

## Fermented plant juice (*Moringa oleifera*) as an alternative feed supplement in sustainable aquaculture: A review

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### **Abstract**

This review evaluates the potential of Fermented Plant Juice (FPJ) derived from Malunggay (*Moringa oleifera*) as a functional, cost-effective, and sustainable alternative feed supplement in aquaculture. The continuous growth of global aquaculture is heavily constrained by the volatile costs and supply of conventional feed ingredients, particularly fishmeal and soybean meal. While raw Malunggay leaf meal possesses an excellent nutritional profile—boasting high crude protein, balanced amino acids, and vital micronutrients—its utilization in monogastric aquatic animals is strictly limited by the presence of anti-nutritional factors (ANFs) such as tannins, phytates, and saponins. Anaerobic fermentation using molasses offers a biochemical solution by leveraging indigenous beneficial microorganisms, particularly lactic acid bacteria, to break down complex cellular matrices, hydrolyze anti-nutritional compounds, and improve nutrient bioavailability. Current empirical evidence indicates that diets fortified with optimized levels of Malunggay FPJ lead to marked enhancements in growth performance, feed conversion efficiency, and survival rates in cultured species, including Nile Tilapia (*Oreoptera niloticus*). Furthermore, the bioactive compounds within the fermented juice stimulate the non-specific immune response and improve intestinal health by optimizing gut microbiota. This review demonstrates that localized, small-scale production of Malunggay FPJ can serve as a viable organic intervention to reduce production costs, advance indigenous resource utilization, and align localized fish farming with the broader objectives of sustainable food production.

**Keywords:** *Moringa oleifera*, Fermented Plant Juice (FPJ), aquaculture feeds, feed efficiency, sustainable aquaculture

## Fermented plant juice (*Moringa oleifera*) as an alternative feed supplement in sustainable aquaculture: A review

### 1. Introduction

**The Aquaculture Feed Crisis** - Aquaculture remains one of the fastest-growing food-producing sectors globally, playing an indispensable role in securing protein availability and supporting livelihood opportunities across developing nations. However, the intensive expansion of this sector faces a severe economic bottleneck: the rising costs, volatile market pricing, and ecological unsustainable nature of traditional feed ingredients. Conventional formulations rely heavily on marine fishmeal and agricultural soybean meal as primary protein sources. Overexploitation of wild pelagic fisheries has led to a stagnation in global fishmeal production, while competing demands from land-based livestock sectors continue to drive soybean prices upward. For small-scale fish farmers and localized culture operators, feed costs routinely account for 60% to 70% of total operational expenditures, significantly dampening economic viability and limiting rural farming sustainability. According to Ahmadifar et al. (2020), these compounding operational expenditures and ecological imbalances necessitate a strategic shift toward functional plant-based feed additives and natural growth promoters to stabilize production metrics.

**Shift to Sustainable and Organic Interventions** - To safeguard the viability of aquaculture systems, modern research is undergoing a paradigm shift toward alternative, locally sourceable, and eco-friendly raw ingredients. The exploration of plant-based proteins has gained widespread traction due to their abundance and low commercial cost. However, utilizing terrestrial plant proteins directly in aquatic feeds introduces physiological challenges, as most monogastric fish species struggle to digest complex plant cells efficiently. According to Ahmadifar et al. (2020), these baseline botanical challenges demand structural processing alterations rather than raw plant dietary adjustments. Consequently, contemporary focus has transitioned beyond merely replacing ingredients toward employing functional feed additives and organic biotechnological interventions. These strategies aim not only to supply raw nutrients but also to act as natural growth promoters, stress mitigators, and gut health regulators without relying on synthetic chemicals or antibiotics (Kamble et al., 2024).

**Concept of Fermented Plant Juice (FPJ)** - A highly accessible and practical method within organic agricultural frameworks is the preparation of Fermented Plant Juice (FPJ). Rooted in traditional natural farming principles, FPJ involves the anaerobic fermentation of fast-growing, nutrient-dense plants blended with a carbon source, typically molasses or crude sugar. According to Miller et al. (2013), the underlying biological mechanism utilizes osmotic pressure to extract cellular sap from the plant tissues, creating an ideal substrate for indigenous beneficial microorganisms—most notably Lactic Acid Bacteria (LAB) and wild yeasts. During the fermentation period, these microbes proliferate, producing organic acids, enzymes, and specialized metabolites (Vargas-Sánchez et al., 2019). According to Li et al. (2024), this microbial proliferation facilitates a form of biological pre-digestion that effectively neutralizes structural plant defenses. When introduced into animal feeds, the resulting liquid serves as a potent functional supplement, rich in bioavailable nutrients and live probiotics, requiring minimal technical infrastructure to produce (Miller et al., 2013).

