determined using spectrophotometric methods (Omuzbuken et al., 2022). The total phenolic (as gallic acid equivalents), alkaloid (as boldine equivalents), and flavonoid substances (as quercetin equivalents) were determined as follows.

Total phenolics: The total phenolics of the bacterial biomolecule extracts were determined with the spectrophotometric method (Rohaeti et al., 2017). Gallic acid (0.9 mL) was used as a standard solution. Folin-Ciocalteu solution (4.5 mL) was used as the reagent. The sample solution was spiked with 3.6 mL of 7.5% Na2CO3 and incubated for 1 h. The samples were measured at 765 nm. The total phenolic concentration was calculated based on three replicates.

Total alkaloids: The total alkaloid content of the bacterial biomolecule extracts was detected with the spectrophotometric method (Shamsa et al., 2008; Patel et al., 2015). The boldine standard solution was used as a standard solution. The bromocresol green solution was prepared with 2 N NaOH. The samples were measured at 470 nm. The total alkaloid concentration was calculated based on three replicates.

Total flavonoids: The total flavonoids of the bacterial biomolecule extracts were measured with the spectrophotometric method (Rohaeti et al., 2017). The quercetin equivalent solution was used as a standard solution. Samples were spiked with 1 M potassium acetate, ethanol, and 10% aluminium chloride and incubated for 30 min at room temperature. Absorbance was measured at 415 nm, and the total flavonoid concentration was calculated based on three replicates.

Statistical Analysis

The statistical data analysis was performed using STATISTICA (v11.0 software). Pearson's correlation test was applied to detect correlations between variables (chemical profiles of extract).

Results

Minimum Inhibition Concentrations of the Biomolecule Extracts as Antibacterial Activity

Results of the antibacterial activity of the complex and their pure biomolecule extracts against the four marine biofilm bacteria are presented in tables 1 and 2, which show that all biomolecule extracts from sediment bacteria have minimum inhibitory activity against the tested biofilm bacteria (*V.lentus*, *A. genoviensis*, *P. alteromonas*, *E. homiense*). The range of activity varies from 0.78 mg/ml to 25 mg/ml, whereas some are without activity. The strongest minimum inhibitory activity of pure extract (0.78 mg/mL) from *Bacillus simplex* was recorded against *Alteromonas genoviensis*, followed by the pure extract of *Kocuria rosea* with 6.25 mg/ml inhibiting *Alteromonas genoviensis*. Also, complex extracts of *Kocuria rosea* and *Bacillus simplex* were effective in inhibiting *Alteromonas genoviensis* at 6.25 mg/ml. The complex extracts of *Kocuria rosea*, *Alkalihalobacillus macyae*, and the complex and pure extracts of *Bacillus simplex* were determined to be ineffective at the minimum inhibition concentration against the tested strain, *Exiguobacterium homiense*. Dimethylsulfoxide (> 99.5%) (Carl Roth) was used as a negative control.

Table 1. The minimum inhibition concentrations (mg/ml) of pure biomolecule extracts against marine biofilm bacteria

Isolates of Biofilm Bacteria	Minimum Inhibition Concentration of Pure Biomolecule Extracts from Sediment Bacteria (mg/mL)		
	Kocuria rosea	***Alkalihalobacillus macyae***	***Bacillus simplex***
Vibrio lentus	12.5	25	25
Alteromonas genoviensis	6.25	12.5	0.78
Pseudoalteromonas agarivorans	12.5	25	25
Exiguobacterium homiense	25	25	(-)

(-) not determined MIC values

Antibiofilm Activity of Biomolecule Extracts

Antibiofilm analyses of the biomolecule extracts, whose antibacterial activities were determined by the MIC test, evaluated each of the extracts for antibiofilm activity against *Pseudoalteromonas agarivorans* and *Exiguobacterium homiense* from marine biofilm bacteria. During the experiments, these two biofilm-forming bacterial species demonstrated more notable biofilm production activity, so they were selected for further analysis. The range of maximum activities of pure and complex molecule extracts in the prevention of bacterial attachment varied from 68.59% to 91.84% for *P. agarivorans* and from 15% to 65.68% for *E. homiense*, as shown in Figure 1. The pure molecule extract of *Kocuria rosea* showed the highest prevention of bacterial attachment activity at 85.19% against *P. agarivorans*. In contrast, the pure biomolecule extract of *B. simplex* didn't prevent bacterial attachment activity against *E. homiense*. The complex biomolecule extract of *B. vietnamensis* showed the highest prevention activity of 91.83% against *P. agarivorans*, followed by the complex biomolecule extract of *B. baekryungensis*. For the prevention of attachment by *E. homiense*, the most effective complex biomolecule extract was determined to be *K. rosea*. Some of the biomolecule extracts demonstrated strong activity against both antibacterial activity and biofilm formation, while others were better against antibiofilm activity and vice versa (Figures 2-3). It can be stated that the decrease in EPS components has the potential to disrupt the structure of biofilms (Viju et al. 2020). Consequently, it is postulated that the antibiofilm effect of the extracts disrupts the structure-activity against biofilm formation. It can result from the antibiofilm activity.

Table 2. The minimum inhibition concentrations (mg/ml) of complex biomolecule extracts against marine biofilm bacteria

Isolates of Biofilm Bacteria	Minimum Inhibition Concentration of Complex Biomolecule Extracts from Sediment Bacteria (mg/mL)						
	Kocuria rosea	***Bacillus safensis***	***Lacisediminihabitans profunda***	***Alkalihalobacillus macyae***	***Bacillus vietnamensis***	***Bacillus simplex***	***Bacillus baekryungensis***
Vibrio lentus	25	25	25	25	25	25	25
Alteromonas genoviensis	6.25	12.5	12.5	12.5	12.5	6.25	12.5
Pseudoalteromonas agarivorans	25	12.5	25	25	25	25	25
Exiguobacterium homiense	(-)	25	25	(-)	25	(-)	25

(-) not determined MIC values

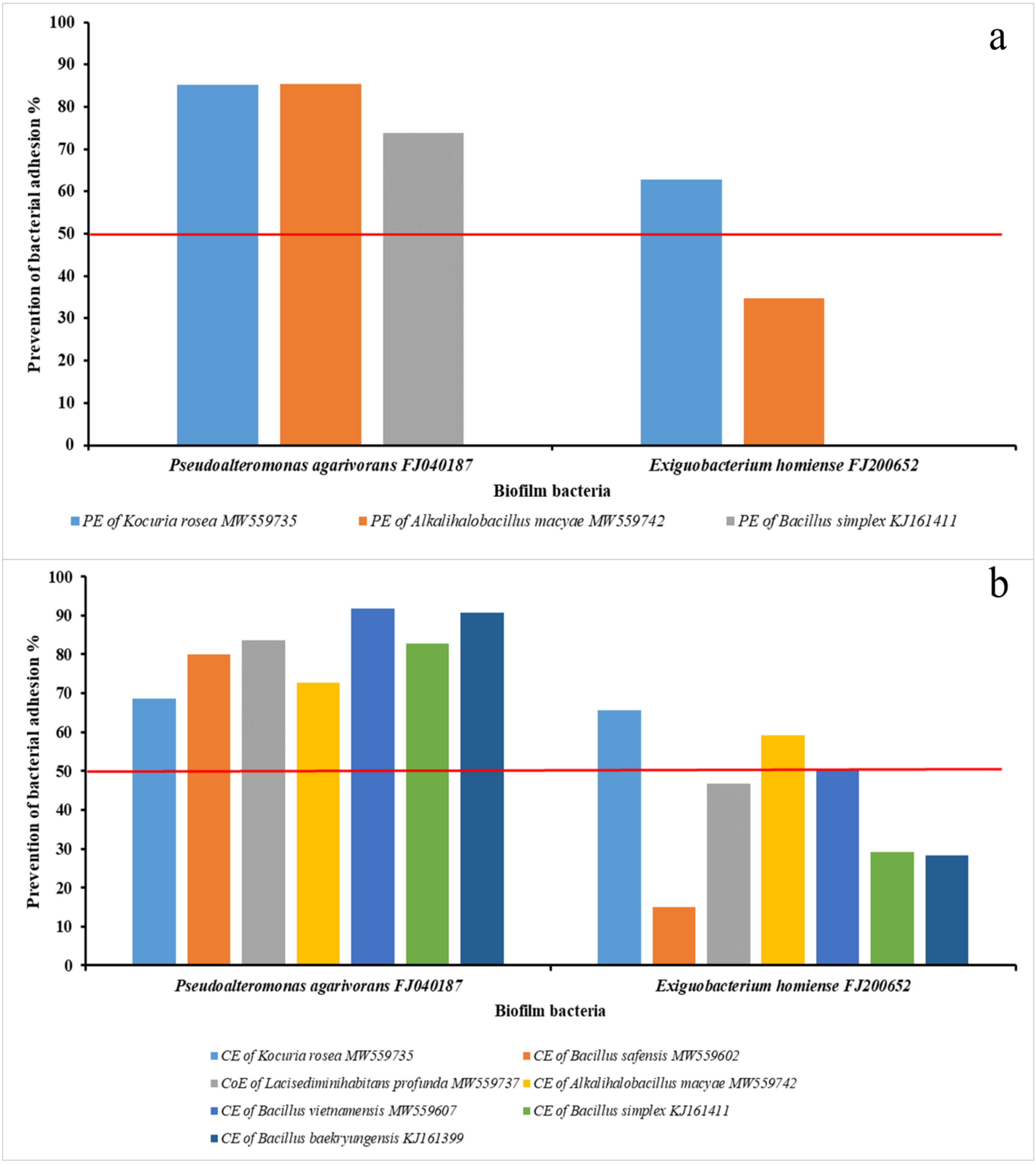

Figure 1. The results of reduction in biofilm bacteria by more than 50% according to prevention tests (this is shown in the figure as a red line).

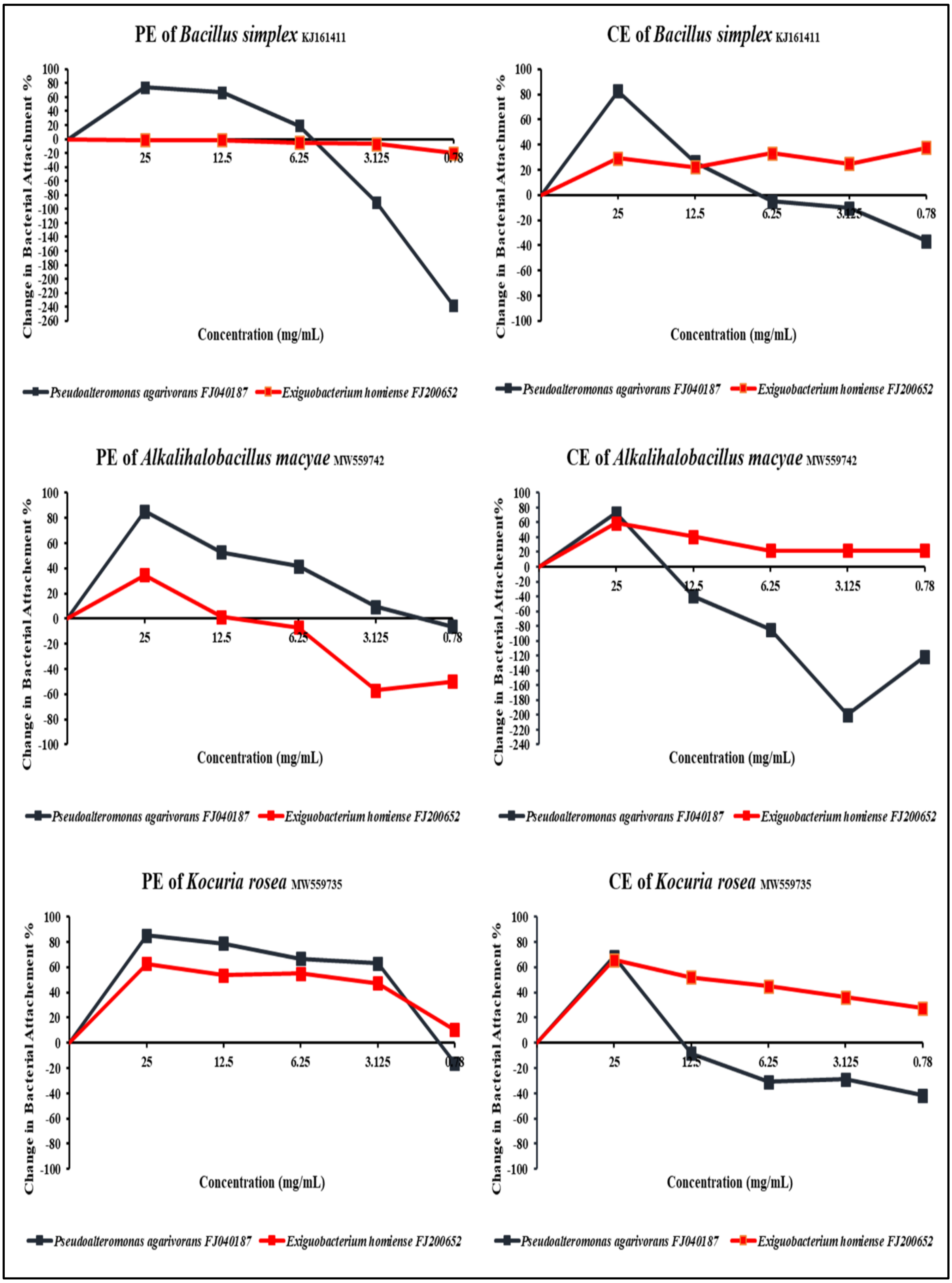

Figure 2. Percentage reduction in bacterial attachment of prevention tests according to biomolecule extracts concentrations of *B. simplex*, *A. macyae* and *K. rosea* (CE: Complex biomolecule extract, PE: Pure biomolecule extract)

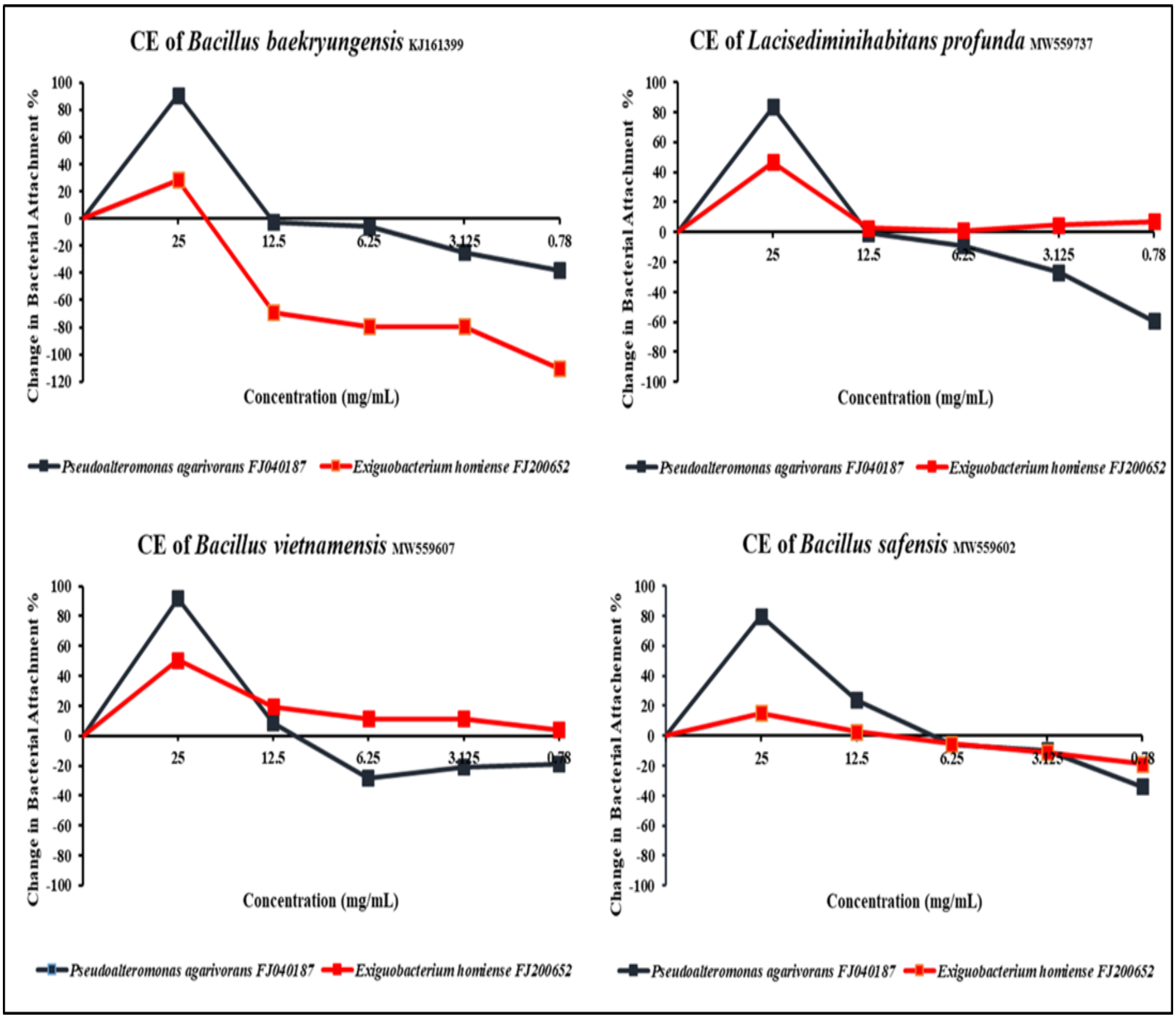

Figure 3. Percentage reduction in bacterial attachment of prevention tests according to biomolecule extracts concentrations of *B. baekryungensis*, *L. profunda*, *B. vietnamensis* and *B. safensis* (CE: Complex biomolecule extract)

Table 3. The results of chemical profile analyses of bacterial biomolecule extracts (PE: Pure biomolecule extract, CE: Complex biomolecule extract)

Bacterial biomolecule extracts	**Total Alkaloid concentration[1]** (mg equivalent boldin / g biomolecule extract)	**Total Phenolic concentration[1]** (mg equivalent quarcetin / g biomolecule extract)	**Total Flavonoid concentration[1]** (mg equivalent gallic acid / g biomolecule extract)
PE of *Bacillus simplex*	21.57 ± 1.08	Nd[2]	Nd[2]
PE of *Kocuria rosea*	56.33 ± 0.54	Nd[2]	Nd[2]
PE of *Alkalihalobacillus macyae*	36.83 ± 1.19	Nd[2]	Nd[2]
CE of *Bacillus vietnamensis*	14.06 ± 0.51	101.57 ± 0.10	5.65 ± 0.18
CE of *Bacillus safensis*	12.77 ± 0.16	73.91 ± 0.77	6.65 ± 0.40
CE of *Lacisediminihabitans profunda*	16.29 ± 0.29	84.92 ± 0	4.12 ± 0
CE of *Bacillus baekryungensis*	3.61 ± 0.17	51.39 ± 0.16	4.51 ± 0.08
CE of *Alkalihalobacillus macyae*	123.51 ± 26.01	71.37 ± 9.46	11.74 ± 0.29
CE of *Bacillus simplex*	22.59 ± 14.48	86.28 ± 18.57	20.08 ± 3.41
CE of *Kocuria rosea*	142.16 ± 10.38	92.58 ± 22.52	12.03 ± 0.57

mean of 3 replicates ± standard deviation, [2] Nd: not detected

Chemical Profiles of Biomolecule Extracts

The chemical profiles of pure and complex biomolecule extracts were analyzed by spectrophotometric methods. Analyzing biomolecule extracts can provide important data about the chemical profiles of sediment bacteria. The research also focused on the chemical evaluation of types of biomolecule extracts, alkaloids, phenolics, and flavonoids, whose antibiofilm activities were determined (Figure 4). As seen in Table 3, all of the pure molecule extracts were found to be alkaloids. The highest number of alkaloids (142.16 ± 10.38 mg equivalent boldine/g biomolecule extract) was observed in *K. rosea* and the lowest one (3.61 ± 0.17 mg equivalent boldine/g biomolecule extract) in *B. baekryungensis*. The phenolic substance ranged from 51.39 ± 0.16 to 101.57 ± 0.10 mg equivalent gallic acid/g biomolecule extract and was highest in *B. vietnamensis*. The highest flavonoid substance (20.08 ± 3.41 mg equivalent quercetin/g biomolecule extract) was noticed for *B. simplex*, whereas the lowest flavonoid substance was found for *Lacisediminihabitans profunda*, with 4.12 ± 0 mg equivalent quercetin/g biomolecule extract. Additionally, Pearson's correlation test was not detected significant positive or negative relationship between the chemical compounds (alkaloids, phenolics, flavonoids).

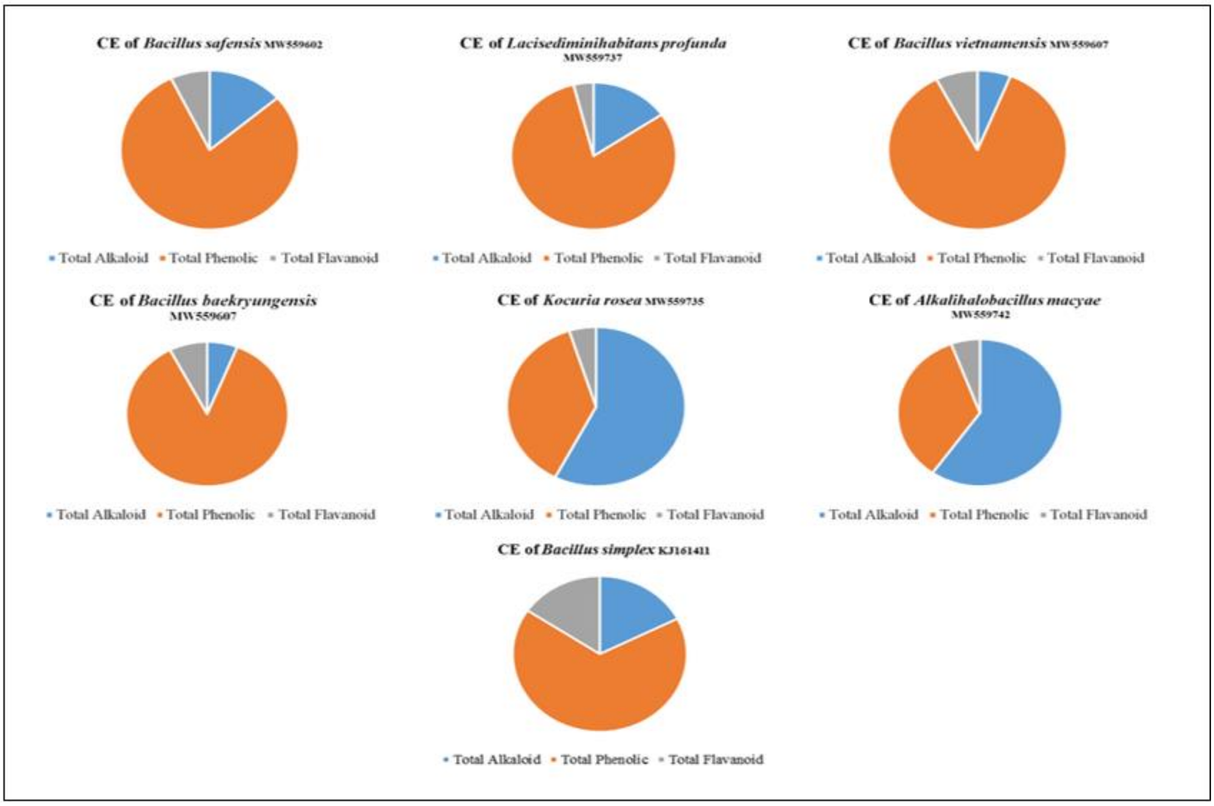

Figure 4. Total alkaloid (mg equivalent boldine/ g biomolecule extract), total phenolic (mg equivalent gallic acid/ g biomolecule extract), total flavonoid (mg equivalent quercetin/ g biomolecule extract) profiles of bacterial complex biomolecule extract (CE: Complex biomolecule extract)

Discussion

In recent years, researchers investigating marine biomolecules have expanded the scope of their studies from macro-organisms, such as ascidians, sponges, soft corals, and algae, to marine microorganisms (Habbu et al., 2016). According to our results, the complex and pure biomolecules were obtained from marine sediment bacteria widely prevented marine biofilm bacteria. It is well known that bacterial initial colonization is the most important stage in the microfouling progression of the fouling process. Prevention of bacterial formation on a surface is an inhibition strategy in controlling the whole fouling formation. Primarily, biomolecules exhibiting both antibiofilm and antibacterial activities have been identified to be more effective in reducing biofouling activity (Viju et al., 2020; Abdulrahman et al., 2022).

The results of the MIC tests illustrate the antimicrobial activity of properties of biomolecule extracts on marine biofilm bacteria. The strong antibacterial activity based on MIC results was attained by the complex biomolecule extract of *Bacillus simplex*. In previously similar studies from other researchers, antibacterial and antibiofilm activity was also declared strong for different *Bacillus* species against marine biofilm bacteria (Sanchez-Rodríguez et al., 2018; Viju et al.,2020; Abdulrahman et al., 2022). Also, Abdulrahman et al. (2022) demonstrated a wide spectrum of activity by endophytic marine bacterial biomolecules from similar *Bacillus* species; *B. subtilis*, *B. licheniformis*, *B. amyloliquefaciens*, *B. cereus*, *B. laterosporus*, and *B. silvestris* (Mondol et al., 2013; Santhi et al., 2017). Presently, biomolecules, including peptides, have exhibited antibiofilm, antifouling, antialgal, insecticidal, and anticancer activities (Ben Khedher et al., 2011; Hamdache et al., 2011; Baruzzi et al., 2011). *Bacillus* species have also been discovered to generate promising compounds that exhibit noteworthy effects against drug-resistant pathogens (Wibowo et al., 2023). In other research, Coasta et al. (2018) isolated *Bacillus* sp. P34, which produced a peptide that showed strong antibiofilm activity against *Staphylococcus* sp. (Viju et al.,2020).

