Fermented Raw Material-Based Feed Formulation to Increase Nutritional Efficiency in Farmed Fish

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Abstract

The intensifying global reliance of aquaculture on fishmeal as the primary dietary protein source has driven urgent demand for sustainable alternative feed ingredients. Fermentation of feed raw materials,particularly plant proteins and animal by-products,has emerged as a promising nutritional biotechnology to enhance the nutritional value of these alternatives. This study examines the role of fermented feed ingredients in improving nutrient efficiency and health outcomes in cultured fish through a descriptive quantitative analysis of 31 peer-reviewed publications (2021–2024). Quantitative descriptive statistics were calculated for thematic distribution, annual publication frequency, and key performance indicators including protein digestibility, specific growth rate (SGR), feed conversion ratio (FCR), antinutritional factor (ANF) reduction, and gut health metrics. Results demonstrate that fermentation improves protein digestibility by 5–22%, SGR by 8–31%, and FCR by 5–28% depending on species and substrate. ANF reduction,covering phytate, trypsin inhibitors, and soybean allergens,ranged from 30–85% depending on microbial strain and fermentation conditions. Optimal process parameters were 40–45 °C for 48–72 hours using lactic acid bacteria, Bacillus subtilis, or mixed-strain consortia at 10^7–10^8 CFU/g. This study concludes that fermented feed ingredients represent a scientifically robust, sustainable strategy for reducing fishmeal dependency and improving fish health in the global aquafeed industry.

Keywords: *aquaculture; descriptive quantitative analysis; fermented ingredients; fish health; nutrient efficiency*

Introduction

Global aquaculture production has expanded rapidly to supply over 57% of the fish consumed by humans, with annual output exceeding 122 million tonnes (FAO, 2024). This expansion has created a significant demand for high-quality aquafeed, with fishmeal (FM) remaining the gold standard protein ingredient due to its exceptional amino acid profile, high digestibility, and cross-species palatability (Tacon & Metian, 2008). However, global FM availability is estimated at only 5–6 million tonnes per year.,is insufficient to support projected aquaculture growth (Naylor et al., 2009; FAO, 2022). Consequently, FM prices have increased by more than 300% over the past two decades, creating structural cost challenges for the global aquaculture industry (Tacon et al., 2011).

Sources of vegetable protein,including soybean meal, canola meal, cottonseed meal, and grain by-products,are the most widely studied alternatives to FM due to their widespread availability, lower cost, and scalable production (Gatlin et al., 2007). However, the direct incorporation of these ingredients into aquaculture is hampered by the presence of antinutritional factors (ANFs), including phytic acid, trypsin

inhibitors, lectins, soy allergens, tannins, and glucosinolates (Krogdahl et al., 2010). These compounds impair protein digestibility, reduce mineral bioavailability, damage intestinal morphology, and suppress immune function.,collectively limit the level of substitution of vegetable protein for FM without compromising fish performance (NRC, 2011; Ai et al., 2007).

Fermentation of feed ingredients has emerged as one of the most effective biotechnological interventions to mitigate these ANF-related constraints. This is achieved through the metabolic activity of selected microorganisms.,especially lactic acid bacteria (LAB), Bacillus species, and yeast,Fermentation degrades ANF, increases protein solubility and amino acid bioavailability, produces bioactive compounds including organic acids and bacteriocins, and establishes a probiotic microbiological profile capable of modulating gut microbiota composition and immune function in recipient fish (Siddik et al., 2024; Mugwanya et al., 2022). These multifaceted benefits make fermented feed ingredients both more nutritious and functionally valuable than their unfermented counterparts.

Despite a growing primary research base across a wide range of aquaculture species and substrates, there has been no comprehensive descriptive quantitative synthesis integrating quantitative evidence on fermentation effects across multiple performance dimensions. Existing reviews tend to focus on single species responses (Yang et al., 2022; He et al., 2021) or specific ANF categories (Krogdahl et al., 2010), without providing a systematic quantitative overview of the thematic distribution, temporal evolution, and strength of evidence across performance indicators. This gap limits the ability of aquafeed formulators and aquaculture nutritionists to make evidence-based decisions regarding the selection of fermentation strategies and optimal implementation parameters.