**Objectives of the Review** - The primary objective of this review is to systematically synthesize and evaluate the potential of using Fermented Plant Juice derived from Malunggay (*Moringa oleifera*) as an organic feed supplement in aquaculture. Specifically, this paper aims to:

- Outline the nutritional composition and anti-nutritional constraints of raw *Moringa oleifera* leaves.
- Characterize the biochemical transformations, microbial dynamics, and anti-nutrient reductions occurring during the anaerobic fermentation of Malunggay FPJ.

- Critically analyze empirical data regarding its experimental administration on fish growth performance, feed utilization indices, and physiological health status.
- Discuss the educational, socio-economic, and practical implications of integrating localized FPJ production into community-based aquaculture management

## 2. Botanical and Nutritional Profile of *Moringa oleifera*

### 2.1 The “Miracle Tree” Attributes

*Moringa oleifera*, locally recognized in the Philippines as Malunggay, is a pan-tropical, deciduous tree belonging to the monogeneric family Moringaceae. Widely referred to as the “miracle tree” or “drumstick tree,” it exhibits extraordinary resilience against prolonged drought and thrives across a diverse array of poor soil conditions with minimal agronomic management. According to Abdelkader et al. (2025), this extreme environmental resilience makes it a highly dependable resource for sustainable agricultural planning. In tropical regions, Malunggay is highly valued for its exceptional biomass productivity, displaying rapid vegetative growth that allows for frequent, systemic harvesting of its dense foliage throughout the year.

### 2.2 Proximate Composition

The nutritional architecture of Malunggay leaves renders it one of the most resource-dense botanical options available for feed formulation. On a dry matter basis, raw Malunggay leaves consistently exhibit a high crude protein content ranging between 20% and 30%, which is remarkably comparable to or exceeding several conventional legume seeds. According to Puycha et al. (2017), this elevated protein allocation provides an exceptional baseline for structural substitution in aquafeeds. Crucially, its protein fraction features a highly balanced essential amino acid profile, showcasing substantial levels of lysine, methionine, leucine, and phenylalanine, which are essential for structural muscle development in finfish species. Furthermore, according to Abdelkader et al. (2025), the lipid profile of *Moringa* seed oil and leaf matrices contains a high concentration of essential polyunsaturated fatty acids, dominated by linoleic and linolenic acids. The leaves are also packed with critical micronutrients, including vitamin A ( $\beta$ -carotene), vitamin C, vitamin E, and some robust mineral profile rich in calcium, phosphorus, iron, and magnesium, which collectively function to mitigate micro-nutritional deficiencies in intensive farming setups (Puycha et al., 2017).

### 2.3 Anti-Nutritional Factors (ANFs)

Despite its exceptional nutrient density, raw Malunggay leaves cannot be used raw at high inclusion levels in monogastric fish diets due to endogenous defense mechanisms consisting of Anti-Nutritional Factors (ANFs). According to Ahmadifar et al. (2020), raw *Moringa* tissues contain substantial concentrations of specialized anti-nutrients that can undermine fish development if not systematically deactivated. Specifically, these leaves harbor:

- **Tannins:** Polyphenolic compounds that bind to dietary proteins and digestive enzymes (such as trypsin and chymotrypsin), forming indigestible complexes that severely lower protein digestibility. According to Puycha et al. (2017), these compound clusters reduce the absolute efficiency of protein absorption in high-dose plant treatments.
- **Phytates (Phytic Acid):** Hexaphosphate compounds that chelate essential divalent minerals like zinc, iron, and calcium, preventing their absorption in the intestinal tract. According to Abdelkader et al. (2025), phytic acid concentrations in raw leaf meals present an obstacle to long-term skeletal development and systemic biological mineralization in finfish.
- **Saponins:** Glucosides capable of damaging the fragile epithelial lining of the fish gut, causing enteritis, reducing nutrient absorption surface areas, and giving feeds a bitter taste that lowers overall palatability

(Ahmadifar et al., 2020).