On the other hand, bioactive metabolites derived from brominated alkaloids have indicated antagonistic effects on biofilm formation (Peters et al., 2003). Le-Norcy et al. (2017) studied a group of alkaloids, and their study has shown activity on biofilm formation in the marine bacterial strain *Paraccocus* sp. Furthermore, another study documented that the marine-derived phenethylamine and tyramine alkaloids obtained from *Shewanella aquimarina* exhibit antibiofilm activity in the initial stage of *Staphylococcus aureus* biofilm formation (Giugliano et al., 2023). Our results revealed that pure biomolecules have chemical profiles consisting predominantly of alkaloids, while complex biomolecules predominantly of phenolic compounds. Almost all concentrations of pure extracts were found to exhibit significant antibiofilm activity, against marine biofilm bacteria. Especially, pyrrolo pyrimidine alkaloids and their synthetic analogs produced by marine bacteria were effective against various biofilm-forming bacteria (Muzychka et al. 2024). Various alkaloids inhibit communication system between biofilm forming bacteria known as quorum sensing and this process causes deterioration of the biofilm structure. Thereby, enabling the facile removal of microbial cells from surfaces (Khalid et al., 2022).

The biomolecules are products of bacterial secondary metabolism in response to different marine environmental signals because of the extreme conditions (De Carvalho and Fernandes, 2010). Besides, the biomolecules are deliberately extricated from the bacterial cell to preserve it from defects compared with the other compounds that are discharged within the bacterial cells (Pinu et al., 2017). Therefore, it is highly significant to know the bacterial biomolecules involved and reveal their bioactive action and knowledge of metabolites from pure and complex biomolecules is highly significant (Abdulrahman et al., 2022).

The studies are focused on experimental approaches where active components were analyzed in relation to novel biomolecule extracts from marine bacteria. As mentioned by De Rop et al. (2022), between the years of 2017 and 2021, 77 novel marine Actinobacteria alkaloid derivatives were represented, mainly pyrroles, indoles, glutarimides, indolizidines, and diketopiperazines. The search for these alkaloids' antimicrobial activity supports the importance of biomolecule extracts from marine bacterial resources. According to Wibowo et al. (2022), the marine-derived indole alkaloids reported from various marine organisms including bacteria, fungi, sponges, algae, and bryozoans were determined. Although the search for the bioactivities of these biomolecules has been revealed, there should be a great amount of assessment, including their mechanisms, to obtain lead substances for developing new chemically active compounds (Wibowo et al., 2022).

Conclusions

The marine environments have a rich microbial diversity, and these organisms could generate various biologically active molecules. These biomolecules, including antibiofilm properties, have been isolated from marine microorganisms and could be used in marine coatings as antifoulant. The present study describes the application of bacterial extracts derived from Turkish marine sediments as an antibiofilm strategy against marine biofilms. Our findings suggest that marine bacterial extracts have the potential to produce chemical compounds since they could perform antibacterial and strong antibiofilm activity. So, these novel microbial bioactive molecules could be used as sources to produce antibiofilm and antifouling products.

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Ethical statement

The authors declare that this study complies with research and publication ethics.

Informed consent

Not available.

Conflicts of interest

There is no conflict of interests for publishing our study.

Data availability statement

The authors declare that data are available from authors upon reasonable request.

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Author contribution

Authors are encouraged to submit an "Author statement" providing individual contributions of authors such as:

Ayse Kazan: Methodology, Formal analysis, Investigation, Resources, Validation,Writing original draft,

Asli Kacar: Supervision, Visualization, Conceptualization, Review, Editing, Funding acquisition,

Burcu Omuzbuken: Investigation, Resources, Methodology, Formal analysis, Validation, Writing original draft.

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RESEARCH PAPER

Effects of Agricultural Carbon Sources On Water Quality and Phytoplankton Community Composition in Flocponic System

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Abstract

Carbon products promote aggregate floc-rich plankton, with diverse roles in flocponic production. Availability, low-cost, and chemical composition of agricultural by-products make them ideal substrates for phytoplankton production. Phytoplankton maintains water quality by reducing toxic substances, but it is problematic under some conditions. Therefore, the study evaluates how agricultural carbon sources affect flocponic phytoplankton community composition and water quality. Five treatments (wheat-bran, Rhodes-hay, maize-cob, maize-stables, and lucerne-hay) and a control (no by-product) were employed in a complete randomized design, each in triplicate for nine weeks. Each treatment and control had Nile tilapia (0.155 ± 0.01 g) and rice (seeds) densities of 98 m^{-3} and 250 m^{-2}, respectively. Temperature, pH, dissolved oxygen, and salinity levels did not differ significantly between treatments and control. However, TDS, soluble reactive phosphorus (SRP), ammonia, nitrite, and nitrate showed significant differences ($p<0.05$) between treatments and control. Lucerne-hay exhibited the highest nitrate levels (0.9 ± 0.06 mg L^{-1}), SRP (0.6 ± 0.05 mg L^{-1}), and the lowest ammonia and nitrite levels compared to other treatments and control. Lucerne-hay had the highest phytoplankton diversity (2.48), while the control (1.37) had the least. Further, there were significant differences in phytoplankton abundance, with lucerne-hay having the highest Charophyta (1.45 ± 0.02 indsL^{-1}), Chlorophyta (1.60 ± 0.02 indsL^{-1}), and Ochrophyta (1.64 ± 0.03 indsL^{-1}) abundance, while the control had the least. The result of the study revealed that carbon sources influence flocponic water quality and phytoplankton. The composition and solubility of lucerne-hay and wheat-bran may have improved water quality and phytoplankton. The study suggests that lucerne-hay and wheat-bran are the best flocponic carbon sources for phytoplankton and water quality.

Introduction

The global demand for safe and healthy food continues to rise in response to the growing human population, which is expected to reach 9.7 billion people by 2050 (UN, 2019). The demand for freshwater fish is increasing due to rising food demand, economic development, shifting consumption patterns, and animal protein competition for human and livestock food (Strauch *et al.*, 2019; Pruter *et al.*, 2020). Freshwater fish's competitiveness has directly influenced fish farming, intensifying Nile tilapia and catfish (Strauch *et al.*, 2019; Pruter *et al.*, 2020). In that case, intensive aquaculture systems are increasing, though organic and inorganic wastes adversely affect the environment (Cao *et al.*, 2007; Farmaki *et al.*, 2014). Hence, investment and research in sustainable food production technologies are essential to produce enough food while minimizing resource use and environmental impacts (Pretty *et al.*, 2010; Boyd *et al.*, 2020).

Most aquaculture production globally is either intensively farmed in cages or semi-intensively raised in pond systems (FAO, 2020). Ponds and cages are efficient for producing fish when properly managed and require little investment in technology (Masser, 2012; Tucker, 2012). However, poor management, such as untreated effluents or disregarding the environment's carrying capacity, may lead to environmental pollution and outbreaks of fish diseases (Boyd *et al.*, 2020; Henares *et al.*, 2020). Therefore, efficient aquaculture systems such as recirculating, aquaponic, biofloc, and flow-through fish farming can contribute sustainably to fish production for a healthy human diet (Thilsted *et al.*, 2016; FAO, 2020). However, flow-through systems require a large amount of water compared to recirculating and aquaponic systems that recycle water, even though they are more expensive to operate (Forster & Slaski, 2010; Engle *et al.*, 2020). Closed aquaculture systems have attracted interest for further research due to their low water consumption and waste output (Soaudy *et al.*, 2018; Khanjani and Sharifinia, 2020; Pinho *et al.*, 2021). Biofloc technology is one of these systems; it works with the idea of a microbial loop and helps certain types of microbes grow. For example, it supports the growth of plankton, heterotrophic, and nitrifying bacteria. Shrimp and some fish eat these bacteria (Avnimelech, 2015; Emerenciano *et al.*, 2017; Samocha, 2019; Boyd *et al.*, 2020). However, these systems experience high nitrate and phosphorus buildup, rely heavily on electricity for proper operation, and operate as monocultures that do not effectively utilize waste products (Badiola *et al.*, 2018; Walker *et al.*, 2020).

Flocponics is a strategy for circular food production that enhances water quality by combining biofloc-based aquaculture with hydroponics (Pinho *et al.*, 2021). Combining hydroponic systems (soilless plant gardening) with biofloc systems is a cost-effective and environmentally friendly technology that simulates a natural ecosystem (Boyd *et al.*, 2020). Reusing nutrients to create circular food minimizes environmental effects while increasing food production and cutting costs associated with fertilizer and water (Bohnes *et al.*, 2019; Reid *et al.*, 2020). The idea is to increase food security by recycling nutrients from fish waste (Kuhn *et al.*, 2010; Pinho *et al.*, 2021). Various microorganisms, including fungi, bacteria, microalgae, protozoans, and rotifers, collaborate to form flocs from organic waste (Avnimelech, 2009). The floc contains around 30 to 40% organic materials, such as colloids, organic polymers, and dead cells, which other organisms can use and reintegrate into the productive chains (Avnimelech, 2009). Specifically, planktons are the primary micro- and macroscopic organisms that produce an initial chain of food webs and indicators of water quality (Nuraina *et al.*, 2020). Planktons in the biofloc system provide nutrients such as proteins, amino acids, and fatty acids to cultured species, as well as remove surplus nutrients (Wasielsky *et al.,* 2006; Azim & Little, 2008; Emerenciano *et al.*, 2012; Emerenciano *et al.*, 2013; Emerenciano *et al.*, 2017). For flocponic technology to work, creating and maintaining diverse floc aggregates with carbon sources that drive floc condition and maintain system integrity is important (Soedibya *et al.*, 2022). It is, therefore, critical to know the available and best carbon sources that stimulate and improve phytoplankton growth and diversity since plankton (phytoplankton and zooplankton) are fish nutrients and biological water quality indicators in aquaculture (Castro-Mejía *et al*., 2017). Flocponics necessitate using a carbon source with suitable carbon-to-nitrogen ratios (C: N ranging from 10 to 20:1) (Pinho *et al*., 2021).

One of the main factors affecting floc characteristics is the carbon source, which usually differs in carbon and nutrient (N and P) content and degradability (El-Sayed, 2021). For this reason, carbon sources are beneficial when they facilitate quick nutrient removal and large-volume production of floc (Khanjani & Sharifinia, 2020). Different carbon sources such as acetate, corn, starch, glycerol, molasses, rice bran, molasses, glucose, and sucrose have been the drivers for the development of biofloc for fish, prawns, shrimps, and crayfish (Dauda, 2019). Some studies have checked the effects of various carbon sources and found out which ones are best for fish and crustaceans in biofloc systems (Ahmad *et al*., 2016; Rajkumar *et al*.,2016; Dauda *et al*.,2017; Khanjani *et al*., 2017; Bakhshi *et al*., 2018). Nevertheless, there is no information available on the effects of different carbon sources on the flocponic production of Nile tilapia, rice, and plankton. Furthermore, no studies have researched organic carbon sources such as lucerne-hay, Rhodes-hay, maize-stable, maize-cob, and wheat-bran in flocponic systems or biofloc technology. Such materials will reduce the core competition of refined organic and inorganic carbon sources and promote aquaculture growth with little or no effluent to the environment. Hence, there is a need to establish flocponic systems using inexpensive and commonly available carbon sources. The application of these products in flocponics is promising due to their composition, cost, and availability. Therefore, the study evaluates how agricultural carbon sources affect flocponic phytoplankton community composition and water quality.

Materials and Methods

Study Area

The study was conducted at the University of Eldoret fish (UoE) hatchery for 63 days from May 2022 to November 2022 under greenhouse conditions and temperatures ranging from 26 to 30^{o}C. The campus is 9 Km Northeast of Eldoret Municipality on the Eldoret-Ziwa Road. The University of Eldoret is within Rift Valley Province, Uasin Gishu County, and Eldoret Town (Kenya).

Experimental Design

The experiment set up included 18 rectangular indoor plastic fish tanks (1.3 m by 1 m by 1 m in length, width, and depth, respectively) using a flocponic system. Nile tilapia fry with similar mean weight (0.16 ± 0.01 g) and length (2.16 ± 0.03 cm) were randomly selected and stocked at the same density (98 fry m^{-3}) in each system. Rice seeds with the same density of 250 plants (seeds) m^{-2} were planted in a suspended plastic egg tray of 100 cm by 30 cm in a flocponic fish-holding unit. Gravels of 0.5 inches were added into the trays to hold and act as the substrate for the rice seeds' germination and growth. The treatments were wheat-bran, Rhodes-hay, maize-cobs, maize-stables, lucerne-hay agricultural by-products, and control (no products), respectively (Figure 1). The treatments were in triplicates in a completely randomized design. Stoichiometry analysis was conducted to calculate each carbon source's carbon, nitrogen, and phosphorus (C: N: P) ratios and quantities. The experimental research used rice seeds from the Ahero rice scheme agro-vet Kisumu County. University of Eldoret (UoE) fish hatchery provided the male sex-reversed *O. niloticus* fingerlings for the research experiment. We purchased commercial fish diets with the same crude protein (30%) from Kenya Marine and Fisheries Training Institute Sangoro and administered to fish in all the treatments. Fish were fed thrice daily, at 0930, 1230, and 1630 h.

Proximate analysis of organic carbon sources

All ground wheat-bran, Rhodes-hay, maize-cob, maize-stables, and lucerne-hay proximate analyses were determined in triplicate, according to standard AOAC methods (AOAC, 1998). Samples were dried in an oven at 60°C until constant weight to determine moisture content. Ash was determined by a combustion method at 550°C for four hours, while crude protein was measured by nitrogen analysis (N x 6.25) using the Kjeldahl method. The crude fiber was determined by digesting dried lipid-free residue with 1.25% sulfuric acid and 1.25% sodium hydroxide and calcining it. We analyzed crude lipid analysis using an automatic fat extraction system (SOCS PLUS-SCS 08 AS, Pelican Equipment, Chennai, Tamil Nadu, India). We finally analyzed carbon and nitrogen using the colorimetric determination method and phosphorus by persulfate digestion followed by acid-molybdate determination (Duguma *et al.*, 2014) (Table 1).

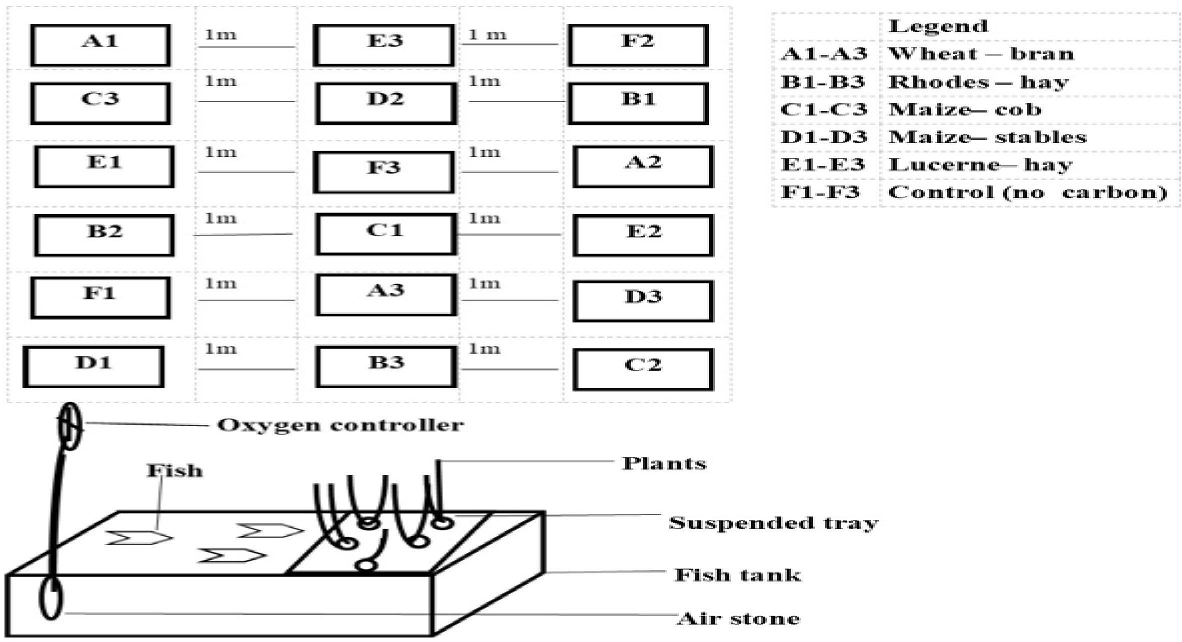

Figure 1. Experimental treatments (wheat-hay, Rhodes-hay, maize-cob, maize-stables, and lucerne-hay) and control layout design in a flocponic set-up.

Table 1. Proximate analysis of organic carbon sources (the daily amount of carbon source addition calculation: using a 15:1 carbon-to-nitrogen ratio)

	Treatments				
Parameters (% in 1g)	**Wheat-bran)**	**Rhode-hay**	**Maize-cob**	**Maize-stable**	**Lucerne-hay**
Ash (%)	5.20± 0.05	7.05±0.10	2.91±0.05	3.30±0.05	7.55± 0.00
Carbon (%)	22.08±0.12	21.18±0.06	23.72±0.12	23.06±0.06	30.01± 0.12
Nitrogen (%)	2.074±0.03	1.41±0.02	1.61±0.01	1.48±0.00	3.41± 0.01
Phosphorus (%)	0.51±0.00	0.43±0.00	0.34±0.27	0.06±0.00	1.1±0.00
Protein (%)	12.96± 0.15	8.8±0.10	10.06±0.04	9.25±0.02	21.3± 0.03
C:P per (1g)	43.3:1	49.3:1	69.8:1	384.3:1	27.3:1
C: N per (1g)	10.7:1	15:1	14.7:1	15.6:1	8.8:1
C: N:P per (1g)	40.9:3:1	49.3:3:1	69.8:5:1	384.3:25:1	27.3:3:1
Quantity (g) in 15:1 (C: N) daily addition to flocponic system	1.36	1.00	1.02	0.96	1.67

Flocponic inoculation

In a flocponic experiment, inoculation was carried out using a similar 15:1 carbon-to-nitrogen ratio of ground wheat-bran, Rhodes-hay, maize-cob, maize-stables, and lucerne-hay. Initial inoculation was employed for one month to enable microbial community stimulation before stocking Nile tilapia and rice. The carbon sources were measured daily, mixed with 100 ml of water, and left overnight in an anaerobic environment before being applied to each flocponic set treatment daily to improve texture for faster breakdown by bacteria (De Schryver *et al.*, 2008). Inoculation was done before and continuously after stocking to provide the system with a substrate and bacterial growth (Crab *et al.*, 2012). Continuous artificial aeration was used to achieve optimal oxygen levels for fish, plants, floc growth, and solid substrate suspension (Crab *et al.*, 2012).

Sampling

Water physical-chemical parameters

Water quality parameters were measured according to the standard methods of the American Public Health Association (APHA, 1989). The following parameters were measured in situ daily using a YSI 540 dissolved oxygen (DO) and Multi-functional water quality tester EZ-9909: dissolved oxygen (DO), temperature, pH, electrical conductivity, and total dissolved solids, respectively. Water nutrients samples were collected weekly for the measurement of the following nutrients: ammonia, nitrite, nitrate, and soluble phosphorus using an optical photometer YSI 9500 (YSI Incorporated, Yellow Springs, OH, USA) (±1percentage precision) (YSI, I. 2014) following the methodologies described by the manufacturer.

Phytoplankton sampling, identification and enumeration

Samples of 50 ml of phytoplankton were collected weekly using a Perspex tube fitted with nylon net. All samples in each treatment were collected from 5 different locations, mixed thoroughly, and transferred to sterile plastic bottles (Thompson, 2002). The samples were filtered with 25 µm mesh nets and preserved using Lugol iodine solution. A standard inverted light microscope with a magnification of 10 x 40 (Swift, M-4000) was used to identify and count phytoplankton cells. A sub-sample of 1ml from each sample was placed on a Sedgewick–Rafter (S–R) cell, which has 1000 fields of 1 mm^3. The S–R cell was left undisturbed for 2 minutes to allow the phytoplankton to settle. Individual phytoplankton cells were identified in 10 randomly chosen S-R cells. Phytoplankton identification to genus level was determined using keys by (Janse *et al*., 2006) and (Haney *et al.*, 2013). Phytoplankton cell counts were recorded in ten randomly selected S-R cells. The number of phytoplankton cells was expressed as the number of natural units/cells per liter. The formula used to determine the total number of phytoplankton cells was as follows:

$$N = (P \times C \times 100) / L$$

Where N=the number of plankton cells or units per liter of original water;

P= the average number of plankton counted in 10 fields; the

C is the volume of concentrates (ml); L is the volume (L) of the pond water sample.

Data Analysis

One-way ANOVA was used after phytoplankton data transformation to test the effect of treatments on phytoplankton abundance using Minitab 19 software. We used Minitab 19 software to compute weekly means for each treatment and control group (total of six weeks) and performed repeated measure ANOVA analysis. We used repeated measure ANOVA to determine how the treatment altered the amount of nutrients and phytoplankton in water over time (the experimental period). The Shannon Diversity Index (Shannon-Wiener Index) measures the diversity of species in a community. A value of H = 0 indicates that the community contains only one species (Zach, 2021). We used Shannon-wiener (H') indices to assess the diversity of phytoplankton communities in treatments and control with the PAST software.

Furthermore, a generalized linear mixed model (GLM) was used to test the effect of carbon sources on response variables SRP, NH_4^+, NO_2^-, and NO_3^- with the lme (Linear Mixed Effects) function in the Statgraphics software. The model incorporated carbon sources (treatments) as a categorical variable and time (weeks 0 to 9) as a fixed effect. We also included the interaction of treatments (Carbon sources) with time (treatments * time) to test for differences in the time changes of responses. Response variables were log-transformed where necessary to meet normality assumptions. Canonical Correspondence Analysis (CCA) was used to determine the relationship between water physiochemical parameters, carbon sources, and phytoplankton among the treatments. Finally, we used PAST software to analyze CCA.

Results

Water quality parameters in the flocponic treatments and control

Among the treatments and the control, there was a significant difference in ammonia ($F_{0.05, 5}$=5.71, p = 0.0001), nitrite ($F_{0.05, 5}$=18.02, p = 0.0001), nitrate ($F_{0.05, 5}$=11.87, p = 0.0001), and soluble reactive phosphorus (SRP) ($F_{0.05,\ 5}$=7.96, p = 0.0001) (Table 2). The ammonia and nitrite levels in treatments and control varied between 0.01 and 0.48 mgL^{-1}. Lucerne-hay had the highest nitrate and soluble reactive phosphorus levels, followed by Rhodes-hay, wheat-bran, maize-cob, and maize-stables. The control had the lowest levels. Temperature, DO, and TDS were statistically similar among treatments and control (Table 2).

The water nutrient analysis for exhibited that ammonia, nitrite, nitrate, and soluble reactive phosphorus concentration increased over time in the treatments and control (Figures 2 to 5). Ammonia, nitrite, nitrate, and SRP significantly ($p<0.05$) differed across all the treatments and control over time. Ammonia levels were statistically different between treatments and control (F (45, 120) = 1.54, p = 0.034) (Figure 2). There was also a significant difference between treatments over time in the following parameters: nitrite (F (45, 120) =0.94, p = 0.028) and nitrate (F (45, 120) =5.2, p = 0.0001) (Figure 3 and 4, respectively). However, there was no significant variation in SRP levels among treatments and control (Figure 5). All nutrients increased significantly after three weeks. During the first three weeks, all nutrients were below 0.5 mgL^{-1}. There was a significant increase in all the nutrients after three weeks. During the experiment period, the control group had the highest levels of ammonia and nitrite, followed by the maize-stables, maize-cob, wheat-bran, Rhodes-hay, and lucerne-hay groups (Figures 2 and 3). However, changes were noticeable in nitrate and phosphorus from week five, where carbon sources lucerne-hay exhibited the highest nitrate and phosphorus levels among the treatments and controls (Figures 4 and 5).

Table 2. Physio-chemical water parameters ($\bar{x}$ ± SE) at different treatments (carbon sources): wheat-bran, Rhodes-hay, maize-cob, maize-stables, lucerne-hay, and control (no carbon) in flocponic system.

Parameter	Wheat-bran	Rhodes-hay	Maize-cob	Maize-stables	lucerne-hay	Control	F-value	p-value
Ammonia ($mg\ L^{-1}$)	$0.3±0.02^{a}$	$0.2±0.02^{a}$	$0.3±0.02^{a}$	$0.3±0.02^{ab}$	$0.3±0.02^{a}$	$0.4±0.03^{b}$	5.71	0.0001
Nitrite ($mg\ L^{-1}$)	$0.3±0.02^{a}$	$0.3±0.02^{a}$	$0.3±0.03^{a}$	$0.4±0.04^{ab}$	$0.3±0.01^{a}$	$0.6±0.04^{b}$	18.02	0.0001
Nitrate ($mg\ L^{-1}$)	$0.7±0.05^{a}$	$0.7±0.05^{a}$	$0.7±0.05^{a}$	$0.5±0.04^{b}$	$0.9±0.06^{c}$	$0.5±0.04^{b}$	11.87	0.0001
Phosphorus ($mg\ L^{-1}$)	$0.4±0.03^{a}$	$0.5±0.05^{a}$	$0.4±0.03^{a}$	$0.6±0.03^{a}$	$0.6±0.05^{b}$	$0.4±0.03^{a}$	7.96	0.0001
Temperature (^{o}C)	$27.9±0.15^{a}$	$27.9±0.14^{a}$	$27.8±0.14^{a}$	$27.8±0.14^{a}$	$27.7±0.19^{a}$	$27.9±0.14^{a}$	0.31	0.910
D.O ($mg\ L^{-1}$)	$5.5±0.06^{a}$	$5.6±0.05^{a}$	$5.5±0.05^{a}$	$5.5±0.05^{a}$	$5.5±0.05^{a}$	$5.5±0.05^{a}$	0.58	0.717
TDS ($mg\ L^{-1}$)	$113.0±4.20^{a}$	$101.4±3.90^{a}$	$109.6±3.65^{a}$	$103.3±2.86^{a}$	$103.4±2.94^{a}$	$104.4±3.42^{a}$	1.59	0.162
pH	$8.5±0.08^{ab}$	$8.5±0.08^{ab}$	$8.3±0.07^{a}$	$8.4±0.07^{ab}$	$8.3±0.06^{a}$	$8.7±0.10^{ab}$	3.87	0.002
Salinity ($mg\ L^{-1}$)	$0.5±0.01^{a}$	$0.5±0.01^{a}$	$0.5±0.01^{a}$	$0.5±0.01^{a}$	$0.5±0.02^{a}$	$0.5±0.01^{a}$	1.29	0.266

Note: Each value represents mean ± SE; Values with varied superscripts letters (a, b, c, d, and e) within the same row are significantly different ($p<0.05$)—abbreviations: DO, dissolved oxygen; TDS, total dissolved solids.