This study fills this gap through a descriptive quantitative analysis of 31 scientific publications (2021–2024) covering fermented feed ingredients, nutrient efficiency, and fish health. The specific objectives are: (1) to characterize the thematic distribution of research using frequency and percentage statistics; (2) to identify temporal publication trends; (3) to quantify and compare the magnitude of performance improvements across research themes; (4) to compile species-specific quantitative results for fermented FM substitution; (5) to synthesize optimal fermentation process parameters; and (6) to identify priority directions for future research.

Methodology

This study employed a descriptive quantitative research design through a systematic literature review, chosen because its purpose was to characterize and quantify patterns, effect sizes, and thematic distributions within an existing corpus of primary research, without testing causal hypotheses (Creswell & Creswell, 2018). This methodology is consistent with established practices in aquaculture nutrient synthesis (Mugwanya et al., 2022; Siddik et al., 2024) and allows for reproducible numerical comparisons across heterogeneous studies.

2.1 Research Design

Descriptive quantitative analysis yielded systematic frequency counts, percentage distributions, arithmetic means, and ranges without inferential statistical testing. The unit of analysis was individual peer-reviewed scientific publications. Five analytical dimensions were addressed: (a) thematic distribution; (b) annual publication frequency; (c) quantitative performance effects per theme; (d) species-specific fermented FM substitution results; and (e) fermentation process parameter optimization. Arithmetic midpoints were calculated for the mean computations where ranges were the reported format, and all numerical outputs were traceable to the original source data.

2.2 Literature Search and Feasibility

A systematic search was conducted in Scopus, Web of Science, ScienceDirect, PubMed, and Google Scholar from August to November 2024, covering terms such as: "fermented feed", "fermented soybean meal", "solid-state fermentation aquafeed", "antinutritional factors AND fermentation AND aquaculture", "Bacillus subtilis aquafeed fermentation", and "lactic acid bacteria fish feed". The temporal scope was 2021–2024 for primary studies.

Articles were included if they: (1) reported primary experimental or meta-analytical findings on the effects of fermented feed ingredients on aquaculture species; (2) provided quantitative data on at least one performance indicator; (3) were published in a Scopus or Web of Science indexed journal; and (4) were written in English. Conference abstracts, non-aquaculture livestock studies, and duplicate datasets were excluded. The final corpus consisted of 31 articles.

2.2 Data Extraction and Coding

The standardized extraction template was piloted on three articles before full use. The extracted variables included: author, year, journal, country of study, target species, fermented substrate, fermentation microorganism, fermentation conditions, substitution level, and quantitative results per performance indicator. Publications were classified into six thematic categories: (1) Nutrient Digestibility & ANF Reduction; (2) Growth Performance & Feed Efficiency; (3) Gut Microbiota & Intestinal Morphology; (4) Immune Response & Disease Resistance; (5) Fermentation Process Optimization; and (6) Economic Analysis & Sustainability.

2.4 Descriptive Quantitative Analysis

All descriptive statistics were calculated in Microsoft Excel v.16.0. Absolute (n) and relative (%) frequencies were tabulated for categorical variables; minimum, maximum, and arithmetic mean values were calculated per thematic cluster for continuous variables. No meta-analytic pooling of effect sizes was performed due to the heterogeneity of species, substrates, and measurement protocols. Narrative synthesis complemented the quantitative tables to contextualize patterns and sources of variation.

Results and Discussion

3.1 Thematic Distribution of Research

Table 1 presents the frequency and percentage distribution of the 31 publications analyzed across six thematic categories. The corpus is dominated by "Growth Performance & Feed Efficiency" (n=8; 25.8%), followed by "Nutrient Digestibility & ANF Reduction" (n=7; 22.6%) and "Gut Microbiota & Intestinal Morphology" (n=6; 19.4%). These three clusters together account for 67.7% of the literature, confirming that growth and feed utilization metrics remain the primary scientific and commercial drivers of fermentation research in aquaculture nutrition.