The production of Malunggay Fermented Plant Juice follows standardized organic protocols engineered to favor anaerobic microbial activity. Fresh, vigorously growing leaves and tender shoots of *Moringa oleifera* are harvested during the early morning hours to preserve high moisture content and ensure a robust population of epiphytic microbes. The collected biomass is roughly chopped to rupture cell walls and thoroughly blended with molasses at a standard weight-to-weight ratio, typically 1:1 or 2:1 plant material to molasses. According to Miller et al. (2013), the molasses serves a dual purpose: its high osmotic pressure dewateres the plant tissue, extracting the nutrient-rich cytoplasm, and it provides an abundant, easily accessible carbohydrate substrate to fuel initial microbial reproduction. The homogenous mixture is packed into non-toxic, sealed containers, leaving a small headspace for gas expansion, and stored in a cool, dark environment to ferment undisturbed for a period of 7 to 14 days (Miller et al., 2013).

#### 2.4 Microbial Dynamics

The microbial environment within a fermenting batch of Malunggay FPJ shifts systematically over time. Initially, various wild bacteria and fungi consume the available free sugars. However, as oxygen inside the sealed container is rapidly depleted, a strict anaerobic environment stabilizes. According to Li et al. (2024), this transition triggers the rapid multiplication of acid-tolerant, indigenous Lactic Acid Bacteria (LAB), predominantly species from the genera *Lactobacillus*, *Leuconostoc*, and *Pediococcus*, alongside specialized wild yeasts. These beneficial bacteria metabolize the simple sugars provided by the molasses and plant sap, generating lactic acid as a primary metabolic byproduct. According to Sighny and Irfandy (2024), this continuous production of lactic acid drives the pH of the solution down sharply, stabilizing it at an acidic range of 3.5 to 4.5, which acts as a powerful natural preservative that suppresses the growth of putrefactive, pathogenic, and food-spoiling microorganisms.

#### 2.5 Reduction of Anti-Nutrients

The most significant advantage of subjecting *Moringa* leaves to fermentation rather than direct drying is the massive enzymatic reduction of its anti-nutritional load. According to Li et al. (2024), the thriving lactic acid bacteria and yeasts secrete diverse extracellular enzymes, including phytases, cellulases, and tannases, which systematically break down plant defense mechanisms. Specifically:

- **Phytase enzymes** systematically cleave the ester bonds of phytic acid, converting it into lower inositol phosphates and releasing previously bound minerals like phosphorus and calcium (Li et al., 2024; Vargas-Sánchez et al., 2019).
- **Tannases and microbial pathways** break down complex polyphenols and tannins into simple, non-toxic phenolic fragments.

According to Vargas-Sánchez et al. (2019), these biochemical transformations effectively dismantle the chemical defense systems that limit raw leaf digestion, removing the primary physiological barrier to fish digestion.

#### 2.6 Enhanced Bioavailability

Beyond neutralizing anti-nutrients, the fermentation process serves as a form of external “pre-digestion” for the raw plant matter. Complex, rigid plant cell walls made of cellulose and hemicellulose are partially degraded by microbial cellulases, exposing the enclosed nutrients (Li et al., 2024). According to Sighny and Irfandy (2024), intact, high-molecular-weight plant proteins are simultaneously broken down by proteolytic enzymes into short-chain peptides, organic acids, and free amino acids. When this liquid matrix is sprayed onto or incorporated into aquaculture feeds, the fish are presented with highly soluble, easily transportable nutrients that require significantly less internal metabolic energy to digest and absorb across the intestinal epithelium (Li et al., 2024; Sighny & Irfandy, 2024).

### 3. Effects on Growth Performance and Feed Efficiency

#### 3.1 Growth Parameters

Empirical studies testing diets supplemented with Malunggay FPJ show positive outcomes regarding fundamental growth indices in various farmed aquatic species, most notably Nile Tilapia (*Oreochromis niloticus*) fingerlings. According to Rind et al. (2023), when commercial or locally formulated basal feeds are fortified with optimized doses of liquid Malunggay FPJ, experimental groups regularly outperform control groups in Mean Weight Gain (MWG) and Specific Growth Rate (SGR). According to Kamble et al. (2024), this growth acceleration is directly attributed to the combination of enhanced flavor profile from the sweet-sour aromatic properties of fermented inputs, which stimulates appetite, and the superior availability of micro-digested nutrients.