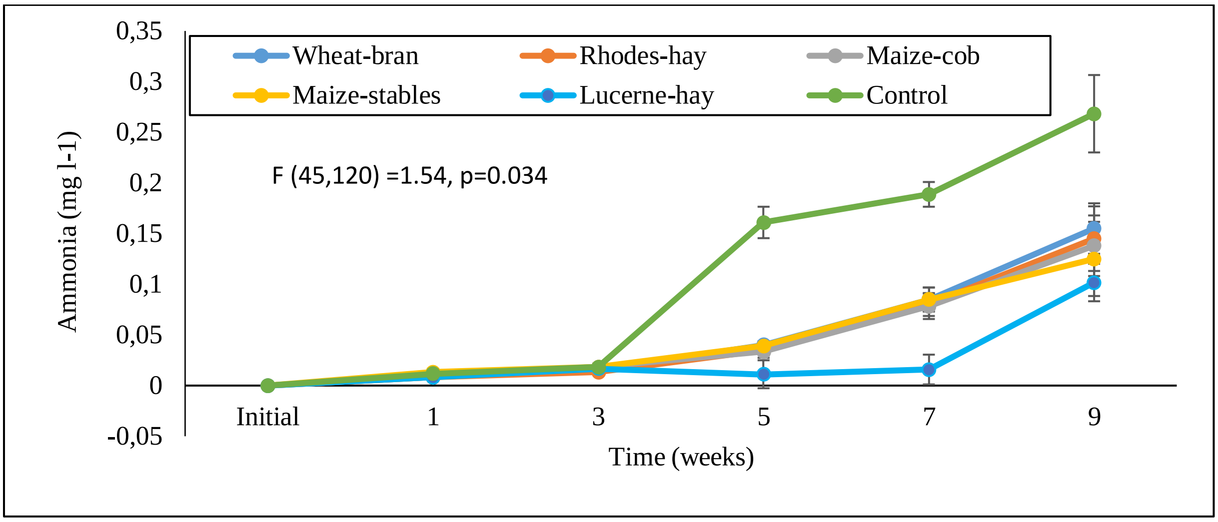

Figure 2. Variation of ammonia at different treatments (wheat-bran, Rhodes-hay, maize-cob, maize-stables, and lucerne-hay and control during the experimental period of nine weeks in the flocponic system.

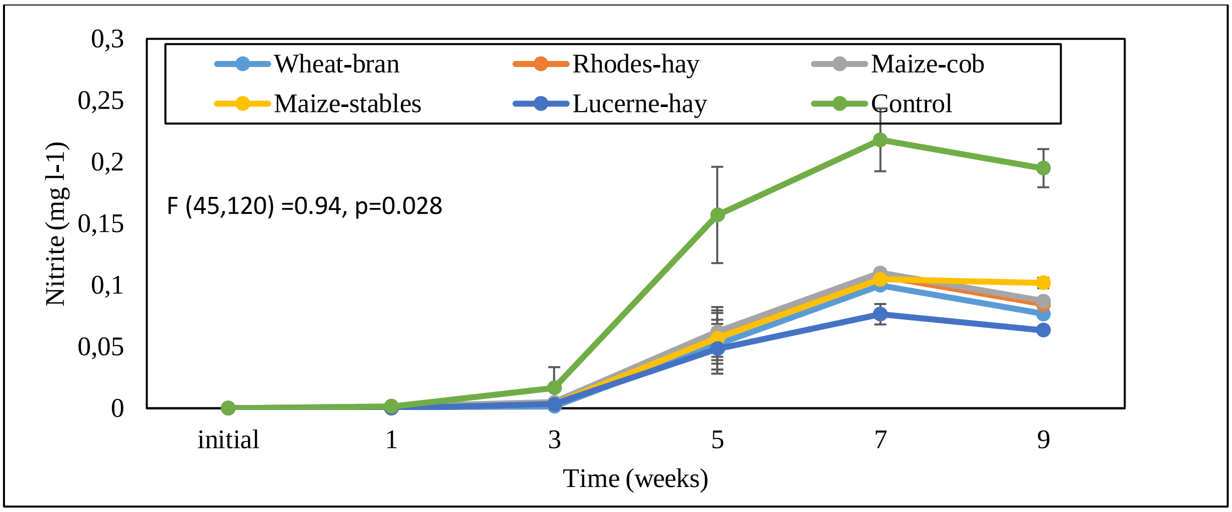

Figure 3. Variation of nitrite at different treatments (wheat-bran, Rhodes-hay, maize-cob, maize-stables, and lucerne-hay) and control during the experimental period of nine weeks in the flocponic system.

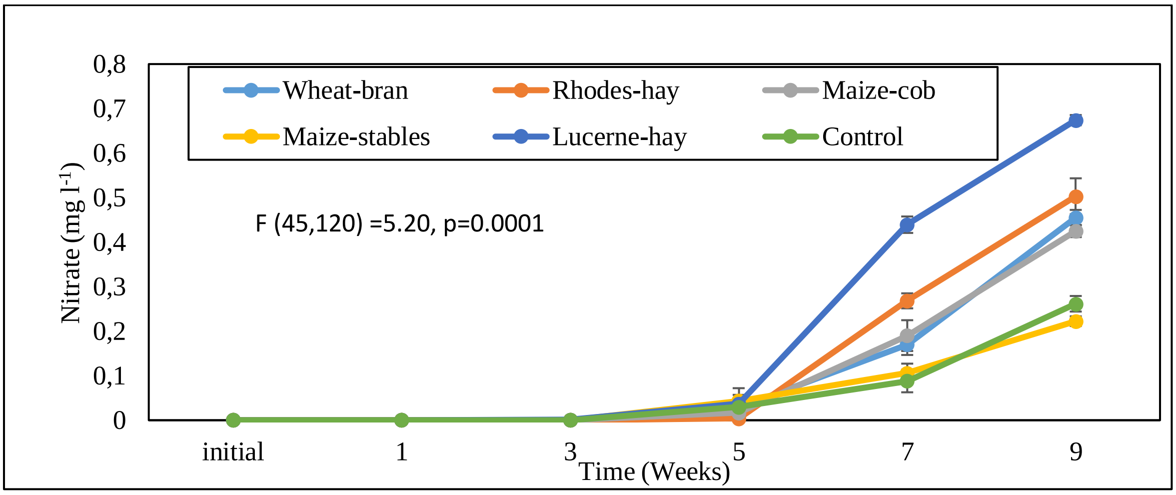

Figure 4. Variation of nitrate at different treatments (wheat-bran, Rhodes-hay, maize-cob, maize-stables, and lucerne-hay) and control during the experimental period of nine weeks in the flocponic system.

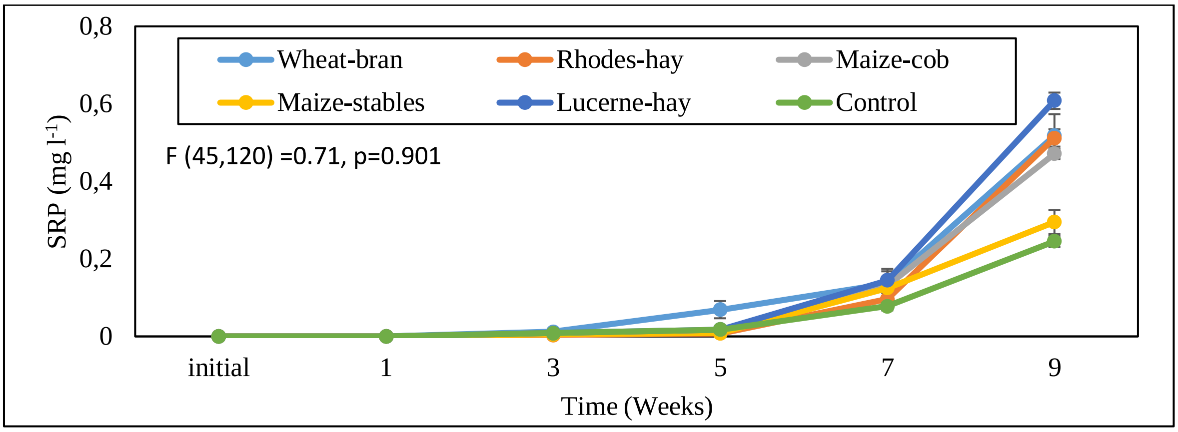

Figure 5. Variation of soluble reactive phosphorus (SRP) at different treatments (wheat-bran, Rhodes-hay, maize-cob, maize-stables, and lucerne-hay) and control during the experimental period of nine weeks in the flocponic system.

General linear mixed model (Water quality, Carbon source, and Weeks)

Ammonia, nitrite, nitrate, and phosphorus did not vary with some treatments (Table 3). However, there was a significant difference ($p<0.05$) between the lucerne-hay and maize-stable treatments on nitrate levels. The control exhibited significant differences ($p<0.05$) in all the water nutrients (ammonia, nitrite, nitrate, and soluble reactive phosphorus) (Table 3). Furthermore, there was a significant difference ($p<0.05$) in ammonia, nitrate, nitrite, and phosphorus levels over weeks. In the ANOVA table, weeks versus water nutrients were significantly different ($p<0.05$) (Table 3). Treatments versus ammonia, nitrite, and nitrate levels were statistically ($p<0.05$) different, with no significant difference in phosphorus nutrient concentration. The weeks (experimental period) * treatments significantly varied ($p<0.05$) on nitrate and ammonia water nutrient levels, while nitrite and phosphorus nutrient concentrations exhibited no significant difference (Table 3).

Table 3. Generalized mixed model for water variables at its interaction with time (weeks) and treatments (wheat-bran, Rhodes-hay, maize-cob, maize-stables, and lucerne-hay) and control

	Ammonia	Nitrite	Nitrate	Phosphorus (SRP)
Fixed effects	β(T-value) P-value	β(T-value) P-value	β(T-value) P-value	β(T-value) P-value
Wheat-bran	-0.009(-1.02)0.311	0.012(1.60)0.113	-0.006(-0.70)0.488	-0.001(-0.05)0.959
Rhodes-hay	-0.012(-1.40)0.165	0.008(1.05)0.295	-0.011(-1.37)0.173	-0.025(-1.23)0.222
Maize-cob	-0.012(-1.40)0.163	0.006(0.78)0.436	-0.002(-0.25)0.803	0.031(1.55)0.124
Maize-stables	-0.010(-1.19)0.237	0.009(1.23)0.222	-0.022(-2.68)0.008	0.027(1.37)0.174
Lucerne-hay	0.015(1.73) 0.087	0.013(1.80)0.075	0.077(9.42)0.000	-0.003(-0.15)0.884
Control	0.052(13.18)0.000	0.050(15.23)0.000	0.076(20.80)0.000	0.065(7.31)0.000
Weeks	0.013(5.64)0.00001	0.014(7.13) 0.0000	0.031(9.25) 0.00001	0.026(5.33) 0.0000
ANOVA	(F-value) p-value	(F-value) p-value	(F-value) p-value	(F-value) p-value
Weeks	(15.55)0.0001	(30.79)0.0001	(103.02)0.0001	(12.97)0.0001
Treatments	(3.35)0.007	(8.45)0.000	(19.66)0.0001	(1.34)0.254
Weeks*treatments	(1.54)0.034	(0.94)0.579	(5.20)0.0001	(0.71)0.901
R-sq (%)	65.31	75.09	91.30	56.44

Note: The 'full' model included carbon sources (treatments) wheat-bran, rhodes-hay, maize-cob, maize-stable, lucerne-hay, and control, time in weeks, treatments and treatments*time as fixed effect as explained by the model. β=coefficient

Phytoplankton in the flocponic system

Phytoplankton

The phytoplankton abundance during the experimental period in flocponic carbon-based treatments and controls is shown in Table 4. There was a significant difference ($F_{0.05, 5}$=16.30, p = 0.0001) in the Charophyta genera group abundance among the treatments and control. The lucerne-hay carbon source exhibited the highest Charophyta abundance (1.45±0.02 indsL^{-1}), and the control recorded the lowest number (1.15±0.04 indsL^{-1}). There were also significant differences in the Chlorophyta ($F_{0.05, 5}$ = 36.59, p = 0.0001) and Ochrophyta ($F_{0.05, 5}$ = 9.54, p = 0.0001) group's abundance. In the Chlorophyta and Ochrophyta groups, lucerne-hay exhibited the highest abundance, while control recorded the lowest (Table 4).

Table 5 shows the phytoplankton genera identified and the diversity at different treatments and controls. *Fragilaria, Pediastrum* (Ochrophyta), *Chlorella, Cladophora, Protococcus, Spirogyra, Spirotaenia, Volvox* (Chlorophyta), *Cosmarium, Mougeotia, Penium, Zygnema, Closterium, Desmidium, and Coleastrum* (Charophyta) are identified phytoplankton genera. Genera phytoplankton *Fragilaria, Protococcus,* and *Zygnema* genera were present in all the treatments. Furthermore, the carbon source, lucerne-hay, recorded all 13 genera of phytoplankton groups, except Pediastrum and Coleastrum, whereas the control only recorded four genera: *Fragilaria, Protococcus, Mougeotia*, and *Zygnema*. All the carbon source treatments had the highest phytoplankton diversity compared to the control. The lucerne-hay carbon source (2.48) had the most diversity, while the control (1.37) had the least (Table 5).

Figures 6-8 illustrate the dynamics of phytoplankton abundance over time. Overall, adding carbon sources increased phytoplankton abundance over time in treatments and the control. Results indicated that Ochrophyta, Chlorophyta, and Charophyta over time were not significantly (p > 0.05) different between the treatments and control. However, the post hoc test revealed variation in pattern of phytoplankton abundance over time, with some carbon sources differing from the control and other carbon source treatments. The abundance of phytoplankton in each treatment increased and stabilized starting in week 3. From week 1 to week 3, the abundance of Charophyta, Ochrophyta, and Chlorophyta rose across all treatments and control. Figure 6 displays the Charophyta abundance throughout the experimental period. Charophyta abundance significantly changed in a time-dependent manner over the study period. Week 3 exhibited the highest peak of Charophyta abundance, with 1.5 indsL^{-1} for the lucerne-hay and 1.18 indsL^{-1} for the control. Figures 7 and 8 showed comparable trends in the abundance of Chlorophyta and Ochrophyta. The highest peak of Chlorophyta and Ochrophyta abundance was detectable in week 3, and the lucerne-hay carbon source had the highest Chlorophyta (1.54 indsL^{-1}) and Ochrophyta (1.55 indsL^{-1}) peak, while the control had the lowest (Figures 7 and 8).

Table 4. Phytoplankton abundance (log10(x+1) ($\bar{x}$ ± SE) at different treatments (wheat-bran, Rhodes-hay, maize-cob, maize-stables, and lucerne-hay) and control in the flocponic experiment.

Phytoplankton	Wheat-bran	Rhodes-hay	Maize-cob	Maize-stables	Lucerne-hay	Control	F-value	p-value
Charophyta (indsL^{-1})	1.34±0.02^{a}	1.38±0.02^{a}	1.40±0.02^{a}	1.21±0.05^{b}	1.45±0.02^{c}	1.15±0.04^{b}	16.30	0.0001
Chlorophyta (indsL^{-1})	1.46±0.013^{a}	1.49±0.016^{a}	1.33±0.034^{b}	1.26±0.02^{b}	1.60±0.02^{c}	1.34±0.02^{b}	36.59	0.0001
Ochrophyta (indsL^{-1})	1.41±0.03^{a}	1.56±0.02^{a}	1.32±0.04^{b}	1.39±0.02^{c}	1.64±0.03^{d}	1.30±0.04^{e}	9.54	0.0001

Note: Each value represents mean ± SE; Values with varied superscript (a, b, c, d, e) within the same row are significantly different (p<0.05) and indsL^{-1}= individuals per litre.

Table 5. Phytoplankton diversity and abundance at different treatments (wheat-bran, Rhodes-hay, maize-cob, maize-stables, and lucerne-hay) and control in the flocponic experiment. Note: √ (present); × (absent).

Phytoplankton	Wheat-bran	Rhodes-hay	Maize-cob	Maize-stables	Lucerne-hay	Control
Ochrophyta						
Fragilaria	√	√	√	√	√	√
Pediastrum	×	×	√	×	×	×
Chlorophyta						
Chlorella	√	√	×	√	√	×
Cladophora	√	√	×	×	√	×
Protococcus	√	√	√	√	√	√
Spirogyra	√	√	×	×	√	×
Spirotaenia	√	√	×	√	√	×
Volvox	√	√	√	×	√	×
Charophyta						
Cosmarium	√	√	×	×	√	×
Mougeotia	√	√	×	×	√	√
Penium	√	√	√	√	√	×
Zygnema	√	√	√	√	√	√
Closterium	×	√	×	×	√	×
Desmidium	×	√	√	×	√	×
Coleastrum	×	×	√	×	×	×
Taxa_S	11	13	8	6	13	4
Dominance_ D	0.097	0.115	0.143	0.172	0.091	0.257
Shannon_H	2.363	2.304	2.007	1.776	2.475	1.373

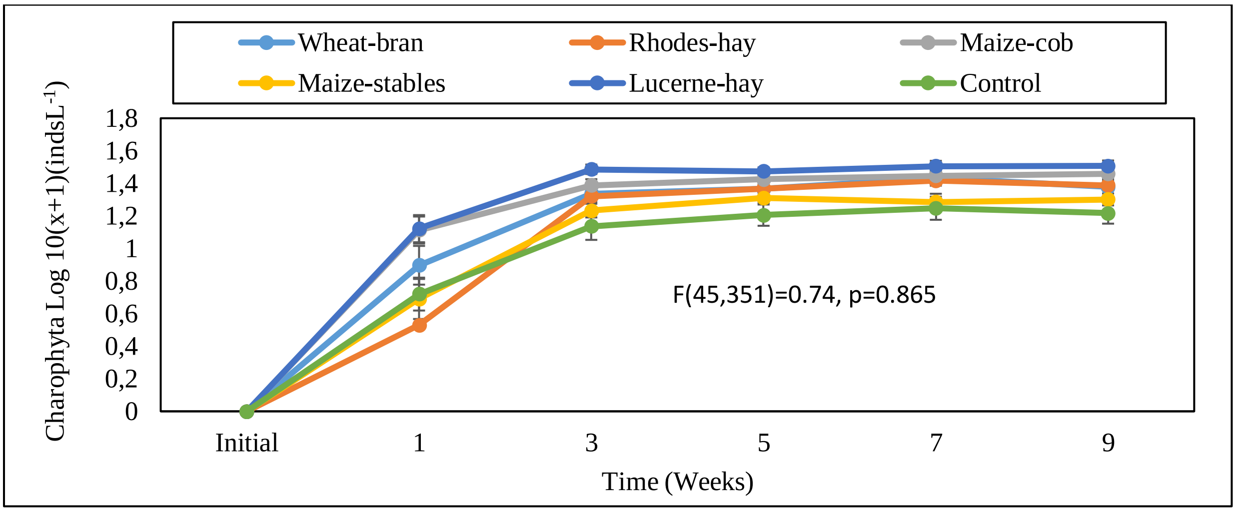

Figure 6. Variation of Charophyta in the flocponic experiment at different treatments (carbon sources) (wheat-bran, Rhodes-hay, maize-cob, maize-stables, and lucerne-hay) and control.

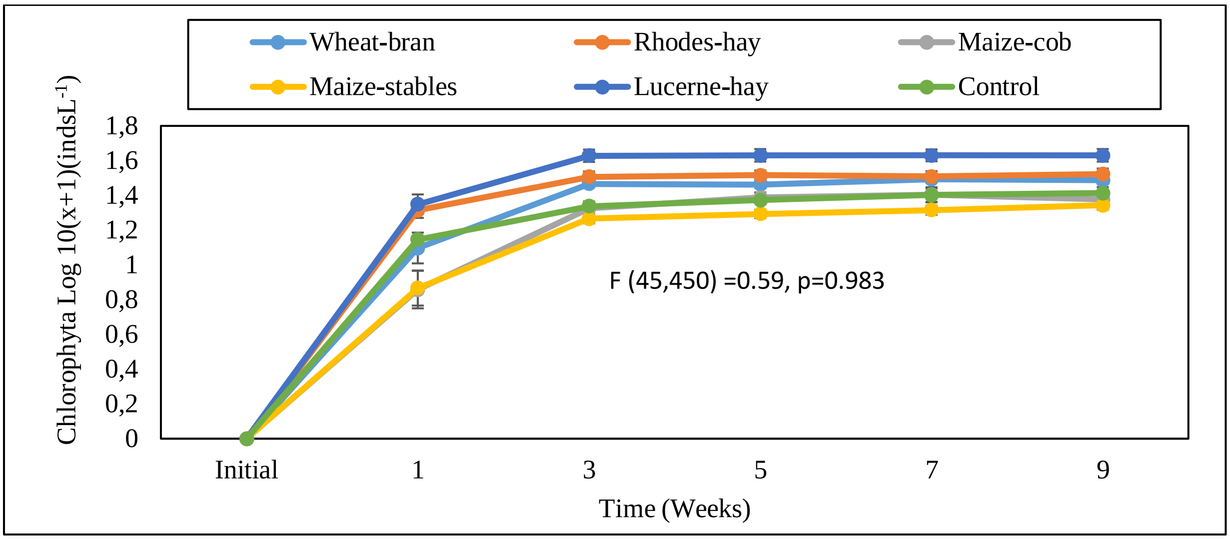

Figure 7. Variation of Chlorophyta in the flocponic experiment at different (carbon sources) treatments (wheat-bran, Rhodes-hay, maize-cob, maize-stables, and lucerne-hay) and control.

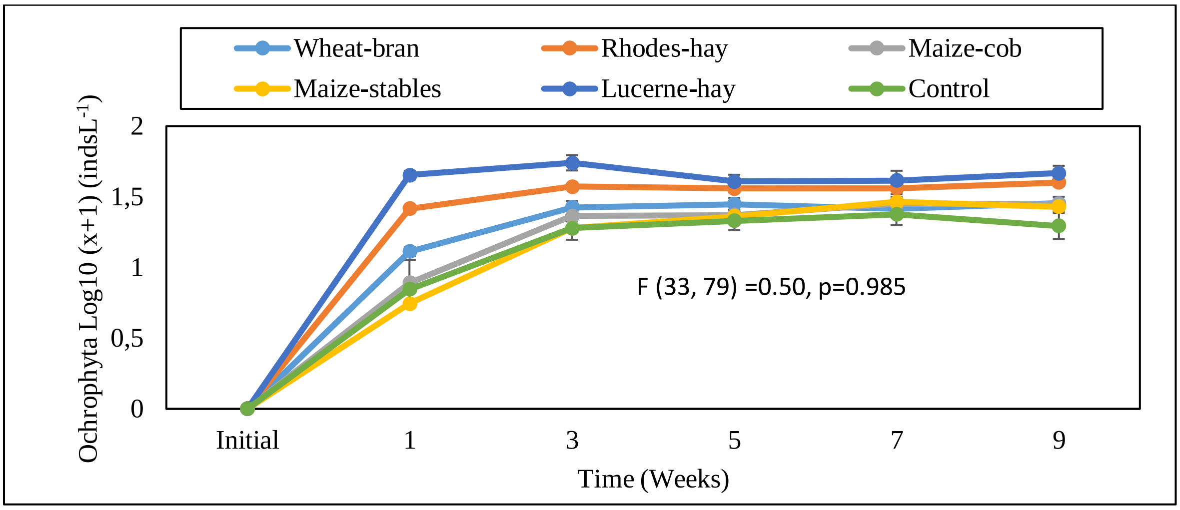

Figure 8. Variation of Ochrophyta in the flocponic experiment at different (carbon sources) treatments (wheat-bran, Rhodes-hay, maize-cob, maize-stables, and lucerne-hay) and control.

Relationship between treatments (carbon sources), phytoplankton, and water quality parameters

CCA was used to discern the possible correlations between the phytoplankton genera, the carbon sources (treatments), and the environmental variables (Figure 9). Rhodes-hay, lucerne-hay, and wheat-bran carbon sources exhibited a positive relationship with the Charophyta (*Cosmarium*, *Closterium*, and *Desmidium*) and Chlorophyta (*Cladophora*, *Spirogyra*, *Volvox*) phytoplankton groups, as well as nitrate and soluble reactive phosphorus environmental variables in axis 1. Along axis 2, the Charophyta (*Zygnema*), Chlorophyta (*Chlorella*, *Spirotaenia*), and Ochrophyta (Fragilaria) groups had positive relationships with maize-stable, as well as electrical conductivity, temperature, ammonia, and nitrite. Charophyta (*Penium*) was positively associated with TDS, salinity, and maize-cob carbon sources. Furthermore, the control with no carbon source positively correlated with Chlorophyta (*Protococcus*) and Charophyta (*Mougeotia*) phytoplankton groups and dissolved oxygen. Generally, Rhodes-hay, lucerne-hay, and wheat-bran carbon sources with soluble reactive phosphorus (SRP) and nitrate were positively associated with the Charophyta (*Cosmarium*, *Closterium*, and *Desmidium*) and Chlorophyta (*Cladophora*, *Spirogyra*, and *Volvox*) phytoplankton groups. Maize-stable carbon sources with electrical conductivity, temperature, ammonia, and nitrite positively affected Charophyta (*Zygnema*), Chlorophyta (*Chlorella*, *Spirotaenia*), and Ochrophyta (*Fragilaria*) phytoplankton. The maize-hay treatment with TDS and salinity provided good conditions only for the Charophyta *(Penium)* phytoplankton. Control with dissolved oxygen had a positive relationship with the Chlorophyta (*Protococcus*) and Charophyta (*Mougeotia*) groups of phytoplankton in a good way (Figure 9).

