

REVIEW ARTICLE OPEN ACCESS

Nutritional Composition of African Catfish (*Clarias gariepinus*) in Ghana: Effects of Culture Conditions, Feed and Processing

Amy Atter¹ | Naomi Taye¹ | Crossby Osei Tutu² | Bernard Kwabena Asiedu^{2,3} | Reuben Acheampong^{2,3} | Hayford Ofori¹ | Stephen Nketia¹ | Richard Yaw Otwey¹ | Christopher Galley¹ | Frank Peget¹ | Jackline Boateng¹ | Patricia Mensah¹ | Stacy Ayitey¹ | Eric Dogbey¹ | Seth Agyakwah⁴ | Wisdom Amoa-Awua⁵

¹CSIR-Food Research Institute, Accra, Ghana | ²Department of Family and Consumer Sciences, University of Ghana, Accra, Ghana | ³Department of Nutrition and Food Science, University of Ghana, Accra, Ghana | ⁴CSIR-Water Research Institute, Achimota, Ghana | ⁵CSIR College of Science and Technology, Accra, Ghana

Correspondence: Crossby Osei Tutu (coseitutu@ug.edu.gh)

Received: 9 April 2026 | **Revised:** 20 July 2026 | **Accepted:** 23 July 2026

Keywords: African catfish | amino acids | aquaculture | chemical composition | *Clarias gariepinus* | fatty acids | Ghana | micronutrients | processing | proximate analysis

ABSTRACT

The African catfish (*Clarias gariepinus*) is central to Ghana's aquaculture sector due to its robustness, fast growth and reliable yields. Its nutritional composition, however, varies widely and is shaped by factors before and after harvest. This review was conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure a systematic and transparent synthesis of available evidence, with the PRISMA guidelines providing the structural framework for study selection, data extraction and quality assessment. This review summarizes available information on the species' chemical makeup, emphasizing Ghanaian contexts. *C. gariepinus* offers 15%–19% high-quality protein with a full essential amino acid profile and a highly variable lipid content (2.5%–15%) rich in oleic, palmitic and linoleic acids, though it contains relatively low levels of long-chain omega-3s compared with marine fish. It also supplies important minerals, such as phosphorus, iron and zinc, and vitamins A, E and B-complex, although detailed local vitamin data remain limited. These nutrients are strongly influenced by feed quality, culture conditions and processing methods. Diet shapes growth and fatty acid composition, whereas environmental conditions affect metabolism and stress responses. Traditional smoking, widely used in Ghana, can reduce heat-sensitive vitamins and promote lipid oxidation. Key gaps include the lack of Ghana-specific nutrient profiles, limited evidence on nutrient retention during local processing and the absence of standardized composition data. Maximizing the species' contribution to food security requires nutrition-sensitive strategies, improved processing and targeted research.

1 | Introduction

Fish represents a critical source of high-quality animal protein and essential micronutrients in human nutrition, offering a unique combination of highly digestible protein, long-chain

omega-3 fatty acids, vitamins and bioavailable minerals (Bakhsh et al. 2023; Pal et al. 2018). Regular consumption is associated with improved cardiovascular, cognitive and metabolic health, making it a vital component of strategies to combat malnutrition and nutrient deficiencies.

This is an open access article under the terms of the [Creative Commons Attribution](https://creativecommons.org/licenses/by/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2026 The Author(s). *Aquaculture, Fish and Fisheries* published by John Wiley & Sons Ltd.

In Ghana, fish is a dietary staple, with per capita consumption exceeding global averages (Asiedu et al. 2023). However, declining marine catches have heightened the importance of aquaculture as a sustainable means to meet this demand. Among farmed species, the African catfish (*Clarias gariepinus*) is of particular significance. Its biological advantages, including rapid growth, tolerance to suboptimal water conditions and high disease resistance, make it a resilient and productive choice for farmers (Amponsah et al. 2021; Ulzen et al., 2018). Consequently, its contribution to the national fish supply and food security is substantial and growing.