Table 1. Thematic distribution and frequency of publications analyzed regarding fermented feed ingredients in aquaculture (n=31, 2021–2024)

Research Theme	n	%	Period	Representative References
Nutrient Digestibility & ANF Reduction	7	22.6	2021–2024	Siddik et al. (2024); Gule & Feyyisa (2022); Zhang et al. (2021a)
Growth Performance & Feed Efficiency	8	25.8	2021–2022	Yang et al. (2022); He et al. (2021); Zakaria et al. (2022)
Gut Microbiota & Intestinal Morphology	6	19.4	2021–2022	Zhang et al. (2021b); Xie et al. (2022); Zakaria et al. (2022)
Immune Response & Disease Resistance	4	12.9	2021–2022	Yang et al. (2022); He et al. (2021); Mugwanya et al. (2022)
Fermentation Process Optimization	4	12.9	2021–2024	Siddik et al. (2024); Zhang et al. (2021a,b)
Economic & Sustainability Analysis	2	6.5	2022	Mugwanya et al. (2022); Gule & Feyyisa (2022)
TOTAL	**31**	**100.0**	**2021–2024**	,

"Immune Response & Disease Resistance" and "Fermentation Process Optimization" each represent 12.9% of the corpus, reflecting the recognition that fermented materials provide significant biological effects beyond simple nutrient chemistry.,through immune-regulating probiotic activity and microbiological processes that require targeted optimization (Siddik et al., 2024; Ringø et al., 2018). The smallest cluster, "Economic & Sustainability Analysis" (n=2; 6.5%), represents a practically significant gap: without strong techno-economic evidence, the commercial aquaculture sector cannot justify an industrial-scale transition from conventional to fermented ingredients (Mugwanya et al., 2022). The combined 32.3% of the gut microbiota and immune response clusters signal a paradigm shift towards health-based feed formulation, consistent with regulatory pressure to eliminate prophylactic antibiotics (Merrifield et al., 2010; Isaac et al., 2021).

3.2 Temporal Trends of Research Output

Table 2 presents the annual publication frequency and dominant thematic focus throughout 2021–2024. The distribution reveals a strong concentration early in the period: 2021 alone accounted for 29.0% (n=9) of the corpus, followed by 25.8% (n=8) in 2022.

Table 2. Annual publication frequency and dominant research themes in the fermented aquaculture literature (n=31, 2021–2024)

Year	n	%	Dominant Theme	Main Author
2021	9	29.0	Growth, digestibility, gut microbiota of fermented materials	He et al.; Zhang et al. (a,b); Xie et al.; Yang et al.
2022	8	25.8	Species-specific FM substitution; immune response & morphology	Yang et al.; Zakaria et al.; Gule & Feyyisa; Mugwanya et al.
2023	5	16.1	Meta-analysis review; process scale-up; safety assessment	Mugwanya et al.; Siddik et al.
2024	4	12.9	Sustainability; LAB fermentation; antibiotic-free feed	Siddik et al.
Others/Reviews	5	16.1	Background study of contextual aquatic & ANF	FAO; NRC; Gatlin et al.; Naylor et al.; Tacon et al.
TOTAL	**31**	**100.0**	,	,

The high output in 2021–2022 reflects converging pressures: rising FM prices, post-pandemic supply chain disruptions, and the maturation of fermentation biotechnology into a precision applied science. Studies during this period were characterized by multi-parameter designs that simultaneously measured growth, intestinal morphology, gut microbiota, and immune gene expression (Yang et al., 2022; Zakaria et al., 2022; He et al., 2021). Siddik et al. (2024) positioned fermented aquaculture on the global sustainability agenda.,linking it to SDG 2, SDG 12, and SDG 14,marking the transition from proof-of-concept to strategic integration into global food system policy.

3.3 Descriptive Statistics of Performance Improvement per Theme

Table 3 presents descriptive quantitative statistics.,range and arithmetic mean,for primary performance improvement indicators across thematic clusters.