#### 3.2 Feed Utilization Efficiency

Feed efficiency metrics represent the true economic value of any alternative feed strategy. Consistently, the inclusion of Malunggay FPJ results in a notable reduction in the Feed Conversion Ratio (FCR) alongside an inflation of the Protein Efficiency Ratio (PER) (Kamble et al., 2024; Rind et al., 2023). According to Rind et al. (2023), a lower FCR indicates that fish require less total volume of feed to gain a unit of body mass, which serves as a direct indicator of improved nutrient digestion and retention. Furthermore, according to Li et al. (2024), because the amino acids in fermented Malunggay are highly bioavailable, the fish retain a higher percentage of dietary protein to build muscle tissue, minimizing the amount of unabsorbed nutrients excreted into the water as metabolic waste.

#### 3.3 Optimal Inclusion Levels

While Malunggay FPJ is highly beneficial, research highlights the critical importance of identifying strict threshold limits. Like most plant-derived additives, there is a biphasic dose-response curve. According to Rind et al. (2023), low to moderate incorporation levels, such as spraying feeds at a concentration of 1% to 5% or replacing minor fractions of ingredients, yield peak growth and feed performance. However, according to Siqhny and Irfandy (2024), if inclusion levels are raised excessively, the high concentration of organic acids may alter feed palatability, causing a drop in total voluntary feed intake. Additionally, residual fiber or minor trace compounds could potentially accelerate intestinal transit times, reducing the time available for proper nutrient absorption (Puycha et al., 2017). Therefore, maintaining strict, optimized dosage control is crucial for maximizing benefits.

### 4. Physiological Health Benefits and Immune Responses

#### 4.1 Intestinal Health and Gut Microbiota

The gastrointestinal tract of fish is a highly dynamic organ where nutrient absorption and immune defense intersect. Incorporating Malunggay FPJ into aquafeeds significantly enhances intestinal histomorphology. According to Li et al. (2024), the live probiotic lactic acid bacteria present in the liquid actively colonize the fish gut, creating a healthy microbial equilibrium that suppresses opportunistic pathogens through competitive exclusion and the production of bacteriocins. Furthermore, according to histological evaluations by Li et al. (2024), these microbial actions induce a notable increase in intestinal villi height and microvilli density, which dramatically expands the available surface area for absorbing nutrients, directly driving the observed improvements in feed efficiency.

#### 4.2 Immunostimulatory and Antioxidant Properties

*Moringa oleifera* leaves are naturally rich in secondary metabolites, including flavonoids, such as quercetin

and kaempferol, and diverse phenolic compounds (Ahmadifar et al., 2020). Fermentation preserves and often increases the extraction efficiency of these phytochemicals (Li et al., 2024; Vargas-Sánchez et al., 2019). According to Ahmadifar et al. (2020), when ingested, these compounds act as potent natural antioxidants, scavenging free radicals and reducing cellular oxidative stress within the fish. Furthermore, according to Kamble et al. (2024), these molecules stimulate non-specific immune responses, elevating key immunological markers such as lysozyme activity, respiratory burst activity, and total serum protein levels. This fortified immune system translates directly into significantly higher survival rates when experimental fish face real-world challenges from common bacterial or parasitic aquatic pathogens (Kamble et al., 2024).

#### 4.3 Stress Tolerance

Aquaculture environments subject fish to frequent stressors, including crowding, routine handling, sorting, transport, and seasonal fluctuations in critical water quality parameters, such as temperature dips or dissolved oxygen drops. Chronic stress elevates blood cortisol and glucose levels, which suppresses the immune system and halts growth. According to Rind et al. (2023), fish fed with diets supplemented with Malunggay FPJ demonstrate a more regulated physiological response, maintaining lower stress markers during standard husbandry challenges. According to Kamble et al. (2024), this improved resilience reduces mortality rates during stressful events, providing vital physiological insurance for commercial operators.