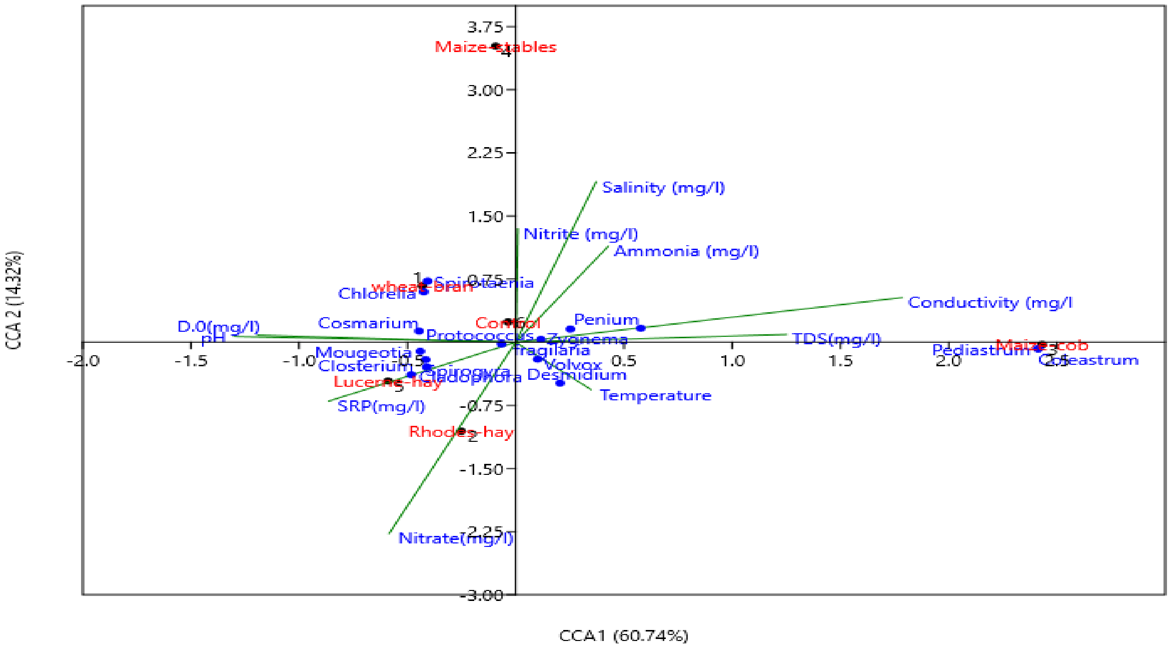

Figure 9. Triplot CCA relationships between treatments (wheat-bran, Rhodes-hay, maize-cob, and maize-stables carbon sources), control environmental variables, and phytoplankton groups.

Discussion

Water quality parameters

The temperature, salinity, and dissolved oxygen (DO) were consistent across the treatments and control throughout the study. Our results concur with Roy *et al.* (2010), Naik and Reddy (2020), Mansour *et al.* (2022), and Sharawy *et al.* (2022) findings on the farming of *L. vannamei* in biofloc systems. Hassan *et al.* (2022) found the same results for temperature (24-28°C), pH (6.4-8.6), and DO (4.5 mg/l) when using sugarcane bagasse, rice bran, and rice straw as carbon sources in a biofloc system to grow *Litopenaeus vannamei* post-larvae. The current study also revealed slight differences in the dissolved oxygen (DO) levels between flocponic treatments with and without carbon sources, potentially due to the constant aeration of the flocponic system. Furthermore, the temperature recorded in this study was within the ideal range for biofloc and hydroponic production (Hostins *et al.*, 2015; Deswati *et al.*, 2021; Khanjani *et al.*, 2021). During the experimental period, the consistent temperature in the greenhouse could have led to this phenomenon.

The lower pH in the treatments, unlike in the control, could be attributed to the higher carbon dioxide concentration from the respiration of microorganisms in flocponic treatments with carbon sources. The floc biomass could also consume oxygen and release carbon dioxide, leading to low pH due to the synthesis of carbonic acid. Xu *et al.* (2016) found that the carbon dioxide levels in the carbon-based biofloc treatments, originating from heterotrophic organism respirations, likely cause the dynamic changes in pH in the biofloc system. The current result corroborates Solima and Mohsen's (2022) findings that carbon treatments lower the pH levels in biofloc-based ponds. However, the current study was conducted in a flocponic system, but the findings could be similar since flocponic integrates the concept of biofloc technology.

Fish excrete total ammonia nitrogen via feces, urine, uneaten feed, the decomposition of debris, and plankton. During the experimental period, ammonia levels (0.01 to 0.03 mg/l) were within the ranges required for culturing Nile tilapia species. The ammonia levels in the carbon-based treatments were lower than in the control. The dynamic changes in ammonia were found in treatments and control over time. The reduced ammonia levels in the flocponic treatments are likely attributed to microorganisms, such as ammonia-oxidizing bacteria, which utilize carbon as an energy source to transform ammonia into nitrite and proteins and facilitate the decomposition of organic matter. Correia *et al*. (2014) and Khanjani *et al*. (2021) indicated that ammonia and nitrite-oxidizing bacteria reduced NH_3 and nitrite in the biofloc carbon-based system compared to the control pond unit. Deng *et al.* (2018) and Soliman and Mohsen (2022) reported that the organic carbon in a biofloc technology-based system increased the number and diversity of microbial communities, particularly ammonia-oxidizing bacteria, reducing the ammonia concentration.

Furthermore, flocponics with carbon sources detected changes in ammonia over time. The lucerne-hay carbon source had the lowest ammonia level compared to other carbon sources. The solubility and composition of the carbon sources, which offer varying energy levels and surface areas necessary for bacterial development, could potentially explain the anomaly. Therefore, both the number and variety of microbes increase, promoting the process of dynamic ammonia conversion. However, there is a scarcity of investigations conducted specifically in the flocponic system. The addition of a carbon source in the biofloc system resulted in a significant increase in the growth of heterotrophic bacteria, thereby preventing the rise of ammonia levels (Deswati *et al*., 2021; Hassan *et al*., 2022; Soliman & Mohsen, 2022). Khanjani *et al*. (2021) also found that NH_3 levels decreased more when using simple carbohydrates such as molasses in a biofloc system. The faster reduction of ammonia using simple carbon sources is probably due to the better absorption and degradation of carbon as a substrate for heterotrophic bacteria that metabolize ammonia, thus improving water quality (Khanjani *et al*., 2021).

Nitrite is a vital water pollutant owing to its high toxicity (Pérez-Rostro *et al*., 2014). The primary harmful effects of NO_2 directly affect oxygen transport, the oxidation of essential chemicals, and tissue destruction (Crab *et al*., 2012). Our results revealed lower nitrite levels in flocponic treatments with carbon sources compared to the control, and this could be attributed to the bacteria's efficient conversion of ammonia and the rapid pace of nitrification. Ebeling *et al.* (2006) reported that the primary factor responsible for reducing NO_2-N levels in biofloc systems is the conversion of ammonia by bacteria within the culture unit, which can also happen in flocponic systems of the present study. Hassan *et al*. (2022) showed similar nitrite levels on the rice bran and rice straw on *Litopenaeus vannamei* post-larvae in the biofloc system. However, different carbon treatments recorded different nitrite levels; the lucerne-hay exhibited low levels, possibly due to organic carbon's absorption and degradation efficiency as a substrate for a microorganism that fastens the nitrification process.

Nitrate results from the nitrification process, and while it is one of the less hazardous inorganic nitrogen compounds, it can become a concern if its levels become too high and buildup (Mallasen & Valenti, 2006). In addition, nitrate boosts plankton production and growth (Middelburg & Nieuwenhuize, 2000). Thus, nitrate was significantly higher in the treatments compared with the control. Lucerne-hay exhibited a higher nitrate concentration but was within the acceptable range for Nile tilapia culture. Bacteria in flocponic treatments could have contributed to dynamic changes in nitrate levels compared to the control. These bacteria could have also facilitated successive ammonia oxidation to nitrite and, subsequently, to nitrate.

Aquaculture relies on phosphorus as the primary ingredient for aquatic organisms and plankton growth (Sugiura *et al*., 2006). The treatments' soluble reactive phosphorus (SRP) levels were slightly higher than in the control. The higher SRP might mean that carbon sources have influenced soluble reactive phosphorus. Butz and Ven-cappell (1982), Kibria *et al*. (1997), and Kong *et al*. (2020) also believe that fish feed ingredients contain a significant phosphorus fraction in a labile form; namely, the total phosphorus in fish feed, the more water-soluble phosphorus. The lucerne-hay carbon product had the highest levels of soluble reactive phosphorus compared to other carbon products and control. The lucerne-hay carbon's nature and simple sugars could have stimulated the growth of more microbes, thereby aiding in the mineralization and production of SRP. Further, the high number of microorganisms in treatments could have facilitated the mineralization of organic carbon, waste, and solid particles into phosphorus. Ruzzi and Aroca (2015) and Brunno and Kevin (2016) reported that microorganisms in biofloc enhance phosphorus (P) availability by mineralizing organic matter and solubilizing precipitated phosphates in the culture system. Pinho *et al.* (2017) also indicated that microorganisms and planktonic communities are essential in biofloc systems as they mineralize nutrients into various elements.

Effect of different organic carbon sources on phytoplankton diversity and Abundance in the flocponic system

In the flocponic system, flocs aggregate that grow in the system are the main drivers for various activities. The phytoplankton and zooplankton are some of the complex living organism that metabolize nitrogenous waste from fish waste, uneaten feed, and debris (Castro-Mejía *et al*., 2017). Although plankton is a component of floc aggregates in biofloc systems, no published studies have examined their dynamic nature in flocponic setups. Generally, the planktonic community is essential in biofloc and aquaponic systems, as they mineralize nutrients and serve as natural food for the farmed fish species and other organisms (Green *et al*., 2014). The current study demonstrates that phytoplankton populations in all flocponic systems undergo temporal changes regardless of carbon source treatments and control. The characteristics of the organic carbon supply, including its type, solubility, and composition, could have influenced water's physical and chemical properties, resulting in fluctuating variations in phytoplankton populations over time. Biological conditions such as competition and predation could also have contributed to this phenomenon. The same is reported by Green *et al*. (2014) and Castro-Mejía *et al*. (2017), who stated that plankton's abundance changes in response to physical-chemical parameters and predators' effects.

During the experimental period, phytoplankton dominance in all flocponic systems consisted of Chlorophyta, Charophyta, and Ochrophyta. A higher abundance of Chlorophyta, Charophyta, and Ochrophyta corroborates Maica *et al.* (2011) and Pinho *et al*. (2017) with *O. niloticus* and *L. vannamei* species, respectively, but contrasts with results reported by Monroy-Dosta *et al.* (2013) in the culture of Nile tilapia in a biofloc system. The high levels of nitrate and soluble reactive phosphorus in the flocponic system with the lucerne-hay carbon product and its ability to break down may have elevated the diversity and abundance of phytoplankton growth over time. Sumitro (2021) and Soedibya *et al.* (2022) indicated that high N, P, and K levels stimulated phytoplankton growth in the biofloc system. Pinho *et al*. (2017) also discovered that the availability of nutrients and the greenhouse's sunlight exposure could cause high levels of Chlorophyta, Charophyta, and Ochrophyta. Emerenciano *et al.* (2013) indicated that phytoplankton grows well at high nitrogen and phosphorus concentrations. Such a dynamic driver might play similar functions in the flocponic system. The high ammonia concentration and absence of carbon in the control could have contributed to phytoplankton's low abundance and diversity. The concentration of water nutrients could have also contributed to the phenomenon. According to Schmittou and Rosati (1991) and Soedibya *et al*. (2022), a level of ammonia concentration that is more than 0.3 mg/l disturbs the absorption of nutrients by phytoplankton, hence hampered growth. Nevertheless, there is a lack of study on the effects of agricultural by-products as carbon sources on the makeup of plankton populations in flocponic systems or any other aquaculture system.

According to Canonical Correspondence Analysis (CCA), there was a close correlation between carbon sources, water quality parameters, and phytoplankton groups. These results corroborate with other studies, which indicated that the abiotic environment affects bacteria and plankton community structure in the aquatic environment (Xue *et al.*, 2021). Zhan *et al*. (2016) demonstrated that abiotic environmental factors, such as total ammonia nitrogen and total nitrate, significantly influence bacterial populations in *L. vannamei* culture in ponds. The addition of carbon to the flocponic system alters various ecological factors. For example, wheat-bran, Rhodes-hay, maize-cob, maize-stables, and lucerne-hay carbon sources exhibited higher nitrate and phosphorus levels than the control. These dynamic changes in water nutrients and carbon source composition over time could have influenced the relationship between phytoplankton groups, environmental variables (water parameters), treatments, and the control. The CCA results indicated that carbon sources and water parameters influenced the phytoplankton groups, which differed among the five treatment types. There was a positive relationship between phytoplankton, carbon sources, and water parameters. All the carbon sources and other water nutrients, particularly nitrate, DO, nitrite, ammonia, and phosphorus, exhibited positive relationships with phytoplankton. Lucia *et al*. (2014) indicated that carbon and water nutrients are essential for controlling bacterioplankton. Our findings showed that water parameters, particularly nitrate, phosphorus, nitrite, ammonia, temperature, and carbon products in flocponic systems, are critical factors affecting phytoplankton community composition.

Conclusion/Recommendation

Water quality parameters such as ammonia, nitrite, and nitrate in the carbon-based flocponics were within the optimal range for the composition of the phytoplankton community. The abundance and diversity of phytoplankton significantly improved in carbon-based flocponics. The lucerne-hay and wheat-bran carbon products exhibited the highest diversity and abundance of phytoplankton. The lucerne-hay proved to be a superior carbon source due to the improved water quality and phytoplankton community composition in the flocponic system. The lucerne-hay carbon source might be rich in bacterial energy components crucial for water quality, culture species, and the phytoplankton community. The richness of lucerne-hay's bacterial energy components suggested a viable carbon source for flocponic systems and aquaculture practices. Further research should examine the impact of organic carbon sources on the dynamics of zooplankton composition in a flocponic system.

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Ethical approval

The author declares that this study complies with research and publication ethics. The experiment was conducted following the standard operating procedures (SOPs) of the University of Eldoret guidelines for handling animals. The standard operating procedures (SOPs) comply with the Prevention of Cruelty to Animals Act 1962, CAP 360 (Revised, 2012) of the laws of Kenya, and EU regulation (EC Directive 86/609/EEC).

Informed consent

Not available.

Conflicts of interest

There is no conflict of interests for publishing this study and the corresponding author is responsible on behalf of all authors' declaration.

Data availability

The authors declare that data are available from authors upon reasonable request

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Author contribution

Rono Kenneth: Conceptualization, methodology, Investigation, data curation, analysis, and writing. Geraldine Matolla: Conceptualization, methodology, writing, review, and editing

Julius O. Manyala: Conceptualization, methodology, data curation, analysis, review, and editing

Frank O. Masese: Conceptualization, methodology, data curation, analysis, review, and editing.

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REVIEW PAPER

Aquaculture chemotherapy in the Philippines: A review

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Abstract

Aquaculture plays a crucial role in global food security, yet it faces mounting challenges in promoting sustainable and responsible practices. In the Philippines, while the aquaculture industry significantly contributes to the economy, its reliance on chemicals—particularly antibiotics—poses serious risks to public health and the environment. The threat of applying excessive amounts of antibiotics in an aquaculture system is reportedly linked to drug-resistant animals. In consequence of the continued use of antibiotics in the system, transferable resistance genes and residues can be passed on to people as they consume animal products, complicating the treatment of conditions in humans. The industry's sustainable development is hindered by a lack of transparent regulatory oversight and limited access to eco-friendly alternatives. This review assesses the current state of chemical use in Philippine aquaculture, focusing on key species and related challenges. It also examines the effectiveness of the regulatory framework governing chemical use, explores emerging drug alternatives, and suggests strategies to improve regulatory oversight and encourage the adoption of environmentally sustainable practices. The Philippine aquaculture industry, dominated by seaweeds, milkfish, tilapia, shrimps/prawns, and shellfishes, is rapidly expanding. However, this growth is often accompanied by increased chemical usage, including antibiotics, antiparasitic agents, antifungal agents, disinfectants, vaccines, inorganic fertilizers, and more. Despite existing regulations, enforcement and public transparency remain questionable. The excessive use of chemicals in Philippine aquaculture poses significant threats to both public health and environmental sustainability. Urgent action is required to enhance regulatory oversight, encourage the use of eco-friendly alternatives, and ensure the industry's long-term viability. To address these challenges, it is recommended that the government enforce stricter regulations and monitoring mechanisms for chemical use in aquaculture, invest in research and development of sustainable alternatives, raise public awareness about the risks of chemical use, and collaborate with international organizations to share best practices and develop harmonized standards.

Introduction

Aquaculture, a key pillar of global food production, relies heavily on external inputs, including chemicals, to optimize yields. These inputs range from simple fertilizers in extensive systems to a complex array of natural and synthetic substances in intensive operations, making them essential for efficient aquaculture practices (Cruz-Lacierda et al., 2000; Subasinghe et al., 2000). The Philippines has experienced remarkable growth in its aquaculture sector, contributing substantially to the country's overall fishery production. In 2022, the industry achieved a total output of 2.35 million metric tons (MT), valued at US$ 2.2 billion (Bureau of Fisheries and Aquatic Resources (BFAR), 2023). Globally, the Philippines ranked 11th in aquaculture production for various aquatic species and 4th in aquatic plant production in 2021 (Food and Agriculture Organization (FAO), 2024). Key aquaculture commodities include seaweeds (*Kappaphycus* and *Eucheuma* spp.), milkfish (*Chanos chanos)*, tilapia (*Oreochromis* spp.), shrimps (*Penaeus* spp., *Metapenaus* sp., and *Macrobrachium* sp.), and shellfishes (*Crassostrea* spp., *Perna* sp., and *Modiolus* spp.), which together account for 98.15% of the total volume and 91.52% of the total monetary value. Milkfish is particularly dominant in the sector. The primary culture systems in use are fishponds, fish cages, fish pens, and mariculture, operating across brackish, freshwater, and marine environments (BFAR, 2023; PSA, 2023; Tahiluddin & Terzi, 2021a).

As aquaculture continues to expand and intensify, it is increasingly important to understand the potential risks associated with chemical use. The potential risks were highlighted with the correlation between rising aquaculture productivity and increased chemical utilization (Tacon & Metian, 2008). Furthermore, the long-term, direct, and indirect environmental impacts of these practices cannot be overlooked (Boyd et al., 2019; Diana et al., 2013). The irresponsible use of chemicals, particularly antibiotics and unsustainable aquaculture practices, poses serious threats to critical ecosystems and their biodiversity (De Silva, 2012; Diana et al., 2013; Garcia et al., 2014; Lavilla-Pitogo, 2011; Primavera, 2006).

While the Philippines' aquaculture industry has achieved significant success, it faces challenges in managing the responsible use of antibiotics. Regulatory oversight is actively involved in addressing antimicrobial resistance (AMR) through national policies aligned with global frameworks (Regidor et al., 2020). However, translating these policies into comprehensive technical regulations remains a challenge (Pineda-Cortel et al., 2024). Research evidence has documented the use of unauthorized substances and drug residues in various aquaculture species in the country, including shrimp, milkfish, tilapia, and their feeds, with some samples exceeding the Maximum Residual Limit (MRL) for antibiotics (Regidor et al., 2020).

There is a pressing need for intensified campaigns to promote the prudent use of antibiotics within both the pharmaceutical and aquaculture industries. In alignment with the U.S. Food and Drug Administration (FDA) approach to fish and fishery products, where information on approved drug effectiveness, dosage, animal safety, and human food safety is made publicly available (U.S. Food and Drug Administration (USFDA), 2024). Hence, the Philippine regulatory bodies should prioritize transparency, ensuring the accessibility of information on aquaculture pharmaceuticals, particularly veterinary medicines, is consistent with the global One Health approach (Pineda-Cortel et al., 2024).

This review synthesizes existing literature on the use of various chemicals in Philippine aquaculture, emphasizing their impact on key species and associated challenges. It examines the efficacy of the existing regulatory framework and explores promising alternatives to harmful chemicals using relevant online resources provided by different government regulatory bodies.

Philippine Aquaculture Production

Table 1 presents the leading aquaculture commodities produced in the Philippines in 2022, detailing their contributions in both volume and value. Seaweeds dominate production, accounting for 65.76% of the total volume (1.54 million MT) and 13.39% of the total value (US$ 292 million).

Milkfish ranks as the second-most produced commodity, comprising 16.51% of the total volume (0.39 million MT) and a significant 37.42% of the total value (US$ 817 million), underscoring its high economic importance. Tilapia contributes 10.72% of the total volume (0.25 million MT) and 17.29% of the total value (US$ 377 million). While shrimp/prawn and shellfish represent smaller portions of the total volume, they contribute substantially to the overall value, with shrimp/prawn at 2.99% of the volume and 22.29% of the value, and shellfish at 2.17% of the volume and 1.13% of the value. These data illustrate the diversity of aquaculture production in the Philippines, with seaweeds leading in volume, while milkfish and shrimp/prawn yield higher economic returns.

Table 1. Top produced aquaculture commodities in terms of volume and value, 2022 (BFAR, 2023; PSA, 2023)

Commodity	Volume (MT)		Value (USD)	
	Amount (in million)	% share	Amount (in million)	% share
Seaweeds (*Kappaphycus*, *Eucheuma* spp.)	1.54	65.76	292.12	13.39
Milkfish (*Chanos chanos*)	0.39	16.51	816.57	37.42
Tilapia (*Oreochromis* spp.)	0.25	10.72	377.21	17.29
Shrimp/Prawn (*Penaeus*, *Metapenaus*, *Macrobrachium* spp.)	0.07	2.99	486.27	22.29
Shellfishes (*Crassostrea* spp, *Perna* sp, *Modiolus* spp.)	0.05	2.17	17.98	1.13
Others	0.04	1.84	185.24	8.56
Total	2.35	100	2,181.68	100

Chemical Use in the Philippine Aquaculture

A wide array of chemicals, both established and emerging, are utilized throughout the aquaculture production cycle—from hatcheries to grow-out phases—to support the health and growth of cultured species. Table 2 categorizes these chemicals into various groups: antimicrobial/antibiotic agents, antiparasitic agents/pesticides, antifungal agents, disinfectants, vaccines, sex control agents, probiotics, immune enhancers, feed additives, soil and water treatment chemicals, plankton growth promoters, and organic matter decomposers (Coloso et al., 2015; Cruz-Lacierda et al., 2000; Somga et al., 2012). Table 3 lists commonly used chemicals in aquaculture, including those used for both consumption and ornamental purposes. Chemicals marked with an asterisk have maximum residue limits (MRLs) and must be applied within legally permitted levels to ensure the safety of fish, fish products, and consumers (Coloso et al., 2015).

Aquaculture hatcheries employ various chemicals to prevent and treat health issues caused by bacteria, external parasites, and fungi. Antimicrobial, antiparasitic, antifungal, and disinfectant agents are widely used, particularly in hatcheries producing shrimp, tilapia, milkfish, and other commodities. Oxytetracycline is one of the most commonly used antimicrobials in aquaculture, often administered as a preventive measure across various species. Other antibiotics, such as trimethoprim-sulfadiazine, florfenicol, erythromycin, and amoxicillin, are used in lower doses, while rifampicin, sulfamonomethoxine, and oxolinic acid are more prevalent in shrimp hatcheries. However, the use of antibiotics, even in small amounts, carries risks, which are mitigated by adhering to prescribed withdrawal periods (Coloso et al., 2015). Formalin is the most widely used antiparasitic agent, effective against external fungal and bacterial infections and parasites. Sodium chloride is preferred for freshwater fish due to its accessibility, properties, and safety (Somga et al., 2012). Formalin, methylene blue, and trifluralin are commonly used antifungal agents, while malachite green is restricted to ornamental fish (Coloso et al., 2015; Somga et al., 2012). Disinfectants such as chlorine, formaldehyde, and iodophores are routinely employed in hatcheries to maintain sanitary conditions for equipment, facilities, and water. They are also used for routine disinfection procedures, including cleaning tanks and farm implements, conditioning water, and disinfecting broodstock, eggs, and larvae (Primavera et al., 1993; Somga et al., 2012). Vaccines, particularly those against *Streptococcus* spp. in tilapia, are less commonly used in Southeast Asia compared to Japan, where they are employed for fish disease prevention (Grisez & Tan, 2005; Somga et al., 2012). Both hatcheries and grow-out facilities utilize probiotics and immune-enhancing agents to improve environmental conditions, animal health, and productivity. Immune enhancers are especially common in shrimp production (Somga et al., 2012). In cases of deformities, diseases, or delayed development, various vitamins, minerals, and hormones are incorporated into feeds. Additionally, soil and water treatment chemicals, plankton promoters, and organic matter decomposers (bioaugmentation products) are employed to enhance the overall health of the primary culture organisms (Cruz-Lacierda et al., 2000; Primavera et al., 1993).

Table 2. Common chemicals used, species and culture, amount, purpose and chemical status of the common chemicals in the Philippine aquaculture (Coloso et al., 2015; Cruz-Lacierda et al., 2000; Primavera et al., 1993; Somga et al., 2012).