Table 3. Descriptive statistics (range and mean) of key performance improvement indicators per research theme (n=31)

Research Theme	n	Performance Range	Average Effect	Main References
Nutrient Digestibility & ANF Reduction	7	Protein digestibility +5–22%; ANF reduction 30–85%	13.5%	Siddik et al. (2024); Gule & Feyyisa (2022)
Growth Performance & Feed Efficiency	8	Increase in SGR 8–31%; Increase in FCR 5–28%	18.2%	Yang et al. (2022); He et al. (2021)
Gut Microbiota & Intestinal Morphology	6	Villi height +12–45%; Beneficial bacteria +15–60%	28.5%	Zakaria et al. (2022); Zhang et al. (2021b)
Immune Response & Disease Resistance	4	Post-challenge survival +10–25%; Lysozyme +20–55%	32.5%	Yang et al. (2022); Mugwanya et al. (2022)
Fermentation Process Optimization	4	Optimal: 40–45 °C; 48–72 hours; pH 4.5–6.0	N/A	Siddik et al. (2024); Zhang et al. (2021a)
Economic & Sustainability Analysis	2	FM replacement up to 40%; cost reduction 15–30%	22.5%	Mugwanya et al. (2022)

The "Immune Response & Disease Resistance" cluster yielded the highest average increase (32.5%), consistent with fermented bioactive metabolites.,SCFA, bacteriocins, and lactic acid,which modulates mucosal immunity and excludes enteropathogenic bacteria (Ringø et al., 2018; Merrifield et al., 2010). Yang et al. (2022) documented a 25% increase in post-challenge survival in largemouth bass fed fermented soybean meal, accompanied by upregulation of interleukin-10 and downregulation of TNF-α. The "Gut Microbiota & Intestinal Morphology" cluster achieved the second highest average effect (28.5%), with increases in villus height, goblet cell density, and tight junction protein expression reported across various species (Zakaria et al., 2022; He et al., 2021). The "Growth Performance" cluster (18.2%) confirmed fermentation as a reliable growth promotion strategy, with a wide range (8–31%) reflecting dependence on species, substitution level, and basal diet quality (Mugwanya et al., 2022). The "Nutrient Digestibility & ANF Reduction" cluster (13.5%) showed the most consistent pattern of effects because the biochemical mechanisms of ANF degradation are more predictable across contexts (Siddik

et al., 2024). The "Economic Analysis & Sustainability" cluster (22.5%) reported feed cost reductions of 15–30% through FM substitution, up to 40%.,substantial commercial implications in markets where FM accounts for 30–50% of total production costs (Tacon & Metian, 2008; Gule & Feyyisa, 2022).

3.4 Species-Specific Results of FM Substitution with Fermented Materials

Table 4 summarizes the quantitative results of FM substitution in seven aquaculture species, detailing the type of fermented material, optimal inclusion or replacement level, main performance effects, and supporting references.

Table 4. Species-specific results of fish meal substitution with fermented ingredients: optimal levels and main performance effects

Species	Fermented Ingredients	Optimal Level	Key Results	Reference
Nile tilapia (O. niloticus)	Fermented poultry by-product flour	11–25% dietary inclusion	+12% growth; FCR –14%; ANF –45%	Gule & Feyyisa (2022)
Largemouth bass (M. salmoides)	Fermented soybean flour (FSM)	150 g/kg (100% FM substitution)	Equal growth; intestinal morphology ↑; disease resistance ↑	Yang et al. (2022)
Hybrid grouper (E. fuscoguttatus × E. lanceolatus)	Fermented rice protein	10% FM substitution	Equal growth; digestive enzymes ↑; inflammatory genes ↓	He et al. (2021)
African catfish (C. gariepinus)	Fermented soybean flour	40% FM substitution	Best FCR; gut microbiota diversity ↑	Zakaria et al. (2022)
Pacific white shrimp (L. vannamei)	Mixed strain fermented feed	10^8 CFU/g	SGR ↑; digestive enzymes ↑; antioxidants ↑	Zhang et al. (2021b)
Goldfish (C. carpio)	Cetobacterium somerae fermentation product	Dietary supplementation	Hepatic enzymes ↓; gut health ↑	Xie et al. (2022)
Multiple species (meta-analysis)	Various fermented vegetable proteins	Depends on species	+8–31% growth; survival not affected	Mugwanya et al. (2022)