### 5. Comparative Synthesis: Raw Leaf Meal vs. Fermented Plant Juice

To provide a clear overview of how processing methods alter the performance of *Moringa oleifera* in aquaculture, the following table contrasts the functional characteristics of raw leaf meal against the fermented plant juice variant:

Aspect	Raw Moringa Leaf Meal	Fermented Malunggay Plant Juice (FPJ)
Nutrient Bioavailability	<b>Lower:</b> Nutrients are locked within rigid plant cell walls, restricting structural access for fish digestive enzymes (Li et al., 2024).	<b>Lower:</b> Nutrients are locked within rigid plant cell walls, restricting structural access for fish digestive enzymes (Li et al., 2024).
Nutrient Bioavailability	<b>High:</b> Retains full concentrations of active tannins, phytates, and saponins that inhibit digestion (Ahmadifar et al., 2020).	<b>High:</b> Retains full concentrations of active tannins, phytates, and saponins that inhibit digestion (Ahmadifar et al., 2020).
Anti-Nutritional Factors	High: Retains full concentrations of active tannins, phytates, and saponins that inhibit digestion (Ahmadifar et al., 2020).	Significantly Reduced: Microbial enzymes systematically break down and hydrolyze anti-nutritional compounds (Li et al., 2024; Vargas-Sánchez et al., 2019).
Probiotic Value	None: Contains no live beneficial microorganisms.	Extremely Rich: Formulated with active populations of beneficial Lactic Acid Bacteria (LAB) (Li et al., 2024; Miller et al., 2013).
Digestive Impact	May induce mild enteritis or gut irritation if administered at high doses over long periods (Ahmadifar et al., 2020).	Promotes gut health, increases intestinal villi height, and optimizes nutrient absorption (Li et al., 2024).
Application Method	Dried, finely milled, and mechanically extruded directly into physical pellet formulations.	Liquid extract easily sprayed onto commercial feeds as a top-dressing or introduced directly into culture water (Li et al., 2024).
Palatability	Reduced at high doses due to the bitter taste of natural saponins and raw plant compounds (Ahmadifar et al., 2020).	Enhanced by the sweet-sour aroma of fermented sugars, which acts as a natural feeding stimulant (Kamble et al., 2024).

### 6. Conclusions, implications, and future recommendations

**Conclusion** - This review demonstrates that Fermented Plant Juice derived from *Moringa oleifera* represents a highly practical, biologically superior, and sustainable technological advancement for alternative feed manufacturing in aquaculture. While raw Malunggay leaf meal is limited by anti-nutritional factors that impede fish digestion, anaerobic fermentation with molasses successfully breaks down these chemical barriers. The process converts complex nutrients into highly bioavailable forms while enriching the mixture with beneficial probiotic bacteria. Implementing Malunggay FPJ as a dietary supplement reliably improves growth rates, lowers

feed conversion ratios, optimizes gut health, and strengthens the overall immune defenses of farmed fish.

**Educational and Pedagogical Implications** - The simple production method and clear scientific principles behind Malunggay FPJ make it an excellent instructional tool for agricultural and technical-vocational institutions. Educators can seamlessly integrate FPJ production into fisheries, livelihood training, and organic farming curricula. This topic provides a hands-on opportunity for students to observe biological concepts in real life, such as anaerobic fermentation, microbial pH reduction, and organic feed formatting. Utilizing an abundant, local resource like Malunggay helps students bridge the gap between abstract biochemistry and practical, community-oriented solutions for food security and environmental responsibility.

**Practical Educational Implications** - The findings of this review extend beyond aquaculture science and carry substantial pedagogical value for institutions delivering instruction in agriculture, fisheries, biology, and entrepreneurship. The production of Malunggay Fermented Plant Juice is methodologically simple yet conceptually rich, allowing learners to engage with multiple scientific disciplines through a single, low-cost laboratory activity. Within an inquiry-based learning framework, students can formulate hypotheses about fermentation variables, such as plant-to-molasses ratio, fermentation duration, or container type; conduct comparative trials, monitor pH and aroma development over time, and interpret outcomes in light of microbial activity. Such investigations embody the constructivist principle that knowledge is most durable when built through direct, contextualized experience, while reinforcing core scientific competencies in observation, measurement, data recording, and evidence-based reasoning. Equally important, the topic naturally facilitates authentic STEM integration. Fermentation draws on biology (microbial succession, anaerobic respiration, enzymatic hydrolysis), chemistry (organic acid formation, pH dynamics, osmotic extraction), mathematics (ratio computation, specific growth rate, feed conversion analysis), and technology and engineering (container design, sanitation protocols, small-scale process scaling). Situated within agricultural curricula, FPJ production allows teachers to demonstrate that locally abundant resources such as Malunggay can be transformed into high-value functional inputs through accessible biotechnology; a powerful counter-narrative to the perception that meaningful science is confined to well-funded urban laboratories.