Chemicals used	Chemical group name	Species & culture system	Dosage/Amount used	Purpose used	Chemical status ***Prohibited*** – Total banned ***No*** – Currently not used ***NDA*** – No Data Available (Status not known) ***YES*** – Allowed to be used
Antibiotics/ Antimicrobials	Amoxicillin	Shrimp hatchery	Not indicated	Preventive measure	Yes
		Tilapia hatchery	80 mg/kg fish for 7 days		
		Marine fish grow-out			
	Doxycycline	Tilapia hatchery	10 mg/kg fish for 3–5 days	Preventive measure	Yes
	Erythromycin	Shrimp hatchery	2–3 ppm for 3 days	Disease control	Yes
		Tilapia hatchery	Not indicated	Preventive measure	
		Marine fish grow-out	Not indicated		
	Enrofloxacin	Tilapia hatchery	Not indicated		Yes
		Marine fish grow-out	Not indicated		
	Florfenicol	Shrimp hatchery & milkfish hatchery	2 ppm	Preventive measure	Yes
		Tilapia grow-out & marine fish grow-out	10 mg/kg fish for 10 days		
	Neomycin sulphate	Marine fish grow-out	Not indicated	Preventive measure	NDA
	Norfloxacin	Tilapia hatchery	50 mL/100 L of water for 10 days	Preventive measure	Yes
		Tilapia grow-out & marine fish grow-out	2.5–5 mg/kg fish for 5 days		
	Oxytetracycline	Shrimp hatchery & tilapia hatchery	2-4 ppm until the disease disappear	Daily disease control until disease disappears	Yes
		Marine fish grow-out	2–5 g/kg feed for 10 days		

		Tilapia grow-out	7-27 g/kg feed/day		
	Oxolinic acid	Shrimp hatchery	20 mg/kg for 7 days	Preventive measure	Yes
	Rifampicin	Shrimp hatchery	1–2 ppm for 7 days; 0.1 and 0.2 ppm	Preventive measure; and daily disease control until disease disappears	Yes
	Bactrin Forte	Shrimp hatchery	0.1 ppm	Every other day from Nuplii to harvest as substitute to rifampicin	NDA
	Sulfamonomethoxine	Shrimp hatchery	2–4 ppm daily	Preventive measure	NDA
	Sulfaquinoxaline	Tilapia hatchery	3 g/kg feed	Preventive measure	NDA
		Marine fish grow-out	4-14 g/kg feed/day		
	Trimethoprim-sulfadiazine	Shrimp hatchery & tilapia hatchery	not indicated	Preventive measure	NDA
		Marine fish grow-out	15–20 g/kg feed for 7 days	Preventive measure	
	Chloramphenicol	Shrimp hatchery	1ppm and 2-4 ppm	Every other day from Z_1 to harvest; and disease control	Prohibited
	Nitrofuran (Furazolidone,98%	Shrimp hatchery	0.5-1 ppm; and 2-3 ppm	Every other day from Z_1 to harvest; and disease control	Prohibited
	Prefuran	Shrimp hatchery	1 ppm	Disease/Preventive measure	NDA
Antiparasitic agents/Pesticides	Belzalkonium chloride (BKC)	Shrimp hatchery	0.5-1 ppm	Treats external parasites; and disease control	Yes
		Tilapia hatchery	1 ppm		
	Copper sulphate	Tilapia and shrimp hatchery, marine fish grow-out	2–5 ppm as 30 min bath	Disease/Preventive measure	Yes
	Formalin	Shrimp hatchery	1–2 ppm	Disease/Preventive measure	Yes
		Tilapia hatchery	200 ppm as 10–30 min bath (also for tail rot, fin rot)		
		Marine fish grow-out	20 ppm as 30-minute bath (also for tail rot, fin rot)		
	Hydrogen peroxide	Marine fish grow-out	2–5 ppm as 30-minute bath	Disease/Preventive measure	Yes

Omnicide	Shrimp hatchery	1–1.25 ppm for *Zoothamnium*	Disease/Preventive measure	Yes
Praziquantel	Tilapia and marine fish grow-out	Not indicated	Disease/Preventive measure	Yes
Potassium permanganate	Shrimp hatchery and grow-out, tilapia hatchery and grow-out, marine fish grow out	1-2 ppm	Pond preparation, spray; and preventive measure	Yes
Quinacrine hydrochloride	Shrimp hatchery	2–3 ppm (mysis) 3–5 ppm (PL	Parasites and disease control	-
Sodium chloride	Tilapia hatchery and grow-out	0.25–1 ppt as indefinite bath	Disease/Preventive measure	Yes
Trichlorfon	Marine fish grow-out	0.5–1 ppm indefinite bath 30 ppt as short bath	Disease/ Preventive measure	-
Saponin (Teaseed powder, 10%)	Shrimp grow-out ponds	8 – 30 ppm; 5 – 25 ppm; and 15 – 35 ppm	Pond preparation, broadcast; Rearing phase; and disease control	Yes
	Milkfish ponds	5 – 400 kg/ha	Pond preparation, broadcast	Yes
Copper control	Shrimp grow-out ponds	2 ppm; and 2 kg/ha/d	Pond preparation, spray; and rearing phase, until phytoplankton bloom	Yes
Nicotine (Tobacco dust, 10%)	Milkfish ponds	400 kg/ha	Pond preparation, broadcast, substitute for teaseed	-
Rotenone (Derris root,10%)	Milkfish ponds	300-800 kg/ha	Pond preparation, broadcast,	Yes
Organotin (Brestan, 60%)	Milkfish ponds	250-600 g/ha	Pond preparation, 1/yr-1/3 yr, broadcast or spray	Prohibited
Gusathion	Milkfish ponds	0.1 ppm	Pond prep	Prohibited
Azimphos ethyl Saponin, flavonoid, and tannin (Hostathion Protek FP (24.5%)	Milkfish ponds	1 L/3 ha; and 45-75 kg/ha	Pond preparation; Pond preparation, broadcast	-

	Benzene hexachloride Endosulfan (Diazinon/Zumithion;and Thiodan)	Milkfish ponds	0.1 ppm	Pond preparation; Pond preparation, broadcast	Prohibited
Antifungal agents	Formalin	Shrimp hatchery, tilapia hatchery, marine fish grow-out	40–60 ppm as indefinite bath	Preventive measure	Yes
	Malachite green	Shrimp hatchery	20 ppm as 20 min bath (not advisable to apply)	Preventive measure	Prohibited
		tilapia hatchery, marine fish grow-out			
		Shrimp hatchery	0.003 – 0.015ppm	Every other day from M_1 to harvest	
		Shrimp grow-out ponds	1 kg/ha	disease control	
	Methylene blue	Tilapia hatchery, shrimp hatchery	3–5 ppm as indefinite bath	Preventive measure	Yes
	Trifuralin (Treflan-R)	Shrimp hatchery	0.05–0.1 ppm for 24 h over 2–3 days	Preventive measure	Yes
		Tilapia hatchery and grow-out marine fish grow-out	0.5 ppm for 14 days		
		Shrimp hatchery	0.1ppm; 5 ppm; and 1 ppm	every 3-5 d from stocking to harvest; for spawners; and disease control	
Disinfectants	Chloramine-T	Shrimp hatchery	Not indicated	For shrimp egg disinfectant	Yes
	Chlorine	Shrimp hatchery and grow-out, tilapia hatchery and grow-out, milkfish/marine fish grow-out	20–100 ppm	For disinfection of water, tanks, pipes and equipment	Yes
	Cypermethrin	Shrimp hatchery	125–200 mL/1 000 m^3 water	Preventive measure/Disinfection	Yes
	Dichlorvos	Shrimp grow-out	1.5–2 ppm	Preventive measure for pond preparation	Yes

Formaldehyde	Shrimp hatchery, tilapia hatchery, marine fish grow-out	50 mL/L	Preventive measure for disinfection of tanks and equipment	Yes
	Shrimp hatchery	8 ppm for water disinfection before stocking, then stock shrimp nauplii after 3 days		
Formalin	Shrimp hatchery	100–500 ppm; and 25 ppm	Shrimp spawner disinfectant; and Rearing phase	Yes
Hydrogen peroxide	Tilapia hatchery	70 ppm as 2-hr flush	For disinfection of tanks, pipes and equipment	Yes
	Shrimp hatchery	Not indicated	Preventive measure/Disinfection	
Iodophores	Shrimp hatchery and grow-out, marine fish grow-out	1–2 ppm	For water conditioning	-
Omnicide	Shrimp hatchery and grow-out	1:400; and 1:100	For routine disinfection and aerial fogging; and for wheel/foot bath:	Yes
Potassium monopersulphate	Shrimp hatchery	50 ppm as 1-min dip	Preventive measure/Disinfection	-
	Shrimp grow-out	3–6 kg/ha at 1 m water depth		
	Tilapia hatchery and grow-out, marine fish grow-out	0.3 ppm as 24-hour bath		
Potassium permanganate	Shrimp hatchery and grow-out	10 ppm	For disinfection of surface, spray; use in foot/vehicle tire bath in shrimp grow-out pond	Yes
	Shrimp grow-out ponds	2 kg/ha	Pond preparation, spray	
Povidone-iodine	Shrimp hatchery	200 ppm; and 20 ppm	For 30 seconds egg washing; and broodstock disinfection upon arrival	NDA

	Trichlorfon	Shrimp grow-out	0.5–1 ppm	Preventive measure for the preparation prior to stocking	Yes
	Calcium hypochlorite (70% chlorine)	Shrimp hatchery	200–1000 ppm; 5–70 ppm; 10–200 ppm; and 20 ppm	disinfection of rearing tanks; rearing water; hatchery paraphernalia; and diseased stocks	Yes
	Benzalkonium chloride	Shrimp grow-out ponds	0.5–6 ppm	Disease control	Yes
	Cococide chloride	Shrimps grow-out ponds	0.5–1 ppm	Rearing phase	NDA
	Didecyl dimethyl ammonium bromide ($C_{22}H_{48}NBr$) (Bromosept-50 50%)	Srimps grow out ponds	0.5–5 ppm; and 0.5–3 ppm	Rearing phase; and disease control	-
	Alkyl dimethyl benzyl ammonium chloride (Fabcide B-50)	Shrimp grow-out ponds	0.5–1 ppm	Preventive measure in rearing phase	-
	Iodine (Biodin)	Shrimps grow-out ponds	5 L/ha	Preventive measure in pond preparation	Yes
	Alkyl dimethyl benzyl ammonium chloride (Aquasept)	Shrimps grow-out ponds	0.25–1 ppm; and 0.5-1.5 ppm	Rearing; and disease control	-
Vaccines	Streptococcus sp. Bacterin	Tilapia hatchery	1 000 mL:100 kg fingerlings by immersion one time	Fingerlings are vaccinated prior for stocking	-
Sex control (hormone)	17 Alpha methyltestosterone	Tilapia fry	60 mg/kg feed until 21 days	For faster and shorter culture period	Yes
Probiotics		Shrimp hatchery and grow-out, tilapia hatchery and grow-out, milkfish/marine fish hatchery and grow-out	Depends on the product applied either in pond or via feeds	For maintaining good environmental culture condition	-

Immune Enhancer	Ergosan (Extract of *Laminaria digitata*, 99% and *Ascophylum nodosum*, 1%)	Shrimp hatchery	0.1–0.7 g per ton of larval rearing tank daily	For immune booster	-
		Tilapia hatchery and grow out, milkfish hatchery and grow out, shrimp grow-out	2–5 g/kg feed daily		
	Shrimp Active (Glucan and mannan polysacharides	Shrimp hatchery a. Zoea b. Mysis c. Early PL1–7 d. PL 8–15	a. 12.5 g/100 000 fry b. 19 g/100 000 fry c. 25 g/100 000 fry d. 60 g/100 000 fry		-
		Shrimp grow-out	2 g/kg of feed		
Feed additives	Vit C (Enervon C and Oderon C)	Shrimp hatchery	1 ppm	For M_1 to harvest, mix w/artificial feed	-
	Immune enhancer	Shrimp hatchery	0.5 – 1ppm	For every 3-4 days from Z_1 to harvest, long bath	-
Antimicrobials	Chloramphenicol	Shrimp grow-out ponds	3 g/kg feed; and 2 – 2.5 g/kg feed	For feeding DOC 1-30; and disease control	Prohibited
	Tetracycline (Oxytetracycline)	Shrimp grow-out ponds	3 g/kg feed; and 1–5 g/kg	For feeding DOC 1-30; and disease control, 3x/d for 3-7d	Yes
	Oxolinic acid	Shrimps grow-out ponds	1 g/kg feed; and 0.2-4 g/kg feed	For feeding DOC 12-60,1-3x/d; and disease control, 1-3x/d for 7d	Yes
	Furazolidone (98%)	Shrimp grow-out ponds	1 g/kg feed; and 1-2.5 g/kg	For feeding, DOC 1-100, 5x/d; and disease control	-
	PE-30	Shrimps grow-out ponds	20 g/kg feed	For feeding, DOC 1-35, alternate w/ vitamin, all feeding for 5-7d	-
	PE-40	Shrimps grow-out ponds	20 g/kg feed	For disease control, 2-3x/d fro 5-7d	-
	PE-60	Shrimps grow-out ponds	20 g/kg feed	For feeding, DOC 1-30, alternate w/ PE-30,4-5x/d	-

Vitamins/Lipids/ Minerals/ Protein	Vit C, Ascorbic acid	Shrimps grow-out ponds	1-5 g/kg feed	For rearing phase, DOC 60-120, 1x/d	-
	Vit C, Aquamix	Shrimps grow-out ponds	20 g/kg feed	For feeding, DOC 37 to harvest, 3x/wk	-
		Shrimps grow-out ponds	20 g/kg feed	For disease control, daily for 3-5 d	
	Rovimix Stay C	Shrimps grow-out ponds	1-20 g/kg feed	For rearing phase, DOC 1 to harvest,1x/d	-
	Enervon C (capsule)	Shrimps grow-out ponds	0.5-5 g/kg feed	For rearing phase	-
	Enervon C (syrup)	Shrimps grow-out ponds	10 mL/kg feed	For rearing phase	-
	SVT	Shrimps grow-out ponds	25 mL/kg feed	For rearing phase	-
	Stroner	Shrimps grow-out ponds	2-3 g/kg feed	For rearing phase, DOC 13 to harvest,5x/d	-
	Hypo 66	Shrimps grow-out ponds	25 g/kg feed	For rearing phase, DOC 1 to harvest, 2x/d	-
	Bactozyme	Shrimps grow-out ponds	5 g/kg feed	For rearing phase, DOC 13 to harvest, 5x/d	-
	Astaxanthin + Vitmin C (Nutri Asta-C)	Shrimp grow-out ponds	4-5 g/kg feed; and 5-10 g/kg feed	For feeding DOC 1 to harvest, 1x/d; and for disease control, 3-4x/d	-
	Vitamin A, C, E (Aquace)	Shrimps grow-out ponds	1-2 g/kg feed	For feeding DOC 1 to harvest, 1x/d	-
	Vitamin A, D + fatty acid + protein (Nutri-Pro)	Shrimps grow-out ponds	5-10 g/kg feed	For rearing phase, 5x/d	-
	Enzyme/vitamin/mineral (Nutri)	Shrimps grow-out ponds	1 g/kg feed	For rearing phase	-
	Fatty acid (Aquatak)	Shrimps grow-out ponds	20 mL/kg feed	Coating medium	-
	Fatty acid (Grow-Well)	Shrimps grow-out ponds	30 mL/kg feed	Coating medium	-

	Fatty acid (Nutri-oil)	Shrimps grow-out ponds	20 mL/kg feed	Coating medium	-
	Fatty acid (Fin-oil)	Shrimps grow-out ponds	2 g/kg feed	Coating medium	-
	Fatty acid (cooking/squid/cod liver oil)	Shrimps grow-out ponds	10 –20 mL/kg feed	Coating medium	-
	Fatty acid (Chicken egg)	Shrimps grow-out ponds	1-2 pc/kg feed	Coating medium	-
	Calcium compound (Calcium lactate)	Shrimps grow-out ponds	10 tablet/kg feed	For rearing phase, 1 wk prior to harvest, 1x/d	-
	Calcium compound, HUFA (B-meg)	Shrimps grow-out ponds	10 mL/kg feed	For rearing phase, 5 d, 5x/d	-
Antimicrobial/Vitamin/Mineral mix	Inoxyline	Shrimps grow-out ponds	2 g/kg feed	For feeding DOC 1-30, 2x/d	-
	Ino-Forte	Shrimps grow-out ponds	2 g/kg feed	For disease control, 10 d, 5x/d, 30 d withdrawal	-
	Ino-moto	Shrimps grow-out ponds	2-3 g/kg feed	For rearing phase, 5x/d	-
	Ino stress	Shrimps grow-out ponds	2-3 g/kg feed	For disease control, 5x/d	-
	Terravite	Shrimps grow-out ponds	5 g/kg feed	For rearing phase, DOC 1-30, 5x/d, alternate with Inoxyline or PE-30	-
	Chronic Prevention Herbal	Shrimps grow-out ponds	20 g/kg feed	For disease control, 7 d, 1x/d	-
Soil and Water treatment chemicals	Lime (Hydrated lime)	Shrimp grow-out ponds	500-2000 kg/ha; 20-300 kg/ha; 50-300 kg/ha	For pond preparation (broadcast); rearing phase; and disease control	-
		Milkfish ponds	150-1,000 kg/ha	For pond preparation, broadcast	-

	Lime (Agricultural lime)	Shrimps grow-out ponds	200-800 kg/ha; 10-500 kg/ha; and 100-300 kg/ha	For pond preparation, broadcast; Rearing phase (1x/wk-daily; and disease control	-
		Milkfish ponds	300-5,000 kg/ha	For pond preparation, broadcast	-
	Calcium hypochlorite (70% chlorine)	Shrimps grow-out ponds	50-150 kg/ha	For pond preparation	-
	Dolomite	Shrimps grow-out ponds	100 kg/ha; and 50-250 kg/ha	For pond preparation; and Rearing phase	-
	Biolite	Shrimps grow-out ponds	100 kg/ha; and 100 kg/ha	For Pond preparation; and rearing phase	-
	Zeolite	Shrimps grow-out ponds	80-300 kg/ha; and 50 kg/ha	For rearing phase; and for disease control, daily until disease disappears	-
	Daimetin	Shrimps grow-out ponds	100-150 kg/ha	For rearing phase	-
	Health lime	Shrimps grow-out ponds	150kg/ha	For rearing phase,1x/wk until harvest	-
	Health stone/Wonder stone	Shrimps grow-out ponds	200-400 kg/ha	For disease control, plankton die-off	-
Plankton growth promoters	Inorganic fertilizer (16-20-0,monoammonium phosphate)	Shrimps grow-out ponds	4-100 kg/ha; and 150-300 kg/ha	For pond preparation, broadcast; and rearing phase, periodic, broadcast	-
		Milkfish ponds	100-300 kg/ha; and 3.2kg/ha	For pond preparation, broadcast; and Rearing phase, every 15 d up to harvest, broadcast	-
	18-46-0, diammonium phosphate	Shrimps grow-out ponds	3.2-50 kg/ha; 0.6-20kg/ha	For pond preparation; and rearing phase	-
		Milkfish ponds	50-150 kg/ha	For pond preparation, broadcast	-
	14-14-14, NPK, complete fertilizer	Shrimps grow-out ponds	7.5-15 kg/ha; and 3 kg/ha	For pond preparation; and rearing phase	-
	46-0-0, urea	Shrimps grow-out ponds	5-120 kg/ha; and 3.2-5kg/ha	For pond preparation; and rearing phase	-

		Milkfish ponds	25-200 kg/ha; and 12 kg/ha	For pond preparation, broadcast; and rearing phase, every 15d up to harvest, broadcast	-
	0-20-0, solophos	Shrimps grow-out ponds	3-20 kg/ha; and 5-10 kg/ha	For pond preparation ; and rearing phase	-
	21-0-0, ammonium sulfate	Shrimps grow-out ponds	100-500 kg/ha	For pond preparation	-
	Calcium nitrate	Shrimps grow-out ponds	3-50kg/ha; and 5-10kg/ha	For pond preparation, broadcast; and rearing phase broadcast	-
Organic Fertilizers	Chicken manure	Shrimps grow-out ponds	100-300kg/ha; and 100-1000kg/ha	For pond preparation, tea bags; and rearing phase, tea bags	-
		Milkfish ponds	500-3,000 kg/ha; and 200 kg/ha	For pond preparation, broadcast; and rearing phase, tea bags	-
	Cow manure	Shrimps grow-out ponds	100-500 kg/ha; and 100-200 kg/ha	For pond preparation, tea bags; and rearing phase, tea bags	-
	Carabao manure	Shrimps grow-out ponds	240-300 kg/ha; and 100-200 kg/ha	For pond preparation, tea bags; and rearing phase, tea bags	-
	VIMACA, chicken/pig manure	Shrimps grow-out ponds	1000 kg/ha	For pond preparation, tea bags	-
	Goat/Pig manure	Milkfish ponds	500-1,000 kg/ha	For pond preparation, broadcast	-
	Bioearth	Milkfishponds	500 kg/ha	For pond preparation, broadcast	-
	B4	Shrimps grow-out ponds	50 kg/ha	Pond preparation, substitute for manure	-
other nutrients	Lab-me	Shrimps grow-out ponds	200 mL/ha/wk	For pond preparation, 2 applications	-
	Algae grow	Shrimps grow-out ponds	0.5 ppm	For pond preparation	-
	Unknown growth factor	Shrimps grow-out ponds	30 kg/ha	For pond preparation, broadcast	-
	PA-100	Shrimps grow-out ponds	0.1-0.2 ppm; and 15 kg/ha	For pond preparation; and Rearing phase, every 15 d up to DOC 90	-

Organic matter decomposers	ER 49	Shrimp grow-out ponds	4-5 kg/ha	For pond preparation, broadcast	-
Bacteria + enzyme preparation	NS-SPO	Shrimps grow-out ponds	160-320 g/ha; 2-3 kg/ha/culture; and 1L/ha	For pond preparation; rearing phase, every 7d until harvest; and disease control	-
	Biozyme	Shrimps grow-out ponds	5 kg/ha; and 5kg/ha	For pond preparation; and rearing phase, every 7d until harvest	-
	Micro aid activator	Shrimps grow-out ponds	5-20 kg/ha; and 5-20 kg/ha	For pond preparation; and rearing phase, 1x/wk up to harvest	-
	Aquazyme	Shrimps grow-out ponds	0.5 kg/ha; and 2 kg/ha	For rearing phase, 2x/wk, every water change; and disease control, daily for 3d	-
	Twinner	Shrimps grow-out ponds	5 kg/ha	Rearing phase, every 7d	-

Table 3. List of chemicals used for food consumption and ornamental fish in Philippine aquaculture (Coloso et al., 2015)

Chemicals	Status	
	Prohibited – Total banned ***No*** – Currently not used ***NDA*** – No Data Available (Status not known) ***YES*** – Allowed to be used	
Antibiotics/Antimicrobial	**Fish For Food Consumption**	**Ornamental Fish**
Tetracyclines *	Yes	Yes
Nitrofurans	Prohibited	Yes
Chloramphenicol	Prohibited	No
Oxolinic acid *	Yes	Yes
Erythromycin *	Yes	Yes
Dimetridazole/Metronidazole	Prohibited	No
Elbaju/Ebazine	NDA	No
Sulfonamides *	Yes	Yes
Oxytetracyclines	Yes	Yes
Chlortetracycline *	Yes	Yes
Sulfamerazine *	Yes	Yes
Nifurpirinol	No	No
Amoxicilin	Yes	Yes
Doxycyclin	Yes	Yes
Enrofloxacin *	Yes	Yes
Florfenicol	Yes	Yes
Norfloxacin	Yes	Yes
Rifamicin / or Rifampicin	Yes	Yes
Ciprofloxacin	NDA	NDA
Sarafloxacin	NDA	NDA
Ormethoprim	NDA	NDA
Sulfadimethoxin + Ormethoprim *	NDA	Yes
Sulfadimethoxin + trimethoprim	Yes	Yes
Disinfectants		
Belzalkonium chloride (BKC)	Yes	-
Calcium Hypochlorite	Yes	-
Lime	Yes	-
Formalin	Yes	-
Sodium chloride	Yes	-
Potassium permanganate	Yes	-
Methylene blue	Yes	-
Malachite green	Prohibited	-
Copper sulphate	No	-
Acetic acid	No	-
Acriflavin	No	-
Hydrogen peroxide	Yes	-
Sodium hypochlorite	Yes	-
Iodine	Yes	-
Cypermethrin	Yes	-
Potassium monopersulfate	Yes	-
Omnicide	Yes	-
Trichlorfon	Yes	-
Glutaraldehyde	No	-
Chloramin T	Yes	-
Sodium Dichloroisoyanurate	No	-
Tricholoroicyanuric acid	No	-
Myristalkonium chloride	No	-
Ethylenediamine tetraacetic acid (EDTA)	No	-
Potassium peroxymonosulfate	No	-
Chemotherapeutants agents		
Copper sulfate	Yes	Yes
Trichlorfon	Yes	Yes
Trifluralin	Yes	Yes

Cypermethrin	Yes	NDA
Sodium chloride	Yes	Yes
Formaldehyde	Yes	Yes
Hydrogen peroxide	Yes	Yes
Praziquantel	Yes	Yes
Potassium permanganate	Yes	Yes
Methylene blue	Yes	Yes
Bronopol	No	No
Levamisol	No	No
Piscicide (use in pond preparation or early culture		
Saponin	Yes	-
Rotenone	Yes	-
Organophosphates (OPs) - The two most commonly used OPs are dichlorvos (dichlorovos) and trichlorfon (dipterex, and neguvon)	Yes	-
Cyanide	No	-
Fentin acetate	No	-
Deltamethrine	NDA	-
Hormones		
Human chorionic gonadotropin (HCG)	Yes	Yes
Luteinizing Hormone – Releasing Hormone Analogues (LHRHa)	Yes	Yes
Gonadotropin Releasing Hormone Analogues (GnRHa)	No	-
Ovaprim	No	No
Pituitary extract	Yes	-
Puberogen	No	No
17 α methyltestosterone	Yes	-
Androgen	No	No
17 - Beta estradiol	No	-
Ovatide	No	No
Anaesthetics		
Tricane methanesulphonate (TMS222)	Yes	Yes
Eugenol, Aqui-S	Yes	Yes
Quinaldine	No	No
Tranquil (Aquacalm)	No	No
Benzocaine	No	No
Phenoxy ethanol	Yes	Yes
Culture System Preparation		
Calcium Hypochlorite	Yes	-
Lime	Yes	-
Urea	Yes	-
Zeolite	Yes	-
Calcium chloride	Yes	-
EDTA	NDA	-
Sodium thiosulphate	Yes	-

*Residues with Maximum Residual Limit

Use of Authorized Chemicals and Antibiotic Resistance in Philippine Aquaculture

Several drugs, including nitrofurans, chloramphenicol, dimetridazole/metronidazole, olaquindox, carbadox, malachite green, and gentian violet, as well as beta-agonist drugs for food animals, are banned for use in food-producing animals in the Philippines (Coloso et al., 2015; DA-BAFS, 2014; Department of Agriculture A.O. No. 60 and Department of Health A.O. No. 91, Series of 1990; Somga et al., 2012). However, there is evidence that some banned chemicals are still used despite these regulations (Regidor et al., 2020; Tahiluddin et al., 2021b). Other aquaculture substances are currently in use, but strict adherence to regulations is necessary to ensure fish producers comply with minimum withdrawal limits and maximum residue limits (MRLs).