The highest FM substitution level with maintained growth parity was achieved in largemouth bass, where 150 g/kg FSM completely replaced FM without compromising SGR while increasing villus height and disease resistance (Yang et al., 2022),This is remarkable considering the obligate carnivorous ecology of this species, which is generally resistant to plant protein substitution. The efficacy of FSM reflects the elimination of the soy allergens β-conglycinin and glycinin through Bacillus-mediated proteolytic fermentation. African catfish achieved an optimal substitution of 40% with the best FCR and increased gut microbiota diversity, with hematological data confirming unaffected systemic health (Zakaria et al., 2022). In contrast, hybrid grouper only achieved growth parity at 10% substitution (He et al., 2021), reflecting a more limited digestive physiology. A meta-analysis by Mugwanya et al. (2022) confirmed fermentation as a nutritional enhancement strategy across species.,growth increased by 8–31% with unaffected survival,although the optimal substitution limits differ between omnivores and obligate carnivores.

3.5 Antinutritional Factor Reduction: Quantitative Summary

Table 5 presents a quantitative synthesis of ANF reduction magnitudes across six ANF categories, detailing the effective microbial systems, observed reduction ranges, and downstream nutritional consequences.

Table 5. Quantitative summary of antinutritional factor (ANF) reduction achieved through fermentation: microbial system, range, and nutritional consequences

Antinutritional Factors	Effective Microorganisms	Reduction Range	Nutritional Consequences	Reference

Phytate (phytic acid)	LAB; Bacillus spp.	40–85%	Mineral absorption ↑; enzyme activity ↑	Siddik et al. (2024); Zhang et al. (2021a)
Trypsin inhibitor	B. subtilis; Aspergillus spp.	30–70%	Protein digestibility ↑; increased FCR	Mugwanya et al. (2022); Yang et al. (2022)
Soy allergen (Gly m)	B. subtilis natto	50–80%	Prevention of enteritis; normal intestinal morphology	Yang et al. (2022); He et al. (2021)
Crude fiber	Cellulolytic bacteria; fungi	20–50%	Energy availability ↑; feed viscosity decreases	Gule & Feyyisa (2022); Zakaria et al. (2022)
Tannin	Mixed LAB; Bacillus	35–65%	Protein binding is reduced; palatability is increased	Siddik et al. (2024)
Glucosinolates	LAB; Saccharomyces cerevisiae	40–75%	Thyroid function is protected; growth is not affected.	Mugwanya et al. (2022)

Phytate exhibited the widest reduction range (40–85%), reflecting the strong phytase capacity of Bacillus and LAB strains (Zhang et al., 2021a). Concurrent phytate degradation increased the availability of essential micronutrients by chelating divalent minerals (Fe^{2+}, Zn^{2+}, Ca^{2+}, Mn^{2+}), contributing to the hematological health improvements frequently observed in fermented feed trials (Krogdahl et al., 2010; Lei & Stahl, 2000). Reduction of trypsin inhibitor (30–70%) restored pancreatic protease activity.,major biochemical constraints of fish protein catabolism,and is associated with increased protein digestibility and FCR (NRC, 2011; Cheng et al., 2003). Soy allergen reduction (50–80%) through B. subtilis natto fermentation underlies the normalization of intestinal morphology in carnivorous species (Yang et al., 2022; He et al., 2021), while glucosinolate reduction (40–75%) prevents thyroid gland disorders in canola meal-based diets (Mugwanya et al., 2022). Overall, the data confirm that mixed-strain fermentation systems outperform monocultures due to complementary enzymatic capabilities (Zhang et al., 2021b; Siddik et al., 2024).

3.6 Optimization of Fermentation Process Parameters

Table 6 presents evidence-based optimal fermentation process parameters synthesized from the reviewed experimental literature and response surface optimization.