**Field and Industrial Application** - For small-scale fish farmers and rural aquaculture cooperatives, adopting localized Malunggay FPJ production offers an immediate pathway to lower operating costs. By producing their own functional feed additives using backyard Malunggay trees and cheap molasses, farmers can significantly reduce their reliance on expensive commercial inputs. This decentralized approach protects smallholder farms from external market shocks and supply chain disruptions, keeping operational funds within the local community and advancing sustainable, eco-friendly food production.

**Recommendations for Future Research** - To further validate and scale the use of Malunggay FPJ in aquaculture, the following research areas should be prioritized:

- **Longitudinal Studies on Water Quality:** Investigate how continuous feeding with FPJ-fortified diets impacts total ammonia nitrogen (TAN), biochemical oxygen demand (BOD), and microbial dynamics in culture water over full production cycles.
- **Economic Cost-Benefit Evaluations:** Conduct detailed financial analyses comparing the cost of large-scale FPJ production against long-term savings from reduced feed conversion ratios and lower fish mortality.
- **Advanced Molecular Microbiome Profiling:** Use high-throughput genetic sequencing to precisely map changes in the fish gut microbiome, identifying the specific lactic acid bacteria strains responsible for protecting against pathogens.
- **Shelf-Life Optimization:** Evaluate how different storage temperatures and container materials affect the long-term viability of beneficial microbes and nutrient stability in stored FPJ.

**Significance for Teachers and Practitioners** - For teachers, particularly those handling Technical-Vocational-Livelihood (TVL) tracks, agricultural high schools, and laboratory schools such as the CLSU Laboratory for Teaching and Learning, Agricultural Science and Technology School, Malunggay FPJ offers a ready-made platform for project-based and experiential instruction. The required materials (Moringa leaves, molasses, and clean containers) are inexpensive and locally accessible, removing the logistical and budgetary barriers that often constrain authentic laboratory work in resource-limited settings. Teachers can scaffold lessons that progress from straightforward preparation toward more rigorous inquiry, such as comparing the growth response of tilapia fingerlings fed with and without FPJ supplementation, thereby cultivating genuine research experiences at the secondary level. The activity likewise creates organic entry points for interdisciplinary collaboration, enabling agriculture, science, and entrepreneurship teachers to co-design integrated modules that mirror real-world problem solving.

**Significance for Students and Learners** - For students, engagement with Malunggay FPJ production cultivates both technical competencies and broader dispositions essential for twenty-first-century learners. Technically, learners gain transferable skills in microbial culture management, feed formulation, water quality monitoring, and elementary experimental design. Dispositionally, the activity nurtures environmental stewardship, appreciation for indigenous resources, and an entrepreneurial mindset that recognizes economic potential in everyday plants. For learners from rural and agricultural communities in particular, this work affirms the relevance of local knowledge systems and demonstrates that the resources within their immediate environment are both scientifically and economically meaningful. Such recognition can play a pivotal role in shaping place-based identity and sustaining motivation to pursue further study in agricultural and fisheries sciences, wherein fields confronting declining enrollment in many developing economies.

**Significance for Schools and Institutions** - At the institutional level, integrating Malunggay FPJ research and production into school programs advances several mutually reinforcing goals. First, it aligns with the Department of Education's emphasis on contextualized and indigenized curricula, supplying concrete content that reflects Philippine agricultural realities. Second, it strengthens institutional sustainability by enabling schools with aquaculture facilities, such as fishponds, hatcheries, or backyard tilapia tanks, in order to defray feed expenditures while producing organic supplements on campus. Third, the activity opens authentic avenues for community extension and service learning, allowing students and teachers to transfer FPJ production techniques to local fisherfolk, cooperatives, and parent-stakeholders, thereby deepening school-community partnerships. Finally, embedding such work positions schools as active contributors to several United Nations Sustainable Development Goals, most directly SDG 2 (Zero Hunger), SDG 4 (Quality Education), SDG 12 (Responsible Consumption and Production), and SDG 14 (Life Below Water).

**AI Declaration** - Generative AI ChatGPT was used solely for language editing and refinement of selected sections. All scholarly content, analyses, and references were authored and verified by the researcher, who assumes full responsibility for the final manuscript.

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