The seaweed industry in the Philippines plays a crucial role in aquaculture production, providing an environmentally sustainable source of income for coastal communities (Trono, 1999). In the southern Philippines, seaweed farmers use inorganic fertilizers, such as ammonium phosphate (16-20-0, NPK) and complete fertilizer (14-14-14, NPK), to enhance growth and boost disease resistance (Muyong & Tahiluddin, 2024; Tahiluddin & Damsik et al., 2023; Tahiluddin et al., 2023; Tahiluddin et al., 2022a; Tahiluddin et al., 2022b; Tahiluddin et al., 2022c; Tahiluddin et al., 2021a; Tahiluddin et al., 2021b). The emerging use of inorganic fertilizers in seaweed cultivation is under scrutiny to assess potential negative effects. Currently, the Philippine National Standard on "Seaweeds – Code of Good Aquaculture Practices (GAqP)" discourages the use of inorganic fertilizers in seaweed farms (BAFS, 2021). However, the use of inorganic fertilizers in seaweed aquaculture persists despite these guidelines (Tahiluddin & Eldani-Tahiluddin, 2024; Tahiluddin & Roleda, 2025).

The irresponsible use of chemicals in aquaculture, particularly for chemotherapy, exacerbates the development of antimicrobial resistance and introduces unprecedented risks. In the Philippines, aquaculture is dominated by tilapia, milkfish, shrimp/prawns, seaweeds, and shellfish, which are also major export commodities. These organisms are commonly cultured in fish ponds, cages, fish pens, and mariculture systems (BFAR, 2023). To mitigate losses, farmers apply various antibiotics and chemical agents as both prophylaxis and therapeutic measures, particularly for finfish and shellfish aquaculture (Baticados & Paclibare, 1992; Coloso et al., 2015; Primavera et al., 1993; Regidor et al., 2020; Somga et al., 2012; Tendencia & De La Peña, 2001).

Although tilapia is a relatively hardy fish, it is not immune to bacterial infections (BFAR, 2023; Tahiluddin & Terzi, 2021b). Common antibiotics used in tilapia culture include chloramphenicol, ampicillin, tetracycline, and erythromycin (Regidor et al., 2020; Tahiluddin & Terzi, 2021b). Studies have reported antibiotic resistance in Nile tilapia, including resistance to oxolinic acid and sulfamethoxazole-trimethoprim (Legario et al., 2020). Resistance to ampicillin, tetracycline, and polymyxin B was also reported in Nile tilapia from Lingayen, Pangasinan (Langaoen et al., 2018). Additionally, antibiotic residues such as tetracycline, ceftiofur, quinolone, and florfenicol have been detected in Nile tilapia cultured in Laguna de Bay (Revilleza et al., 2021). High resistance of *Aeromonas hydrophila* and *A. sobria* to amoxicillin, erythromycin, neomycin, and oxytetracycline, with many isolates showing resistance to at least three antibiotic categories, indicating multiple drug resistance was reported (Pakingking et al., 2022). Heavy metals like lead, cadmium, and chromium have also been detected in tilapia marketed in Metro Manila (Solidum et al., 2013). Despite increased awareness, continuous education campaigns and regular inspections are essential to address the use of chemicals and residue buildup (Coloso et al., 2015; Cruz-Lacierda et al., 2000; Regidor et al., 2020; Subasinghe et al., 2000).

Milkfish, another key export commodity, also faces issues with unauthorized substances and antimicrobial treatments (Langaoen et al., 2018; Regidor et al., 2020; Solidum et al., 2013). When cultured with shrimp, it can harbor pathogenic bacteria (Arnaiz, 2015). Studies have documented antibiotic and multi-drug resistance in milkfish from Lingayen, Pangasinan (Langaoen et al., 2018). Organochlorine pesticides (OCPs) exceeding threshold limit values have been detected in brackish water ponds used for milkfish, tiger shrimp, tilapia, and other aquaculture commodities (Catacutan et al., 2015). Heavy metal contamination, such as cadmium in organic milkfish farming in Negros Occidental was documented (Albarico & Pador, 2019). Other contaminants like lead, cadmium, and chromium in milkfish marketed in Metro Manila were also reported (Solidum et al., 2013). These challenges pose further health issues not only for the culture stock but for the consumer and the environment too.

The shrimp aquaculture industry is grappling with significant multi-drug resistance challenges. The presence of an identified multidrug-resistant strain of *Salmonella enterica* serotype isolated from seafood in Asia, including shrimp imported from the Philippines, was documented (Karp et al., 2020). Similarly, a reported multidrug-resistant strain of *Vibrio parahaemolyticus* from a shrimp farm was found (Saloma et al., 2019). The antibiotic-resistant pathogen found in shrimp ponds was primarily caused by Vibrios, especially *Vibrio harveyi* (Tendencia & De La Peña, 2001). The antibiotics detected included oxytetracycline, furazolidone, oxolonic acid, and chloramphenicol. Earlier studies had already reported resistance to erythromycin, kanamycin, penicillin, and streptomycin in luminous strains of *V. harveyi* and *V. splendidus* isolated from shrimp larvae (Baticados et al., 1990). High levels of antimicrobial resistance to oxytetracycline (OTC) and oxolinic acid have also been observed in *P. monodon* ponds (Tendencia & Dela Peña, 2002). A survey conducted in the selected areas further detected chlortetracycline residues above the maximum residue limit (MRL) in shrimp, suggesting the widespread use of antibiotics (Regidor et al., 2020).

The shellfish industry in the Philippines is primarily focused on oysters and mussels (*Crassostrea* spp., *Perna* sp., and *Modiolus* spp.) (BFAR, 2023). Studies conducted in Lingayen Gulf have detected cadmium, lead, arsenic, and mercury in oysters, with cadmium levels exceeding acceptable limits (Vinarao et al., 2014). These heavy metals pose serious risks to public health. In Bacoor, Cavite, isolates of pathogenic Vibrios, including *V. alginolyticus, V. cholerae, V. parahaemolyticus*, and *V. vulnificus*, from mussels were found to be resistant to ampicillin, nalidixic acid, tetracycline, co-trimoxazole, and neomycin (Tabo et al., 2015). Some of these isolates were even multidrug-resistant. Studies also reported a high incidence of microbial pathogens *Escherichia coli, Salmonella*, and *Vibrio* spp. load in bivalve flesh and its water growing area, possibly due to the discharge of wastewater from residential houses and aquaculture activities (Peralta & Andalecio, 2011). Additional studies have reported high counts of *E. coli, V. parahaemolyticus, V. cholerae*, and *Salmonella* spp. in culture waters and sediment in Capiz, Western Visayas (Nuñal et al., 2023). The isolation of these potential pathogens from mussels and oysters underscores the health risks involved, highlighting the need for long-term monitoring programs. The reported use of various chemicals in key aquaculture species in the Philippines raises significant concerns about environmental issues, food safety, and public health.

The reported studies on the threat of using excessive antibiotics in any aquaculture system have been linked to drug resistance in animals. Due to the prolonged use of antibiotics in the system, the transfer of resistance genes can be passed on to humans when consuming animal products, complicating the treatment of infections in humans (Pelić et al., 2024; Schar et al., 2020)

Regulatory Framework for Veterinary Drugs and Products in Philippine Aquaculture

The distribution and marketing of veterinary drugs and aquaculture products in the Philippines are subject to strict regulatory oversight. Prior registration with the appropriate authorities is mandatory, requiring a thorough examination and certification of products as per the guidelines established in the Food and Drug Administration Act of 2009. A comprehensive legal framework, including various Philippine legislations such as Republic Acts (RAs), Administrative Orders (AOs), and Memoranda, ensures effective monitoring of retail outlets, accredited laboratories, aquaculture farms, feed mills, and the distribution and sale of these products (Table 4). To promote intra- and extra-Association of Southeast Asian Nations (ASEAN) trade and enhance the long-term competitiveness of ASEAN food, agriculture, and forestry products, the Philippines has implemented the Philippine National Standards for Code of Good Aquaculture Practices. This initiative highlights the country's commitment to maintaining high standards in the aquaculture sector.

Table 4. Various Government competent authorities governing the registration of veterinary drugs, products, and technical requirements and standards for aquaculture commodities.

RA/AOs/Memoranda No/PNA	**Title**	**Agency**
RA No. 9711, 2009	the Food and Drug Administration (FDA) Act of 2009	Food and Drug Administration (FDA)
RA NO. 1556, 1956	the Livestock and Poultry Feeds Act	Bureau of Animal Industry (BAI)
RA No. 3720, 1963	the Food, Drug, and Cosmetic Act	Department of Health (DOH)
RA NO. 6675, 1988	the Generics Act of 1988	Department of Health (DOH)
RA No. 1071, 1954	An Act to Regulate the Sale of Veterinary Biologics and Medicinal Preparations	
RA NO. 8550 as amended by RA10654, 2014	the Philippine Fisheries Code of 1998	Department of Agriculture, Bureau of Fisheries and Aquatic Resources (DA-BFAR)
RA NO. 7394, 1992	the Consumer Act of the Philippines	Department of Health (DOH)
Special Order No. 167, Series 2004	Creation of Aquatic Feeds Monitoring Task	Department of Agriculture (DA)
Special Order No. 69, Series of 2004	Deputation of BFAR Fish Health Officers and DA Regional Veterinary Personnel as Aquatic Animal Feed and Veterinary Drug and Product Control Officers Following the Terms of Agreement in the Memorandum of Agreement Between BAI and BFAR	Department of Agriculture (DA)
Memorandum Circular No. 6, Series of 2003	Guidelines Governing the Disposal and Destruction of Banned Veterinary Drugs and Products Used in All Food-producing Animals	Bureau of Agricultural Industry (BAI)
Special Order No. 23, Series of 2002	Deputation of BFAR Fish Health Officers as Aquatic Animal Feed and Veterinary Drug and Product Control Officers	Department of Agriculture (DA)
DA-BFAR and BAI Memorandum of Agreement (2001)	Regulation on Animal Feed, Veterinary Drugs and Products in Aquaculture	Department of Agriculture Bureau of Fisheries and Aquatic Resources and Bureau of Animal Industry (DA-BFAR and BAI)
AO No. 9, Series of 1994	Guidelines Governing the Conduct of Clinical Trials of Veterinary Drugs and Products	Bureau of Agricultural Industry (BAI)
AO No. 27, Series of 1993	Minimum Requirements for Determining/Evaluating the Efficacy and Safety of Veterinary Drugs to Target Animals	Bureau of Agricultural Industry (BAI)
AO No. 35, Series 1975	Rules and Regulations Governing the Manufacture, Importation, Labelling, Advertising, Distribution and Sale of Livestock and Poultry Feeds and Feeding Stuffs	Bureau of Agricultural Industry (BAI)
AO No. 118, Series of 1992	Rules and Regulations on the Process of Review and Evaluation of Questioned Veterinary Drugs or Veterinary Drugs Combinations	Department of Agriculture Administrative Order (DA AO) No. 3 and Department of Health (DOH)
AO No. 111-A and AO No. 33, Series of 1991	Rules and Regulations on Registration of Veterinary Drugs and Products	Department of Health and Department of Agriculture (DOH and DA)
Special Order No. 23, Series of 2002 and Special-Order No. 69, Series of 2004	Aquatic Animal Feed and Veterinary Drug and Product Control Officers	Department of Agriculture Bureau of Fisheries and Aquatic Resources (DA-BFAR) (Fish Health Officers)
PNS/BAFS 334:2022	Grouper – Code of Good Aquaculture Practices (GAqP)	Department of Agriculture, Bureau of Agriculture and Fisheries Standards (DA-BAFS)

PNS/BAFS 208:2021	Seaweeds – Code of Good Aquaculture Practices (GAqP)	Department of Agriculture, Bureau of Agriculture and Fisheries Standards (DA-BAFS)
PNS/BAFS 280:2019	Code of Good Aquaculture Practices (GAqP) on Hatchery for Shrimp	Department of Agriculture, Bureau of Agriculture and Fisheries Standards (DA-BAFS)
PNS/BAFS 281:2019	Code of Good Aquaculture Practices (GAqP) on Hatchery for Freshwater Prawn	Department of Agriculture, Bureau of Agriculture and Fisheries Standards (DA-BAFS)
PNS/BAFS 196:2017	Code of Good Aquaculture Practices (GAqP) for Milkfish and Tilapia	Department of Agriculture, Bureau of Agriculture and Fisheries Standards (DA-BAFS)
PNS/BAFS 197:2017	Code of Good Aquaculture Practices (GAqP) for Shrimp and Crab	Department of Agriculture, Bureau of Agriculture and Fisheries Standards (DA-BAFS)
PNS/BAFS 101:2016	Halal Agriculture and Fisheries Products	Department of Agriculture, Bureau of Agriculture and Fisheries Standards (DA-BAFS)
PNS/BAFS 187:2016	Organic Aquaculture Feeds	Department of Agriculture, Bureau of Agriculture and Fisheries Standards (DA-BAFS)
PNS/BAFS 135:2014	Code of Good Aquaculture Practices	Department of Agriculture, Bureau of Agriculture and Fisheries Standards (DA-BAFS)
PNS/BAFPS 84:2010	Philippine National Standard for Aquaculture feeds	Department of Trade and Industry-Bureau of Product Standards (DTI-BPS)

The BFAR has appointed Fish Health Officers as Aquatic Animal Feed and Veterinary Drug and Product Control Officers (AAFDVPCOs). These officers are crucial in regulating the use of veterinary drugs and products in the aquaculture sector. AAFDVPCOs are tasked with inspecting and sampling at aquaculture facilities, fish ports, processing plants, and markets. They are also authorized to diagnose fish diseases and recommend suitable medications for aquatic animals. However, the use of restricted veterinary drugs necessitates a prescription from a licensed veterinarian and must adhere to relevant regulations, including those specifying minimum withdrawal periods (Somga et al., 2012). This regulatory framework is designed to ensure the responsible use of veterinary drugs in aquaculture, thereby protecting human health by minimizing potential drug residues in seafood products.

Alternative Antibiotic Strategies in Philippine Aquaculture

Given the growing issue of antibiotic resistance, it is crucial to explore alternative strategies for controlling its spread in aquaculture. This study categorizes the alternatives into pathogen-directed and host-directed approaches. Pathogen-directed strategies include inhibiting the growth and virulence of pathogens, using antibacterial compounds, and employing phage therapy. Host-directed strategies focus on enhancing overall health, reducing stress, stimulating the immune system, and selective breeding for disease resistance (Defoirdt et al., 2011).

Adhering to Good Aquaculture Practices (GAqPs), such as maintaining high water quality, proper sanitation, and balanced nutrition, is essential for both aquaculture farms and feed manufacturers (Regidor et al., 2020). Preventive measures throughout the production cycle, from hatchery to grow-out, are beneficial when implemented correctly. Natural substances like derris roots, rotenone, and tobacco dust can effectively manage pests, predators, and other undesired species (Cruz-Lacierda et al., 2000). Prophylactic agents act as a primary defense against infections, helping to prevent the development of pathogenic and drug-resistant strains (Cruz-Lacierda et al., 2000; Primavera, 1993).

In response to antibiotic-resistant pathogens, environmental and biological disease prevention methods are gaining prominence (Cruz-Lacierda et al., 2000). The Food and Agriculture Organization (FAO) and the World Health

Organization (WHO) advocate for the use of probiotics in aquaculture to enhance the aquatic environment (FAO/WHO, 2001; Sharifuzzaman & Austin, 2017). Probiotics offer numerous benefits, including improved health, disease prevention and control, enhanced growth performance, better body composition, reduced malformations, improved gut morphology and microbial balance, increased feed efficiency, and enhanced water quality (Das et al., 2017; Hancz, 2022; Merrifield et al., 2010). Recent studies in the Philippines have explored probiotic applications. For instance, *Staphylococcus aureus* isolated from saline tilapia in green water culture systems has shown promise in inhibiting gut colonization and protecting against *A. hydrophila* infections *in O. niloticus* (Albances & Traifalgar, 2022). *Bacillus* spp. isolated from African nightcrawlers (*Eudrilus eugeniae*) have been reported to improve growth, feed utilization, and disease resistance in Nile tilapia (Samson et al., 2020). Probiotic-treated groups infected with *A. hydrophila* exhibited higher survival rates (Hortillosa et al., 2022). Encapsulated probiotic isolates, including *Lacticaseibacillus* sp. FSPL001, *Saccharomyces* sp. FSPL011, and *Bacillus* sp. FSPL020, have been used to supplement tilapia diets, leading to increased body weight gain without adverse effects on feed utilization (Dumandan et al., 2024). Meanwhile, two strains of probiotic *Bacillus* isolated from the mucus of tilapia significantly helped to decline the population of *V. harveyi* resulting higher survival rate (Doroteo et al., 2018). Additionally, probiotics such as *Bacillus subtilis* BF12 and *Proteus mirabilis* MJA2.6S have been shown to inhibit pathogenic *V. parahaemolyticus* and *V. harveyi* in *P. monodon* culture, resulting in better growth, survival, and reduced ammonia levels (Apines-Amar et al., 2022; Temario et al., 2022). Probiotics have also positively impacted water quality and milkfish production in polluted ponds (Pleto et al., 2021).

Harmonization of Drug Registration Requirements in the Philippines

Harmonizing national drug registration requirements with VICH (International Cooperation on Harmonization of Technical Requirements for Registration of Veterinary Medicinal Products) guidelines involves aligning local regulations with globally recognized standards. This process aims to streamline the global registration and approval of veterinary medicinal products (VMPs), ensuring their safety, efficacy, and quality (Holmes & Hill, 2007).

The Philippines actively engages with VICH to help establish standardized guidelines and protocols for pharmaceutical product registration. By aligning its regulations with VICH standards, the Philippines aims to enhance the efficiency of its drug registration process, improve public health and safety, and increase access to high-quality medications. This engagement highlights the country's commitment to international cooperation and best practices in pharmaceutical regulation.

Several government agencies, including the FDA, DA-BAI, DA-BFAR, DOH, and DTI, collaborate to ensure that the Philippines meets its obligations to international harmonization efforts like those promoted by VICH. This coordinated approach benefits public health and safety and facilitates access to quality pharmaceutical products.

Despite existing legislation governing VMP use, challenges persist in implementation, affecting end-users and consumers. Unregulated use of VMPs can result in antibiotic residues passing from cultured animals to humans, underscoring the need for stricter regulation and ongoing monitoring (Pineda-Cortel et al., 2024).

While the Philippines may not fully meet all VICH technical requirements, its efforts to harmonize international regulatory standards are noteworthy. Continued dedication to international cooperation, including adopting best practices, enforcing stricter regulations, and conducting periodic monitoring and reporting on chemical production, is crucial. To prevent chemical hazards and ensure food safety, promoting regulatory harmonization based on international guidelines and adopting sound stewardship in Philippine aquaculture are essential. While antimicrobial treatments may be necessary for efficient animal production, they should not replace proper nutrition and hygiene management.

Conclusion

The rapid expansion of the Philippine aquaculture industry necessitates stringent measures to ensure the safety and quality of aquatic products, especially in the context of global trade. Food safety is a critical concern for the seafood industry, making compliance with regulatory frameworks essential to protect public health. Proper chemical use in aquaculture is crucial and must adhere to guidelines established by competent authorities. Aquaculturists and ornamental fish hobbyists should consult regulatory bodies or veterinarians to ensure the use of approved chemicals and their responsible application. Adhering to withdrawal periods is essential to avoid excessive chemical residues in edible aquatic products. A shift towards more sustainable and environmentally friendly practices, including reduced chemical use, is encouraged. Interagency collaboration is vital to mitigate chemical hazards and safeguard food safety. Harmonizing domestic and international regulations, alongside implementing robust stewardship programs for antimicrobial agents, will support responsible chemical use in aquaculture. Additionally, establishing transparent systems for reporting and tracking chemical usage, particularly antibiotics, can improve accountability and support evidence-based decision-making.

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Informed consent

Not available

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REVIEW PAPER

A Review of fish value-added products in Kenya: Current status, challenges and areas for improvement

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Abstract

Fish products are essential to Kenya's economy and nutrition, yet their high perishability limits their accessibility and export potential. Developing fish value-added products—such as fish samosas, sausages, fillets, and powders—presents a promising solution, potentially enhancing resource utilization, reducing waste, and expanding markets. Despite contributing approximately 0.6% to Kenya's GDP and supporting over 1.2 million livelihoods, the fish sector remains underutilized due to limited value addition. This review provides the first comprehensive synthesis of Kenya's fish value-added sector—bridging fragmented insights on product types, technologies, economic potential, and policy gaps—offering a practical foundation for informed decision-making and investment. Key products included in this review are samosas, fillets, sausages, fish balls, smoked fish, fish oils, burgers, and soups, alongside primary processing techniques such as improved smoking kilns, Mama Karanga boxes, chilling, and freezing. The review followed the PRISMA framework to systematically identify, screen, and analyze relevant peer-reviewed articles, grey literature, and government reports. Out of 625 initially identified documents, 64 high-quality sources were included in the final synthesis. Results show that value-added products such as fish fingers, sausages, and samosas are increasingly preferred due to their profitability, consumer appeal, and potential to reduce post-harvest losses. However, their development is hindered by weak market linkages, poor regulatory and quality controls, limited access to technology, inadequate policy support, and limited awareness among consumers and producers. Increasing consumer and producer awareness through training, improved market information systems, and accessible financing options could stimulate growth of the fish value addition sector. This paper's insights underscore the need for strategic interventions to unlock the potential of Kenya's fish value-added sector, fostering livelihood enhancement and food security. Implementation of targeted programs and policies can transform the fisheries and aquaculture sector into a robust contributor to the country's economic resilience and community well-being.

Introduction

Globally, the fish consumption rate is growing faster than the global population due to the awareness of the health benefits of consuming fish, increased incomes, and rising urbanization (Issifu et al., 2022). Fish and fishery products are critical for nutrition and food security and play a vital role in the economy of many countries, particularly those in the developing world (FAO, 2020). Fish has been recognized to contain polyunsaturated fatty acids, protein (rich in essential amino acids), and other nutrients that contribute positively to good health (Khalili & Sampels, 2018). Many of these beneficial micronutrients are generally more abundant in aquatic animals and plants than in meat or terrestrial vegetables. Also, fish enzymes have applications in many other industries, and many nutraceuticals from fish have enormous applications in human health. Fish consumption also contributes immensely to heart health and proper growth and development in children. Fish is recommended to be consumed more after certain ages for the superior alternative benefits they provide (Rondanelli et al., 2020). Value-added products, such as fish oils and nutraceuticals, can further amplify these health benefits, providing a convenient and nutritious food option (Peñarubia et al., 2023).

In Kenya, the demand for aquaculture products is increasing due to the rapid population growth and the declining catches from capture fisheries (Nyawade et al., 2021). The fisheries sub-sector comprises marine, inland fisheries and aquaculture. The main freshwater species are Nile tilapia (*Oreochromis niloticus*), African catfish (*Clarias gariepinus*), Omena (*Rastrineobola argentia*), Nile perch (*Lates niloticus*), and Nile carps (*Labeo niloticus*). Tilapia and African catfish are the main cultured species in the country, with the supply of other species from inland capture fisheries (Kyule et al., 2016). Owing to their high perishability and shorter life, Kenyan fresh fish availability as animal-sourced protein food is threatened and is of little significance to international trade. This inefficiency is a critical issue that undermines the sustainability and profitability of the fish industry. Further, micronutrient deficiencies affect hundreds of millions in the world, particularly women and children in Kenya, leading to increased risks of prenatal and maternal mortality, growth retardation, child mortality, cognitive deficits, and reduced immune function (Lokuruka, 2020). As a result, there is a need for superior farmed fish products that meet consumer preferences.

One potential solution to these challenges is the development and commercialization of fish value-added products, which can enhance the utilization of fish and fishery products, reduce waste, create new market opportunities, and improve community livelihoods (Magesa et al., 2024). The Kenyan fisheries and aquaculture industry contributes approximately 0.6% to the GDP (KNBS, 2024). It has been argued that fisheries' contribution to GDP could be higher if value addition along the supply chain and interventions against post-harvest losses are promoted (Muma, 2015). Value-added products are usually perceived to have added ingredients such as a coating or sauce, are prepared, trimmed, or provide more convenience to the user. Value combines quality, service, and price (Binsi & Parvathy, 2021).

In the context of the fish industry, value-added products can include a wide range of items such as ready-to-eat meals, smoked and dried fish, fish fillets, fish oils, and nutraceuticals (Abiodun-Solanke, 2020). These products can cater to diverse consumer preferences, offer convenience, and provide functional benefits, adding significant value to the original raw fish. The development of fish value-added products is not only a means to improve profitability for producers but also a strategy to utilize low-value fish species in a better way to meet the growing demand for high-quality, convenient, and nutritious food options (Mehta et al., 2023). Omega (2023) reported that a substantial portion of fish catches are either discarded or processed inefficiently, leading to economic losses and environmental degradation. Therefore, the fish value-added product sector holds immense potential for addressing some of the critical challenges faced by the fishing industry in Kenya. By enhancing the value of fish products, reducing waste, and creating new market opportunities, this sector can contribute to the sustainability and profitability of the fish industry (Stevens et al., 2018).

Despite the critical role of value addition in enhancing the fish industry's sustainability and profitability, the current status, challenges, and opportunities of fish value-added products have not been comprehensively documented. This lack of comprehensive documentation hinders the industry's ability to fully leverage on the potential of value-added products to address critical issues such as resource inefficiency, waste, and market access. The absence of detailed information on the development, processing technologies, market dynamics, and regulatory frameworks of fish value-added products creates a significant knowledge gap that needs to be addressed to drive innovation and growth in this sector.

This review provides a detailed and comprehensive analysis of the fish value-added product sector's current status, challenges, and areas for improvement. This review provides valuable insights that can guide policy decisions and the allocation of resources to support the growth of value-added fish products. For producers, processors, and marketers, understanding the current trends and challenges in the value-added product sector is crucial for making informed business decisions. Additionally, this review can increase consumer awareness and demand for these products by highlighting the benefits and availability of fish value-added products. This, in turn, can drive market growth and support the industry’s overall sustainability goals (Stevens et al., 2018).