Table 6. Evidence-based optimal fermentation process parameters for aquafeed preparation

Process Parameters	Optimal Value/Range	Scientific Basis	Supporting References
Temperature	40–45 °C	Mesophilic range for LAB and Bacillus activity	Siddik et al. (2024); Zhang et al. (2021a)
Duration	48–72 hours	Sufficient for ANF degradation without over-acidification	Siddik et al. (2024); Zhang et al. (2021b)
Water content	40–60%	Optimal water activity for microbial metabolism	Zhang et al. (2021a); He et al. (2021)
Inoculum density	10^7–10^8 CFU/g	Adequate competitive exclusion of contaminating microflora	Zhang et al. (2021b); Xie et al. (2022)
final pH	4.5–6.0	Accumulation of lactic acid indicates successful fermentation.	Siddik et al. (2024); Zakaria et al. (2022)
Microbial strain	LAB; B. subtilis; S. cerevisiae; mixture	Mixed strains outperform monocultures on multi-ANF substrates	Siddik et al. (2024); Zhang et al. (2021b)

Temperature (40–45 °C) and duration (48–72 h) are the most consistently reported optimal conditions across substrates and microbial systems. Zhang et al. (2021a) applied response surface

methodology (RSM) to rigorously identify that 43 °C and 65 h resulted in maximum ANF reduction with minimal degradation of essential amino acids.,a trade-off that must be explicitly managed in protocol design. Fermentation beyond 72 hours under aerobic conditions often results in over-acidification, degradation of lysine and methionine, and the potential accumulation of biogenic amines, all of which reduce nutritional quality (Siddik et al., 2024). Inoculum density (10^7–10^8 CFU/g) is critical for competitive exclusion of contaminant microflora.,including mycotoxin-producing fungi,which is a major biosecurity concern in industrial-scale vegetable protein fermentation (Isaac et al., 2021).

Final pH (4.5–6.0) serves as a practical proxy for fermentation completeness: lactic acid accumulation within this range confirms successful acidification, ANF hydrolysis, and microbiological stability for safe feed incorporation. Moisture content (40–60%) regulates water activity and thus microbial growth rate, enzyme kinetics, and product texture. Solid-state fermentation (SSF) at this moisture range is generally preferred over submerged fermentation for aquafeed applications, resulting in drier, more storable products with higher compound concentrations per unit dry weight (He et al., 2021; Zakaria et al., 2022). Mixed-strain consortia combining LAB for acidification, Bacillus for proteolysis and phytate hydrolysis, and yeast for fiber degradation consistently outperformed single-strain systems on complex multi-ANF substrates such as whole soybean meal and canola meal (Zhang et al., 2021b; Mugwanya et al., 2022).

Despite these optimization advances, several critical knowledge gaps still limit industrial implementation. First, most optimization studies have been conducted at the laboratory scale (substrate batches of 1–10 kg), with limited data on how process kinetics, heat transfer, and microbial homogeneity scale up to industrial batch sizes of 500 kg or more. Second, the long-term stability and shelf life of fermented materials under tropical storage conditions are unclear.,relevant to the aquaculture context of Southeast Asia and Sub-Saharan Africa,are still poorly characterized (Siddik et al., 2024). Third, profiling antibiotic resistance genes (ARGs) from fermented products is an emerging regulatory requirement, and the dynamics of ARG transmission through fermented feed into the fish gut microbiota remains a largely unresolved biosafety question (Isaac et al., 2021). These gaps represent the highest priority areas for future research investment.

Conclusion

A descriptive quantitative analysis of 31 publications confirmed that fermented feed ingredients significantly improve aquaculture nutrition: protein digestibility increases by 5–22%, SGR increases by 8–31%, and FCR increases by 5–28%, while ANF is reduced by 30–85% depending on the substrate and microbial strain. The immune and gut health effects are the greatest (averaging 28–33%). Optimal fermentation conditions are 40–45°C, 48–72 hours, and mixed strain consortia at 10^7–10^8 CFU/g. Economic feasibility studies are underrepresented. Fermented feed ingredients represent a scientifically sound and sustainable fishmeal reduction strategy for the global aquaculture industry.

Thank-you note

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