Materials and Methods

The methodology followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework (Figure 1; Page & Moher, 2017), which supports transparency and replicability. An exhaustive literature search was conducted in August 2024 across multiple electronic databases, including Google Scholar, ScienceDirect, PubMed, and the Aquatic Sciences and Fisheries Abstracts (ASFA). The search targeted peer-reviewed articles, government and institutional reports, and grey literature relevant to Kenya’s fish value-added products. Search terms were constructed to include “fish value-added products in Kenya,” “fish processing challenges in Kenya,” “Kenya fisheries sector,” and “aquaculture product development.” Boolean operators (AND, OR) were employed to refine the results and capture a broad range of relevant studies.

The initial search yielded a total of 625 articles, which then underwent a thorough screening process to ensure alignment with the study’s objectives. The initial screening removed 230 duplicates, resulting in 395 unique studies. Titles and abstracts of these studies were reviewed against the inclusion and exclusion criteria. Studies were included if they specifically addressed fish value-added products, fish processing methods, or challenges in the Kenyan context. Only articles in English and accessible in full-text were considered to maintain consistency and reliability across data sources. Conversely, studies focusing solely on fisheries outside Kenya, articles not directly relevant to fish value addition (such as those focused on general aquaculture or unrelated food products), and studies without empirical data were excluded. Following this title and abstract screening, 198 articles were selected for a full-text review. In this stage, each article was evaluated by two independent reviewers to confirm relevance and adherence to the review’s scope, leading to a final selection of 42 articles. Any disagreements between reviewers were resolved through discussion or by consulting a third reviewer, reducing selection bias and ensuring accuracy in the final dataset.

To ensure consistency and rigor, a structured data extraction form was developed to systematically capture essential information from each study. Data points included the study’s authors, year of publication, study design, objectives, types of fish value-added products, processing methods, reported challenges, and suggested improvements. The extraction process was performed independently by two reviewers to maintain consistency, with cross-validation to ensure reliability. Quality assessment was conducted using the Mixed Methods Appraisal Tool (MMAT) (Hong et al., 2018), which evaluates each study on methodological soundness, relevance, and rigor. This tool provided a standardized assessment framework suitable for diverse study types, including qualitative, quantitative, and mixed-method studies. Studies were rated on clarity of research questions, appropriateness of study design, and validity of findings. Out of the 82 full-text articles, 64 met the MMAT quality threshold, with a score of 75% or higher, and were thus included in the synthesis, ensuring that only high-quality data contributed to the review findings.

Data synthesis was achieved through a thematic analysis approach, where extracted data were organized into key themes: types of fish value-added products, processing techniques, and technologies, challenges faced by the sector, and potential strategies for improvement. This thematic framework enabled the identification of cross-cutting issues and emerging trends that affect the fish value-added sector in Kenya. Data from selected studies were triangulated with grey literature, industry reports, and government publications to provide a comprehensive, multi-dimensional perspective.

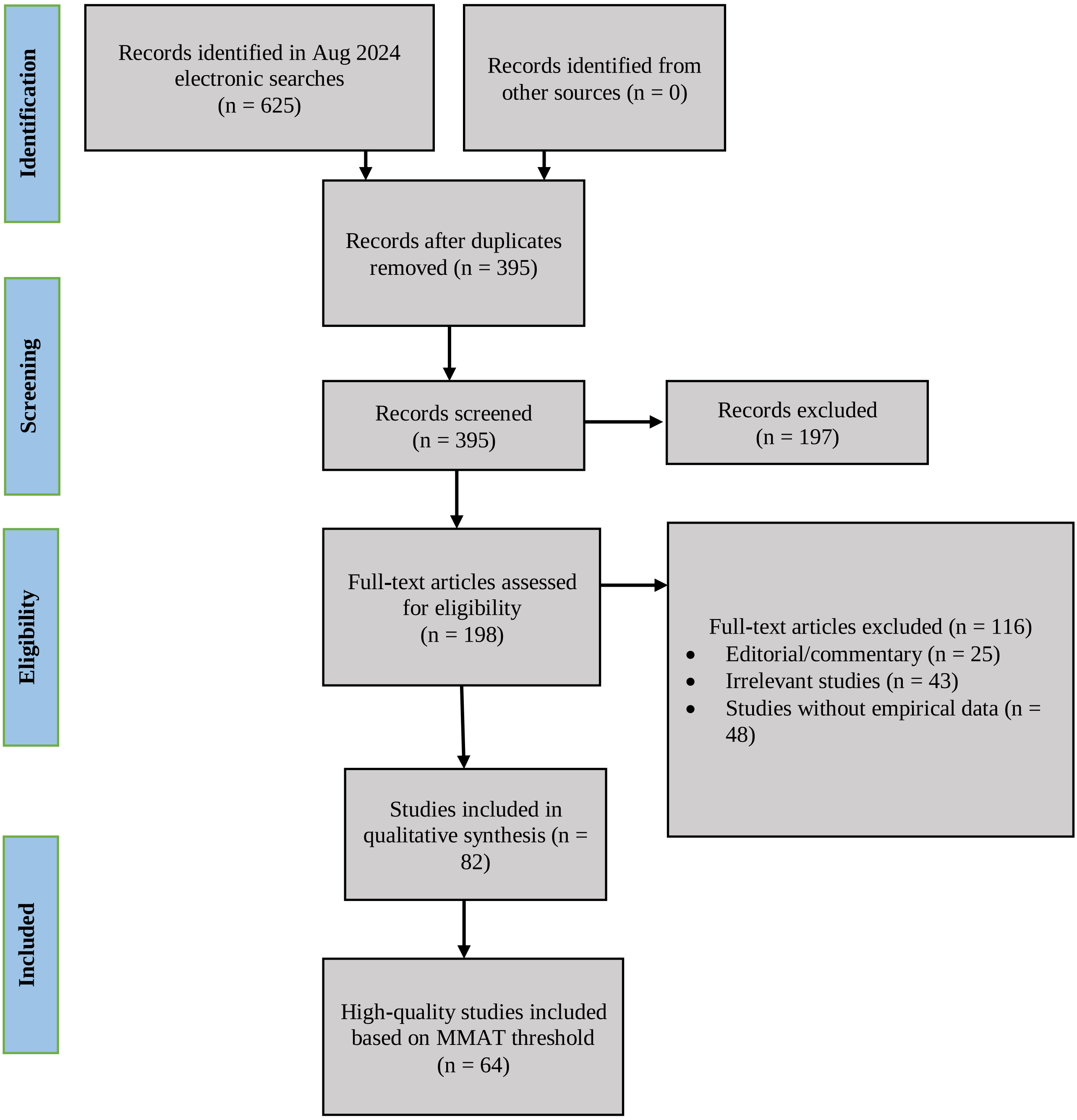

Figure 1. Flow diagram of identification, screening, and inclusion of studies for the review.

Results

Current state of fish value-added fish products available in Kenya

Fish samosas

Fish samosas are a popular value-added fish product in Kenya (Figure 2), widely enjoyed for their unique blend of flavors and nutritional benefits. They are crafted from minced fish and finely chopped onions, ginger-garlic paste, chili powder, black pepper powder, and garam masala. The samosa pastry and cones are made using plain wheat flour, cold water, and salt (Kyule et al., 2014). Fish samosas have gained traction in Kenya due to their versatility and appeal across consumer groups. This value-added product enhances the economic value of fish and provides an avenue for culinary innovation and cultural integration in Kenyan cuisine. The rising popularity of fish samosas can be attributed to their convenience, taste, and the nutritional benefits associated with fish, which is a good source of protein, omega-3 fatty acids, and essential nutrients.

Figure 2. Typical appearance of fish samosa (Kyule-Muendo et al., 2021).

Producing fish samosas contributes to food security and nutrition, providing a tasty alternative to traditional fish dishes. The ability to incorporate various spices and ingredients enhances the flavor. It caters to diverse palates, making fish samosas a favored snack or meal option across different demographic segments in Kenya. Nyamwaka et al. (2020) noted that fish samosa are considered a source of high-quality animal protein available both in urban and rural areas for human consumption in Kenya. Further, developing value-added products like fish samosas has helped reduce post-harvest losses and created new market opportunities for fish farmers and processors. This has been particularly beneficial in regions around Lake Victoria, where fish processing and trade are vital to the local economy (Kimani et al., 2022). In a study conducted by Kyule et al. (2016; 2020), fish samosas were the most preferred fish valued-added product in various counties in Kenya due to their delicious taste compared to other products.

Fish sausages

Fish sausages (Figure 3) are typically made by combining minced fish with various spices and binders and encasing the mixture in a natural or synthetic casing before cooking (Ninan, 2021). The primary ingredient, minced fish, provides a high-quality source of protein, omega-3 fatty acids, and essential nutrients vital for a healthy diet (Danilyuk et al., 2024). Making fish sausages involves several steps, including selecting fish, mincing, mixing with spices and binders, stuffing into casings, and cooking by steaming, boiling, or grilling.

Fish sausage offers a nutritious alternative to traditional meat sausages, catering to the growing health-conscious population segment in Kenya. Fish sausages are lower in fat and calories than their meat counterparts, making them an attractive option for consumers looking to maintain a healthy lifestyle. Moreover, using locally sourced fish to produce these sausages supports the local fishing industry and promotes sustainable fishing practices. This enhances the economic value of fish and helps reduce post-harvest losses, a significant challenge in the Kenyan fish industry (Odoli et al., 2019).

Figure 3. Typical appearance of fish sausages (Courtesy of Dr. Domitila Kyule, KMFRI Sagana)

Fish sausages can be flavored in various ways, allowing for various product variations that cater to different taste preferences (Nkrumah, 2015). This diversity in flavors and preparations makes fish sausages a versatile product that can be enjoyed as a snack, a meal component, or in various culinary applications. The production of fish sausages also aligns with the broader trend of value addition in the Kenyan food industry. By transforming raw fish into a ready-to-eat product, manufacturers can extend the shelf life of fish and create new market opportunities. This value-addition process is essential in addressing food security challenges, as it ensures that fish products remain available and accessible to consumers over a more extended period (Ninan, 2018).

In recent years, there has been a noticeable increase in the number of small and medium-sized enterprises (SMEs) involved in the production of fish sausages in Kenya (Wairimu, 2020). These businesses play a crucial role in driving innovation and providing employment opportunities in the local economy. The growth of SMEs in this sector is supported by various initiatives aimed at enhancing the capacity of fish processors through training and access to modern processing technologies (Hasan et al., 2020). These efforts are vital in ensuring that the quality and safety standards of fish sausages are maintained, thereby boosting consumer confidence and market acceptance.

Fish Fingers

Fish fingers (Figure 4) have emerged as a popular value-added fish product in Kenya, gaining significant traction due to their convenience, taste, and nutritional benefits. Made by coating strips of fish fillets with breadcrumbs and then deep-frying or baking them, fish fingers are appreciated for their crispy texture and appealing flavor. According to Kyule et al. (2014), fish fingers were second in preference only to samosas in several study areas in Kenya, highlighting their wide acceptance among consumers. This preference is primarily driven by fish fingers' palatability, making them a favored choice among children and adults. Additionally, including catfish in the production of fish fingers diversifies the product range and enhances traders' profitability. Kyule et al. (2014) also reported that traders could achieve a 100% profit margin above the total cost by incorporating catfish fingers, indicating a lucrative market potential.

Figure 4. Typical appearance of fish fingers (Courtesy of Dr. Domitila Kyule, KMFRI Sagana)

Fish fingers address the growing demand for quick and easy meal options in urban areas by transforming raw fish into convenient, ready-to-eat products. This trend supports the local fish industry by creating new market opportunities and reducing post-harvest losses (Binsi & Parvathy, 2019). Furthermore, the production of fish fingers aligns with health-conscious consumer preferences, as they offer a low-fat, high-protein alternative to traditional meat products. Studies have shown that value-added fish products like fish fingers contribute significantly to the economic sustainability of the fish sector in Kenya, providing employment opportunities and supporting livelihoods in fishing communities (Kyule et al., 2014).

Fish fillets

Fish fillets (Figure 5) are among Kenya's most prominent value-added fish products, offering a versatile and convenient option for consumers seeking high-quality protein. These products involve removing the bones from the fish and slicing the flesh into clean, ready-to-cook pieces (Ninan, 2022). The process not only enhances the usability of the fish but also increases its market value by catering to the demand for boneless, easy-to-prepare fish products. Fish fillets are particularly popular in urban areas where busy lifestyles drive the preference for quick and healthy meal options. In Kenya, fish fillets are primarily derived from species like Nile perch and tilapia, which are abundant in Lake Victoria. The production and marketing of fish fillets have provided significant economic benefits, particularly for small-scale fish processors and traders, by creating employment opportunities and boosting local economies (Ayuya et al., 2021).

Figure 5. Typical appearance of fish fillet (Courtesy of Dr. Domitila Kyule, KMFRI Sagana)

Studies have shown that the fish fillet industry in Kenya has been expanding, with innovations in processing and packaging contributing to better product quality and shelf life. Kenya is a leading exporter of fresh and frozen fish fillets in East Africa. In 2022, fish fillets and other fish meat made up 0.216% of Kenya's total exports, which was an increase from 2021's 0.182%. The main destinations for Kenya's fish fillet exports in 2022 were the Netherlands ($3.55 million), Italy ($2.1 million), Israel ($1.65 million), Romania ($1.4 million), and Spain ($1.35 million) (Trend Economy, 2024) (Figure 6).

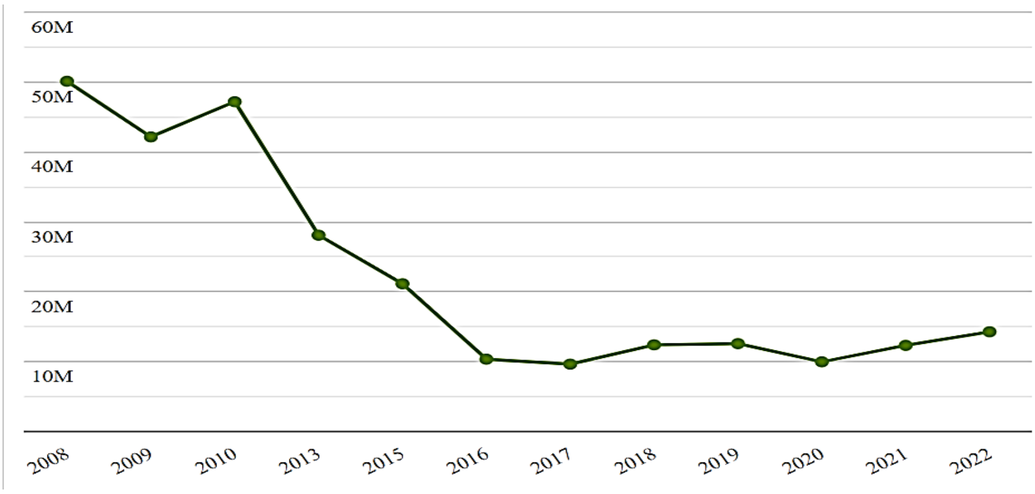

Figure 6. The value of exports of fish fillets and other fish meat (whether or not minced), fresh, chilled, or frozen from 2008 to 2022 (Trend Economy, 2024).

Fish balls

Fish balls are a popular value-added fish product in Kenya, made from minced fish fillet mixed with seasonings and binders (Kyule et al., 2016). Fish balls are shaped into small, round portions and then cooked by boiling, steaming, or frying (Figure 7). This product is particularly favored for its ease of preparation and the ability to incorporate a variety of fish species (Herdiana & Widaputri, 2022), including tilapia and Nile perch, which are abundant in Kenya's lakes and rivers. The popularity of fish balls is evident in both local markets and urban centers, where busy lifestyles drive the demand for quick and healthy meal options. Recent studies have shown that Kenyan consumers are increasingly embracing fish balls due to their taste and nutritional value, providing a significant source of protein, omega-3 fatty acids, and essential vitamins and minerals (Kyule et al., 2020). The current state of fish balls in Kenya reflects a growing industry with substantial economic potential. Small-scale processors and entrepreneurs have capitalized on the rising demand, creating employment opportunities and supporting local economies. The production of fish balls also plays a crucial role in reducing post-harvest losses by transforming less marketable fish into valuable products, thereby enhancing food security.

Figure 7. Typical appearance of fish balls (Courtesy of Dr. Mary Opiyo, KMFRI Sagana)

Smoked fish (Catfish and tilapia)

Smoked fish, particularly catfish and tilapia, is a prominent value-added product in Kenya, reflecting both traditional culinary practices and modern market demands (Kyule et al., 2014). This method of fish preservation involves curing the fish with smoke, which not only imparts a distinctive flavor but also significantly extends its shelf life by reducing moisture content and inhibiting bacterial growth (Barros et al., 2023). The process typically involves cleaning and gutting the fish, salting or marinating it, and then smoking it over low heat for several hours. This technique is especially valuable in regions with limited access to refrigeration, providing a practical solution for preserving fish and ensuring food security. Though they are one of the least preferred value added products, smoked catfish and tilapia are popular in both rural and urban markets across Kenya, catering to a wide range of consumers who appreciate the convenience and rich taste of smoked fish (Obiero et al., 2014). Small-scale fish processors and traders have benefited from adopting improved smoking technologies that enhance product quality and safety ((Kyule-Muendo et al., 2021).

Kyule et al. (2014) reported that traders in Kirinyanga and Meru counties have been specializing in deep-fried catfish for their livelihood which they claimed was a good business and they further reported an increase in profit and the number of consumers after introducing the diversified products into the market hence an increase in the number of people consuming fish

Dried tilapia

Dried tilapia, locally known as Obambo in the Lake Victoria region, is a significant value-added fish product in Kenya, particularly cherished for its long shelf life and distinctive flavor (Theuri et al., 2014). The traditional drying process involves cleaning and gutting the tilapia, followed by salting, sun-drying, or smoking to reduce moisture content and prevent spoilage. This method is especially advantageous in areas with limited access to refrigeration, allowing fish to be stored for extended periods without the risk of spoilage (Odour-Odote, 2020). Dried fish is a staple in local diets and a vital source of income for fishing communities, who can sell the fish in local and regional markets. The demand for the value added fish has remained robust due to its versatility in cooking and its ability to retain nutritional value, including high levels of protein and essential minerals (Banna et al., 2022). Innovations in drying techniques, such as solar dryers, have been introduced to improve efficiency and hygiene, resulting in a better-quality product that meets food safety standards (Ochieng et al., 2015).

Fish oil

Fish oil is a notable value-added fish product in Kenya, renowned for its extensive health benefits and economic potential. Derived primarily from species like Nile perch, fish oil is rich in omega-3 fatty acids, vitamins A and D, and essential nutrients that support cardiovascular health, brain function, and overall wellness (Mwanja & Munguti, 2010; Aloo, 2014). The extraction process typically involves using modern techniques such as wet pressing (WP), cold extraction, enzymatic extraction, and supercritical fluid extraction (SFE) (Eshari et al., 2022) to ensure the purity and quality of the oil, making it suitable for both human consumption and industrial applications. In Kenya, fish oil production has gained traction as a means to maximize the utilization of fish by-products, thereby reducing waste and enhancing the profitability of the fish processing industry (Patrick, 2021). The growing awareness of the health benefits associated with omega-3 fatty acids has spurred demand for fish oil supplements, contributing to a burgeoning market locally and internationally (Opiyo et al., 2018).

Fish burgers

Fish burgers are typically made from minced fish such as tilapia or Nile perch (Figure 8). They are mixed with various seasonings and binders before being shaped into patties and cooked (Lithi et al., 2020). These burgers offer a healthy alternative to traditional beef or chicken burgers, providing high levels of protein, omega-3 fatty acids, and essential nutrients while lowering fat and calories (Iman et al., 2024). The popularity of fish burgers is particularly evident in urban areas where busy lifestyles drive the need for quick, ready-to-eat meals that do not compromise nutritional value. Recent studies indicate that consumers appreciate fish burgers' taste and health benefits, contributing to their rising market presence (Paci et al., 2018).

Figure 8. Typical appearance of fish burgers (Courtesy of Dr. Domitila Kyule, KMFRI Sagana).

Fish soup

Fish soup is a valued and traditional value-added product that typically includes fish such as tilapia or Nile perch, combined with a variety of local vegetables, spices, and herbs to create a hearty and nutritious meal (Van Der Knaap & Maxillion, 2006). Fish soup is particularly popular in coastal and lake regions, where fresh fish is abundant. It offers a significant source of protein, omega-3 fatty acids, vitamins, and minerals, making it an essential part of the diet for many Kenyan households (Duru et al., 2009). The preparation of fish soup varies across regions, reflecting diverse culinary traditions and preferences. In recent years, there has been a notable increase in the commercialization of fish soup, with packaged and ready-to-eat versions becoming available in urban markets, catering to busy consumers seeking convenient yet healthy food options.

Nutrition-based value-added products, e.g. Fish powders for infants, "Boneless fish supplements

Small-sized fish, usually not very marketable but produced on a large scale, can be dried and crushed into powder and made available (Obiero et al., 2019). Fish powder is high in protein and contains many essential micronutrients even after four months of storage (Sroy et al., 2023). According to the 2014 Kenya Demographic and Health Survey, the national prevalence of stunting was 26%, underweight at 11%, and wasting was estimated at 4%, which leads to cognitive and physical damage. Findings show that chances of such children recovering decreased after they reached two years. In Kilifi, for example, one out of five children under five years old are underweight and stunted due to chronic nutritional deficiency (Cheruiyot et al., 2022). Stunting is being severely short for one's age. It is an irreversible consequence of poor maternal diet, poor hygiene and sanitation practices, and an inadequate diet during the first two years of a child's life. Stunting undermines children's health through increased illness. It also impacts children's educational achievement by limiting cognitive development and years of schooling and reducing lifetime earnings (Ekholuenetale et al., 2020).

Overview of the technologies and methods used for processing and fish value-addition

Smoking

Most fishermen and a few farmers apply this technique using traditional smoking kilns (Ngaruiya, 2021). The most commonly used fuel is wood, free from timber preservatives, paint, gum, or any other added substances. The fish is exposed to temperatures of 70 °C.

Improved Fish Smoking Kiln

Traditional kilns had significant limitations, such as low capacity and inefficient use of firewood, which exacerbated deforestation. Additionally, the smoke produced posed health risks, affecting the eyes and lungs of operators, and the direct heat exposure often led to burns on their fingers, making the process very labor-intensive. Users also experienced poor-quality smoked fish prone to mold due to ineffective smoking techniques. These challenges highlighted the need to develop various models of improved ovens and kilns to utilize different fish species more effectively and efficiently in order to address the shortcomings of traditional kilns and enhance performance (Obiero et al., 2019).

The enhanced smoking kiln is constructed using readily available materials (Figure 9). It features a rectangular design with an inner lining of stainless steel. This stainless-steel sheet is insulated with fiberglass and coated with an additional stainless-steel layer. The double-wall construction with insulating material helps conserve heat energy by reducing heat loss, ensuring a comfortable working environment, and improving the kiln's overall efficiency. The kiln includes four shelves with six trays made of stainless wire gauge and fine wire mesh edges to prevent dried fish from falling through. These trays can be pulled out smoothly without tilting. The fish drying capacity varies depending on the species and thickness. The kiln also has a double-wing door that opens and closes easily, enhancing air and heat circulation within the chamber and effectively removing moisture from the dried product. A chimney at the top of the kiln serves as an outlet for moisture-laden air. For smoking and drying, the kiln can use sawdust, charcoal, or firewood (Ogello et al., 2023).

Figure 9. Improved fish smoking kiln (courtesy of Dr. Domitila Kyule of KMFRI, Sagana)

Mama Karanga Box

Mama Karanga refers to female small-scale fishery actors: traditional fishmongers and processors, well-known for their characteristic fried fish sold in the street markets of coastal Kenya. Their fish is mainly used at the household level. The improved fried fish display box comes with a solar lantern that runs for six hours on a high setting and 15 hours on a low setting and can be put out in the sun to charge during the day. The box can hold 10 to 15 kg of fish and is lined with aluminium instead of the newspapers that line traditional boxes. It is also well-ventilated and easy to clean, thereby boosting food safety and hygiene.

Chilling and freezing

To increase fish's shelf life, the technology of chilling at between 7°C and 16°C and freezing at -18°C has been used (Figure 10). Freezing is the most commonly used method.

Figure 10. Fish in a freezer (courtesy of Dr. Domitila Kyule of KMFRI, Sagana)

Sun-drying is practiced in northern and coastal Kenya, where the climatic conditions are hot in nature. Others employ slow refrigeration where the fishermen and farmers store fresh fish in ice boxes with ice blocks for 2 to 3 days. Additionally, there is the combined technology for Solar-wind dryers. For instance, Vanga and Kipini at the coast employ a solar-wind dryer and most traders practice drip drying before deep frying.

Economic analysis of some of the value-added products

An economic analysis involves the determination of the prevailing economic conditions, which is essential to the survival of the business. It's a method of arriving at a decision that involves a comparison of a detailed analysis of costs and of the expected benefits. This guides the investor to determine the selling price of the products to be assured of the business making profits. Besides, the investor would be able to decide on the value-added products to concentrate on, considering the margin and demand of products by his consumers.

This analysis helps the investor to a great extent in knowing whether he is in profit or loss. Cost-benefit analysis is one of the best types of economic analysis; it uses monetary terms and tries to determine if the business is gaining or losing. It helps a user adjust ingredients to get the most profit used in formulating the recipes to prepare value-added products (Kyule-Muendo, 2017). Any benefit that arises from the effort is measured against its cost in a cost-benefit analysis. Value addition is any activity that tends to make the product increase its value such that the investor earns better profits. Apart from extending the shelf life of fish, thus preventing unwarranted losses incurred due to spoilage, there is an increase in consumption as more varieties come to the market. Table 1 below provides the costing and percentage profit summary for the fish value-added products (Kyule-Muendo, 2017).

Table 1. Costing and percentage profit for fish value-added products (adapted from Kyule-Muendo, 2017).

Production type	**Cost of production/piece (KES)**	**Selling price/ Piece (KES)**	**Profit/piece (KES)**	**% profit**
Catfish samosa	32	40	8	25
Fish finger	15	30	15	100
Fishball	28	30	2	7
Deep fried catfish	50	100	50	100
Smoked catfish	130	200	70	54
Fish burger	150	200	50	33
Fish pie	150	200	50	33
Fish sausage	18	30	12	67
Fish soup	10	20	10	100
Fish skewer	20	50	30	100

Challenges facing the fish Value-addition Subsector

Regulatory and quality control

For retailers, value addition is limited by the enforcement of standards for product handling, development, differentiation, and packaging to satisfy customer preferences. The retailer is the end point from where human consumers buy the product. While standards for food handling and safety exist, they are often not adequately enforced by stakeholders, leading to unmet consumer demands. For example, hazard analysis and critical control point (HACCP) protocols are not widely implemented for most fish species like Omena, such that not all retailers are aware of the bare minimum or maximum temperature levels, durations over which the product is to be stored, shelf life, and handling to ensure food safety and quality. In rural markets, for example, Omena is not packaged, and hygiene safety is not guaranteed. Therefore, any value addition undertaken earlier is compromised by exposure to dust and dampness to which the product is subjected (Owaga et al., 2009).

Maina (2011) analyzed the performance of the Omena market in Kisumu, Nakuru, and Nairobi and found a lack of standardization of the product for human or industrial processing. This suggests constraints to value addition when raw materials or products are not standardized. The study also found only basic value-addition activities regarding drying, storage, and sorting (removing impurities) performed mainly by small-scale processors and wholesalers, save for industrial processing of Omena. Manyala and Adoyo (2011) analyzed the demand and supply for high-quality Omena value chain in Kisumu, Nakuru, Eldoret, and Nairobi among fishermen, processors, wholesalers, retailers, and consumers through primary data collection, a survey, and stakeholder validation. The study found challenges related to the lack of enforcement of standards for grading and processing Omena for human and animal feed, as well as the lack of proven processing technology, among other challenges in the value chain.

Another example of a lack of enforcement of standards for the product concerns different packaged products in smaller and more significant weight units at supermarkets with varying tags of price (Muma, 2015). First, consumers cannot be guaranteed about the shelf life and food safety of the packaged product since the shelf life is not marked on the packets. Second, smaller units are costly, while larger packaged units are less costly. This will affect demand, yet the packaging and pricing of the different weights (packaged) are not based on market research on consumer preferences. This, therefore, affects value addition through demand (Roheim et al., 2007).

Lack of access to capital and technology

Lack of access to capital and technology in Kenya manifests in several ways, including limited modernization of processing facilities, inadequate technological advancements, and restricted financial support for small and medium-sized enterprises (SMEs) engaged in the fish value-addition sector (Mahmud et al., 2020). Access to capital is critical for the growth and sustainability of value-added fish processing. However, many SMEs in Kenya struggle to secure the necessary funding to invest in modern processing equipment and technologies. This financial constraint limits their ability to produce high-quality, value-added fish products that meet international standards (Ogello et al., 2023). The high cost of borrowing due to high interest rates, stringent collateral requirements, and limited availability of financial products tailored for the fisheries sector exacerbate this problem. Consequently, many fish processors rely on outdated and inefficient technologies, which hampers productivity and reduces the competitiveness of Kenyan fish products in both local and international markets.

Technological advancement is another critical area where the fish value-addition sector in Kenya lags behind. Advanced technologies in processing, packaging, and preservation can significantly enhance the quality and shelf-life of fish products. However, adopting such technologies is often hindered by the high initial investment costs and the lack of technical expertise (Theuri, 2015). Many fish processors in Kenya cannot access modern processing equipment such as automated filleting machines, vacuum packaging systems, and advanced refrigeration units. This technological gap affects the quality of the products and limits the range of value-added products that can be offered to the market (Theuri, 2015).

Several studies have underscored the profound impact of these challenges on Kenya's fish value-addition sector. For example, Kimani et al. (2020) revealed that financial capital is the most significant constraint hindering sector growth, as reported by fish processors during their analysis of constraints and opportunities in marine small-scale fisheries along the Kenyan coast. The same study also highlighted the critical absence of modernized equipment, noting that an efficient cold chain is essential for providing ice to fishing vessels and for storage during fish gluts. This deficiency in financial and technological resources severely limits the capacity of fish processors to enhance productivity, maintain quality, and expand market reach, thereby stifling the sector's potential for growth and development.

Lack of infrastructure

One of the foremost challenges facing the value addition of fish products in Kenya is the lack of or limited infrastructure. This constraint significantly hampers the growth and development of the fish industry, which is vital for enhancing food security, creating employment, and boosting the economy. The infrastructure necessary for the fish value chain includes adequate facilities for landing, storage, processing, and transportation. In many parts of Kenya, these facilities are either non-existent or inadequately maintained, leading to substantial post-harvest losses. For instance, a study by Njiru et al. (2008) highlighted that a high percentage of fish harvested in Lake Victoria is lost due to poor handling and inadequate preservation facilities. This loss is a direct consequence of insufficient cold storage and ice production facilities which are essential for maintaining the quality of fish from the point of capture to the market (Theuri, 2015). Moreover, the absence of efficient transportation networks further exacerbates the problem. Fish must be transported over long distances to reach processing facilities or markets, often under suboptimal conditions. This results in the deterioration of fish quality and significant economic losses for fishermen and traders. A study by Syanya et al. (2024) pointed out that the poor state of roads around Lake Victoria makes it challenging to transport fish quickly and safely, leading to delays that affect the freshness and market value of the fish.

Processing facilities are another critical aspect where infrastructural inadequacies hinder fish value addition. In Kenya, most fish processing plants are concentrated in urban areas, far from the main fishing grounds (Wamukota, 2009). This geographic disparity means fishermen have limited access to processing facilities, reducing their ability to produce value-added products such as fillets, smoked fish, and fish meal. A study by Theuri (2015) emphasized that the lack of nearby processing facilities forces many fishermen to sell their catch in raw form at lower prices, thus missing out on potential higher earnings from value-added products. Mahmud et al. (2020), in a study on the Kenyan coast, also reported the freezer/fridge/chiller is the dominant equipment owned by the fish traders; as such, the opportunities to engage in scale fish value addition are limited. This is because fish value addition requires investment in equipment and tools for cutting, frying, filleting, packaging, etc. It is therefore imperative that the fish traders invest in more equipment to upscale value addition activities.

Additionally, the lack of infrastructure constricts market access for value-added fish products. Modern market facilities with cold storage and hygienic conditions are scarce, which limits the distribution and retail of processed fish products (Alliance, 2016). This infrastructure gap not only affects domestic sales but also limits the potential for export, as international markets demand stringent quality standards that require advanced processing and storage facilities. Odoli et al. (2019) highlighted the need for investment in infrastructure to support the sustainable growth of the fish fillet industry. A study conducted by Mwirigi & Theuri (2012) regarding the challenge associated with the value addition of the seafood value chain on the northern coast of Kenya found that there are inadequate facilities to undertake value addition.

Lack of research and innovation

Research and innovation is critical in the fish value-addition sector in Kenya. Lack of research and innovation hampers the development of effective strategies to address various issues within the sector. Limited research leads to an inadequate understanding of market trends, consumer preferences, and the best practices in processing and preservation techniques, which are vital for producing competitive value-added fish products (Theuri, 2015). One of the studies highlighting this challenge is by Obiero et al. (2014), which examined consumer preferences and marketing of farmed Nile Tilapia and African Catfish in Kirinyaga and Vihiga Counties. The study underscored the need for targeted research to understand consumer behavior better and to develop marketing strategies that align with these preferences (Obiero et al., 2014). This gap in consumer-focused research indicates a broader issue of insufficient market research, which is necessary to tailor products that meet specific consumer demands and enhance market penetration.

In addition, Esilaba et al. (2017) conducted a study on urban consumers' fish preferences in Nakuru Town, revealing key determinants influencing fish selection, such as price, convenience, safety concerns, and consumer experience. The study suggests that introducing fish labeling and enhancing convenience traits like filleting could potentially increase fish consumption. However, the lack of comprehensive research on these determinants means that many processors are not fully aware of how to adjust their products to meet market demands effectively (Esilaba et al., 2017).

Further, the factors that affect value addition through packaging, storage, and transportation of the product are not controlled for because stakeholders in the fishery sub-sector have not agreed on specifications of the conditions that influence the biophysical integrity and food safety of the products under transportation. For example, the fumigation of the transport facility, the handling of the product, and the methods for stacking bags could affect the quality of the product (Ninan, 2021). The main factor behind this problem is the lack of basic and applied research knowledge in Kenya regarding food safety and sanitary requirements for transportation of fish. There are no guidelines available regarding how fish should be compacted and stacked to allow aeration of the product and avoid risks to food safety (Ninan, 2021).

Lack of policy and legal framework

The lack of a robust policy and legal system is a big challenge that hampers the development of fish value-added products in Kenya. This deficiency manifests in various ways, including inadequate regulatory support, inconsistent and conflicting policies, and insufficient enforcement of existing regulations (Akullo, 2023), all of which create an uncertain environment for stakeholders in the fish value-addition sector. One of the critical issues is the inconsistency and lack of clarity in the regulatory framework governing fish processing and value addition (Theuri, 2015). Policies related to food safety, quality standards, and export requirements are often fragmented and poorly enforced, leading to significant challenges for processors trying to comply with international standards. For instance, Henson et al. (2000) highlighted the difficulties Kenyan fish exporters face in meeting the stringent food safety requirements of the European Union. The study pointed out that the lack of comprehensive policies and effective regulatory mechanisms hampers the ability of fish processors to access lucrative international markets, thereby limiting the sector's growth potential.

There is also a barrier to value addition in terms of a lack of policy and legal framework for dried fish standards related to the export and domestic markets. There are no dried fish quality standards, for the domestic, regional, and international markets by the Kenya Bureau of Standards (KEBS) (Muma, 2015). The potential markets for dried fish products in these markets are huge. These markets are therefore lost because no value addition and trade in fish products is possible since the importation standards of overseas and regional countries cannot be met. For the domestic market, losses are incurred from costs for re-processing poor quality products and time loss (Muma, 2015).

Furthermore, the historical perception of fishing as a subsistence occupation has led to limited governmental support and resource allocation for the development of the fish value-addition sector. According to Ibuuri (2008), the Kenyan government initially overlooked the fishery resources, only recognizing their economic potential with the emergence of Nile perch for export in the early 1990s. This delayed recognition has resulted in a policy environment that does not fully support the sector's needs, contributing to the slow growth and development of fish value-added products.

Lack of knowledge and skills

The lack of knowledge in the fish value-addition sector in Kenya encompasses several aspects, including awareness of value-added fish products, preparation and cooking skills, and the benefits associated with consuming these products. This lack of knowledge affects both producers and consumers, limiting the potential for growth and development in the sector (Kyule et al., 2014; Cheserek et al., 2022). In a study conducted by Cheserek et al. (2022) in Western Kenya, it was found that more than two-thirds of fish consumers did not consume value-added fish products such as samosas, fish fingers, fish balls, and fish fillets. However, the majority of consumers expressed a keen interest in incorporating value-added fish products into their diets, including feeding their babies with them. This low consumption rate was primarily due to the unavailability of these products and a lack of knowledge about their existence and preparation methods. The study highlighted that many consumers and fish traders were unaware of how to prepare and cook these products, which significantly hindered their adoption and incorporation into daily diets. This knowledge gap also limits the market for value-added fish products, reducing the economic opportunities for fish processors and traders (Cheserek et al., 2022).

Similarly, Kyule et al. (2014) reported that more than half of their respondents in Kirinyaga and Meru Counties consumed value-added fish products for the first time during market trials. This indicates a substantial lack of prior exposure and knowledge about these products among the population. The market trials provided an opportunity for consumers to experience these products, demonstrating the potential for increased demand if awareness and knowledge are improved (Kyule et al., 2014).

Lack of market information

Most fishermen and small-scale fish processors in Kenya have limited access to international markets due to a lack of comprehensive market information (Kimani et al., 2020). This information gap means they are often unaware of prevailing market prices and lucrative market opportunities abroad. According to Mwirigi and Theuri (2012), the marketing channels available to fishermen are insufficient and poorly linked, contributing to their ignorance of market dynamics. This disconnect in the value chain results in the sale of a significant portion of seafood products in their raw forms, with minimal value addition (Mwirigi & Theuri, 2012).

A study by Cheserek et al. (2022) in Western Kenya revealed that the lack of market information severely limits the ability of fish processors to expand their businesses and reach new markets. The study highlighted that many fish consumers and processors were not aware of the potential for value-added products such as fish samosas, fish fingers, and fish balls. This lack of awareness is largely due to insufficient market research and the absence of effective communication channels to disseminate market information. Moreover, the value chain for fish products in Kenya remains significantly underdeveloped, with little emphasis on value addition at various points along the chain. The weak linkages within the value chain indicate that opportunities for adding value through processing, packaging, and branding are often missed. As a result, most fish products are sold in their raw forms, which fetch lower prices than processed products. This situation underscores the need for better market information and stronger value chain linkages to enhance the competitiveness of Kenyan fish products.

The study by Kyule et al. (2014) also pointed out that the lack of market information contributes to the low consumption of value-added fish products in regions such as Kirinyaga and Meru Counties. The market trials conducted in these areas showed that when consumers were introduced to value-added products and provided with information about their benefits and availability, there was a significant increase in demand. This finding suggests that improving access to market information can play a crucial role in boosting the adoption of value-added fish products (Kyule et al., 2014). Addressing the lack of market information requires a coordinated effort to improve data collection, market research, and the dissemination of market intelligence to all stakeholders in the fish value-addition sector. Government agencies, industry associations, and non-governmental organizations can play a pivotal role in bridging this information gap by establishing robust market information systems and conducting regular market research.

Areas for Improvement

Create awareness through training

Improving consumer skills in preparing value-added fish products and improving the market performance of all fish species — through value addition, for example — will improve not only food security but also consumers' health and nutrition status. According to Githukia et al. (2014), women mostly participated in the peripheral parts of the fish value chain, such as post-harvest processing, marketing, and trading. Therefore, their participation in small-scale fisheries and the production of value-added fish products could lead to their empowerment, with greater control over income, resulting in purchasing and consuming nutritious foods and leading to the improvement of health care for children, and thus improved nutrition outcomes.

There is a need for comprehensive educational programs and extension services that can enhance the knowledge and skills of both producers and consumers. A study by Acharjee et al. (2023) in Bangladesh found that factors such as farmer education, fish farming experience, and access to extension services positively influenced decisions around value addition, while older age had a negative effect. These findings underscore the importance of tailored extension services in developing a modern and efficient fish market system. Training programs should focus on the benefits of consuming value-added fish products, preparation and cooking techniques, and ways to incorporate these products into daily diets. Additionally, creating awareness about the availability and advantages of value-added fish products through marketing campaigns can help increase their adoption and consumption.

Despite the challenges facing the fish value-addition sector in Kenya, numerous opportunities for growth and development can be harnessed to enhance the sector's productivity, competitiveness, and sustainability. These opportunities include improving regulatory and quality control standards, increasing access to capital and technology, investing in infrastructure, enhancing research and development, strengthening policy and legal frameworks, increasing knowledge and skills, and improving market information systems.

Improving regulatory and quality control standards

Improving regulatory and quality control standards presents a significant opportunity for growth and development in Kenya's fish value-addition sector. Strengthening these standards can enhance product quality, boost consumer confidence, and open up new markets, particularly for exports (Ababouch, 2006). One key opportunity lies in enforcing the existing standards and aligning Kenya's fish processing standards with internationally accepted standards, such as the Codex Alimentarius, which are already used for imported fish. These standards can be applied to value-added fish products consumed locally, ensuring high food safety and quality. The safety standards applied by Kenya, which are the European Union (EU) standards that have been adopted in domestic settings, emphasize the importance of meeting stringent food safety requirements (Henson et al., 2000). Ensuring compliance with these standards through improved regulatory frameworks can significantly enhance the export potential of Kenyan fish products and increase their competitiveness on the global stage.

The improvement of regulatory and quality control standards has shown promise especially on the global stage. The benefits of implementing HACCP systems are well documented in other countries. For example, a study by Qatan et al. (2015) in the Sultanate of Oman reported that the top five advantages identified by stakeholders included: improved product quality and easier market access; entry into markets with stringent quality requirements; enhanced customer satisfaction; better quality control; and improved employee morale and commitment to quality. Notably, the adoption of HACCP significantly reduced product rejections in the European Union (EU) market, with only one case reported in 2009. Okpala and Korzeniowska (2023) reported that the adoption of ISO 9001:2015, a leading global standard for quality management, assures consistency in product quality improvement regardless of the field of activity and size of the company. ISO 22000, a management system standard favored by the agro-food industry, unifies standards across different food chains internationally through the issuance of certificates. By 2014, more than 30,000 ISO 22000 certificates had been issued worldwide, illustrating the standard's widespread adoption and impact. These regulatory controls have significantly improved food product quality and consumer protection/safety through the practice of quality assurance, good hygiene practices, legislative and regulatory standards, and other quality-related processes.

Affordable financing options and modern technology

Access to affordable financing enables fish farmers and processors to invest in modern technologies that enhance productivity and product quality (Allison, 2011). This financial support is critical in bridging the gap between traditional practices and modern, efficient methods that can boost the sector's overall performance. To expand financing options, tailored microfinance models, such as group lending schemes and rotating savings and credit associations (ROSCAs), can be introduced for artisanal processors and small-scale traders. Furthermore, access to finance and research and development (R&D) have a strong relationship with export performance and value addition. Operatives with greater access to finance and R&D capabilities tend to exhibit stronger export performance, as they can invest in advanced processing technologies, quality control measures, and market expansion strategies (Jaabi, 2014). These investments enable fish operatives to produce higher-value products that meet international standards, thus enhancing their competitiveness in global markets. This correlation supports the general theory that financial access and technological advancements are critical for improving export performance and value addition (Jaabi, 2014).

Rowan, (2023) also notes that modern digital technologies can inform novel fish and seafood processing, including the potential for future automation, training, and improved standardization. Thus, digitalization will support and enable our ability to make informed decisions on the use and protection of our natural resources. There is a pressing need to conduct a life-cycle assessment that is aligned with developing e-waste recycling technologies that will be met through better infrastructure, upskilled staff, and appropriate policies (Rowan, 2023). To accelerate technology adoption, public-private partnerships (PPPs) should be leveraged to co-finance digital traceability tools, cold chain logistics, and automated processing systems. Mahmud et al. (2020), in a study on factors influencing value addition on the Kenyan coast, also recommended that fish traders should increase their internal capabilities by adopting modern technologies and equipment to enhance fish value addition activities. Additionally, targeted government subsidies or tax incentives can be introduced to lower the cost of essential processing equipment, making modern technology more accessible to small and medium enterprises (SMEs).

Investment in infrastructure

One of the significant challenges faced by the fish value-addition sector in Kenya is the lack of adequate cold storage facilities. This inadequacy leads to significant post-harvest losses, impacting the sector's profitability and sustainability. By investing in modern cold storage and refrigeration facilities, fish products can be preserved for extended periods, reducing spoilage and maintaining quality from harvest to the market (Maulu et al., 2020). Cold storage hubs should be established in high-production areas and equipped with solar-powered refrigeration systems, supported through public-private partnerships (PPPs) to reduce electricity costs and ensure sustainability. This investment is crucial for ensuring fish products meet local and international quality standards, thus enhancing their marketability. Transportation infrastructure also plays a vital role in the fish value-addition chain. Efficient and reliable transportation networks are essential for timely fish movement from production sites to processing facilities and markets. Improved roads, ports, and logistics systems can reduce transportation costs and times, lowering the overall cost of fish products and making them more competitive. Moreover, better transportation infrastructure facilitates access to remote fishing areas, expanding the supply base and supporting the growth of the fish value-addition sector (Kimani et al., 2020). Upgrading feeder roads that link major landing sites with processing zones using county-level infrastructure funds would reduce transit time and spoilage, especially during peak seasons.

Processing plants are another critical component of infrastructure investment. Modern processing facilities equipped with advanced technology can enhance the value of fish products through activities such as filleting, packaging, and canning. These value-added processes improve the quality and shelf life of fish products and increase their market value. Deploying mobile modular fish processing units that are co-financed through development grants and SME credit programs can expand reach to underserved rural areas and support artisanal processors. Investments in processing infrastructure can also create job opportunities and stimulate economic development in local communities (Montgomery et al., 2022). For example, India's well-equipped fish processing units that are built to meet the quality and regulatory standards of major markets such as the EU and the USA have contributed significantly to the country's expanding seafood exports. Kenya can draw valuable lessons from such models to build a more resilient, inclusive, and competitive fish value-addition sector (Ravishankar & Elavarasan, 2024)

Moreover, developing aquaculture infrastructure, including hatcheries and feed mills, is essential for supporting the sustainable growth of the fish value-addition sector. Well-equipped hatcheries can provide high-quality fingerlings, while efficient feed mills can produce affordable and nutritious fish feed. These facilities are fundamental for increasing fish production and ensuring the availability of raw materials for value addition (Munguti et al., 2021). Establishing regional aquaculture innovation centers that integrate hatchery services, feed production, and technical extension would help build local capacity and ensure year-round production continuity.

Enhancing Research and Development (R&D)

Increasing investment in R&D can lead to significant innovations in fish processing, packaging, and marketing, ultimately boosting the sector's competitiveness both locally and internationally. Investing in R&D allows for the exploration and adoption of new technologies and methods that can improve the efficiency and quality of fish processing (Kulradathon, 2021). For instance, advanced processing techniques can increase the shelf-life of fish products, reduce post-harvest losses, and enhance product safety and quality (Mboya et al., 2023). By integrating modern packaging technologies, producers can ensure that fish products maintain their freshness and appeal during transportation and storage, thereby meeting the high standards required by export markets.

Research institutions and universities play a crucial role in this development by collaborating with industry stakeholders to conduct in-depth studies on consumer preferences, market trends, and best practices in fish value addition. Such collaborations can help identify and develop new value-added products tailored to specific market demands. For example, studies by Esilaba et al. (2017) have shown that understanding urban consumer preferences in Nakuru Town can guide the development of fish products that meet the unique tastes and expectations of different consumer segments. This consumer-centric approach can significantly enhance the marketability and acceptance of fish products, driving growth in the sector.

Moreover, R&D can help improve existing fish value-added products by optimizing production processes and introducing innovative solutions. For instance, research on better preservation methods or more efficient processing technologies can reduce costs and improve the profitability of fish value-added products. By continuously refining these processes, the industry can maintain a competitive edge in the market (Esilaba et al., 2017). The benefits of enhancing R&D are not limited to technological advancements alone. R&D can also provide valuable insights into sustainable practices that ensure the long-term viability of fish resources. Researchers can develop strategies that minimize ecological damage and promote sustainable fishery practices by studying the environmental impacts of different fishing and processing methods. This is crucial for ensuring that the fish value-addition sector can continue to thrive without depleting natural resources (Wang & Azam, 2024).

Strengthening policy and legal framework

Developing and implementing comprehensive policies and legal frameworks that support the fish value-addition sector is essential for providing a stable and conducive environment for all stakeholders. Clear and consistent regulations on food safety, quality standards, and export requirements can significantly enhance the sector's stability and attractiveness to investors (Theuri, 2015). A robust policy framework ensures that fish products meet international standards, thereby enhancing their competitiveness in global markets. For instance, the study by Njiru et al. (2021) highlights the potential of Kenya's marine fisheries for economic growth through value addition, which could be substantially realized with strong policy support (Kimani et al., 2020). Such policies would not only improve the quality of fish products but also ensure that they are safe for consumption, thereby boosting consumer confidence both locally and internationally.

Moreover, policies that promote sustainable fishing practices are crucial for the long-term viability of the fish value-addition sector (Stevens et al., 2018). Sustainable fishing practices ensure that fish populations are not depleted, thus guaranteeing a continuous supply of raw materials for value addition. This can be achieved through regulations that control fishing quotas, protect breeding grounds, and promote aquaculture as an alternative to overfishing in natural waters (Aloo et al., 2017).

Another critical component of an effective policy framework is providing incentives for value addition. These incentives can take various forms, such as tax breaks, subsidies, and grants for businesses involved in fish processing and marketing (Mwaijande & Lugendo, 2015). By reducing the financial burden on these businesses, the government can stimulate investment and innovation in the sector, leading to the development of new and improved fish products.

Improving Market Information Systems

Improving market information systems is a crucial opportunity for growth and development in Kenya's fish value-addition sector. Developing robust market information systems can bridge the gap in market knowledge and help stakeholders make informed decisions (Quagrainie et al., 2007). Government agencies, industry associations, and non-governmental organizations can collaborate to collect, analyze, and disseminate market data on prices, trends, and opportunities. This information can help fish processors identify lucrative markets, set competitive prices, and tailor their products to meet consumer needs, thereby enhancing their market reach and profitability.

A well-functioning market information system ensures that all stakeholders in the fish value-addition sector have access to timely and accurate information (Haimbala, 2019). For example, the study by Njiru et al. (2021) highlighted the importance of reliable market data in exploiting Kenya's marine fisheries for economic growth. With comprehensive data on market trends and consumer preferences, fish processors can develop strategies to meet the demands of both local and international markets, thus driving economic development in the sector.

Moreover, robust market information systems can help mitigate risks associated with market volatility. These systems enable fish processors and traders to make informed decisions that can reduce losses and enhance profitability by providing real-time updates on fish prices and market conditions. Aloo et al. (2017) discussed how improved market information can support aquaculture development in Kenya, contributing to poverty alleviation and food security by ensuring that fish products are competitively priced and widely available.

Conclusions

This review provides the first comprehensive synthesis of Kenya's fish value-added products, consolidating fragmented data on product types, processing technologies, market dynamics, and policy barriers. It offers a timely resource for policymakers, industry stakeholders, and development practitioners seeking to enhance the sector's efficiency, profitability, and contribution to national development. By illuminating both the existing bottlenecks such as weak regulatory enforcement, limited infrastructure, and inadequate access to technology and capital and the sector's underexploited opportunities, this study lays a clear foundation for evidence-based interventions. This integrated approach bridges technical, economic, and policy perspectives, offering a fresh lens to guide decision-making and stimulate investment in value-added fish enterprises. With strategic support, Kenya's fish value-added sector holds immense potential to unlock regional export markets, enhance food and nutrition security, create jobs, and uplift rural livelihoods. In the long term, strengthening this subsector will not only contribute to blue economy growth but also advance Kenya's broader sustainability and economic resilience goals.

Ethical approval

The authors declare that this review complies with research and publication ethics.

Informed consent

Not available.

Conflicts of interest

There is no conflict of interest in publishing this review.

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Mary: Writing original draft, Resources, Review, Editing.

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