The nutritional value of catfish, like all fish, is not inherent or constant; it is fundamentally determined by its chemical composition, which includes proximate components (moisture, protein, lipid and ash), amino acid and fatty acid profiles and micronutrient content. This composition is highly dynamic, influenced by a triad of key factors: The diet provided during culture, the environmental conditions of the aquaculture system and the methods used for post-harvest processing and preservation. In Ghana, where traditional smoking is the dominant processing technique, understanding how this and other practices alter the nutrient profile is essential (Bomfeh et al. 2019; Olopade et al. 2023; Koranteng et al., 2026). A lack of such knowledge risks undermining the potential health benefits of this widely consumed food.

Although existing studies have examined aspects of the nutrient content of *C. gariepinus*, the data remain fragmented. Comprehensive, Ghana-specific datasets detailing its full vitamin and mineral profile are scarce. Furthermore, systematic analyses of how locally relevant feed ingredients and prevailing processing methods quantitatively affect nutrient retention are limited (Hasselberg et al. 2020). This gap hinders evidence-based strategies to optimize production for nutritional outcomes.

Therefore, this review aims to synthesize current scientific evidence to provide a consolidated overview of the chemical composition of the African catfish (*C. gariepinus*) with a focus on Ghana, using a structured approach guided by Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) principles. Specifically, it seeks to (1) detail its proximate, amino acid, fatty acid and micronutrient profiles; (2) analyse the primary factors of feed, aquaculture environment and processing that govern variability in this composition; (3) briefly contextualize its nutritional value through comparison with other commonly consumed fish; and (4) identify critical research gaps that must be addressed to harness this species fully for improving dietary quality and nutrition security in Ghana.

2 | Review Methodology

This review was conducted using the PRISMA framework to ensure a transparent and structured approach to evidence synthesis. The PRISMA 2020 checklist guided the reporting of this review, ensuring comprehensive coverage of all essential elements, including the rationale, objectives, eligibility criteria, search strategy, screening process, data extraction and synthesis methods.

2.1 | Search Strategy

A comprehensive literature search was conducted across multiple electronic databases, including PubMed, Scopus, Web of Science, Google Scholar and African Journals Online (AJOL). The search was performed in October 2025 and covered publications from January 2000 to October 2025. We used a combination of keywords and Boolean operators: ('African catfish' OR '*Clarias gariepinus*') AND ('nutrition composition' OR 'proximate composition' OR 'amino acid' OR 'fatty acid' OR 'mineral' OR 'vitamin' OR 'feed' OR 'diet' OR 'aquaculture environment' OR 'processing' OR 'smoking' OR 'food safety') AND ('Ghana' OR 'West Africa'). Reference lists of relevant articles were also hand-searched to identify additional studies.

2.2 | Eligibility Criteria

Studies were included if they (1) reported original data on the chemical composition (proximate, amino acid, fatty acid, mineral or vitamin content) of African catfish (*C. gariepinus*); (2) were conducted in Ghana or, when Ghana-specific data were lacking, in comparable sub-Saharan African settings; (3) examined factors influencing composition (feed, culture environment and processing methods); (4) were published in peer-reviewed journals, as books or as official reports; and (5) were written in English. We excluded conference abstracts without full data, opinion pieces, letters to editors and studies that did not provide quantitative data or that focused exclusively on non-nutritional aspects (e.g., genetics and disease without nutritional end points).

2.3 | Screening and Study Selection

The titles and abstracts of all retrieved records were independently screened against the eligibility criteria. Full texts of potentially relevant articles were then obtained and assessed independently. Disagreements were resolved by discussion or, if necessary, by consultation with a third reviewer (C.O.T.). The screening process is summarized in a PRISMA flow diagram (see Figure 1). A total of 1247 records were identified through database searching; after removal of duplicates ($n = 312$), 935 records were screened by title and abstract. Of these, 792 were excluded because they did not meet the eligibility criteria. The remaining 143 full-text articles were assessed, and 108 studies met the inclusion criteria and were included in the final synthesis. Figure 1 presents the PRISMA flow diagram documenting the systematic screening and selection process used to identify studies for this review. The diagram illustrates the number of records identified, screened, assessed for eligibility and ultimately included in the synthesis.

2.4 | Data Extraction and Synthesis

From each included study, we extracted the following: author(s), year of publication, study location, sample size, type of sample (fillet, whole fish, liver, etc.), farming system (pond, cage and tank), feed type (if reported), processing method (fresh, smoked, frozen, etc.) and quantitative data on proximate composition,

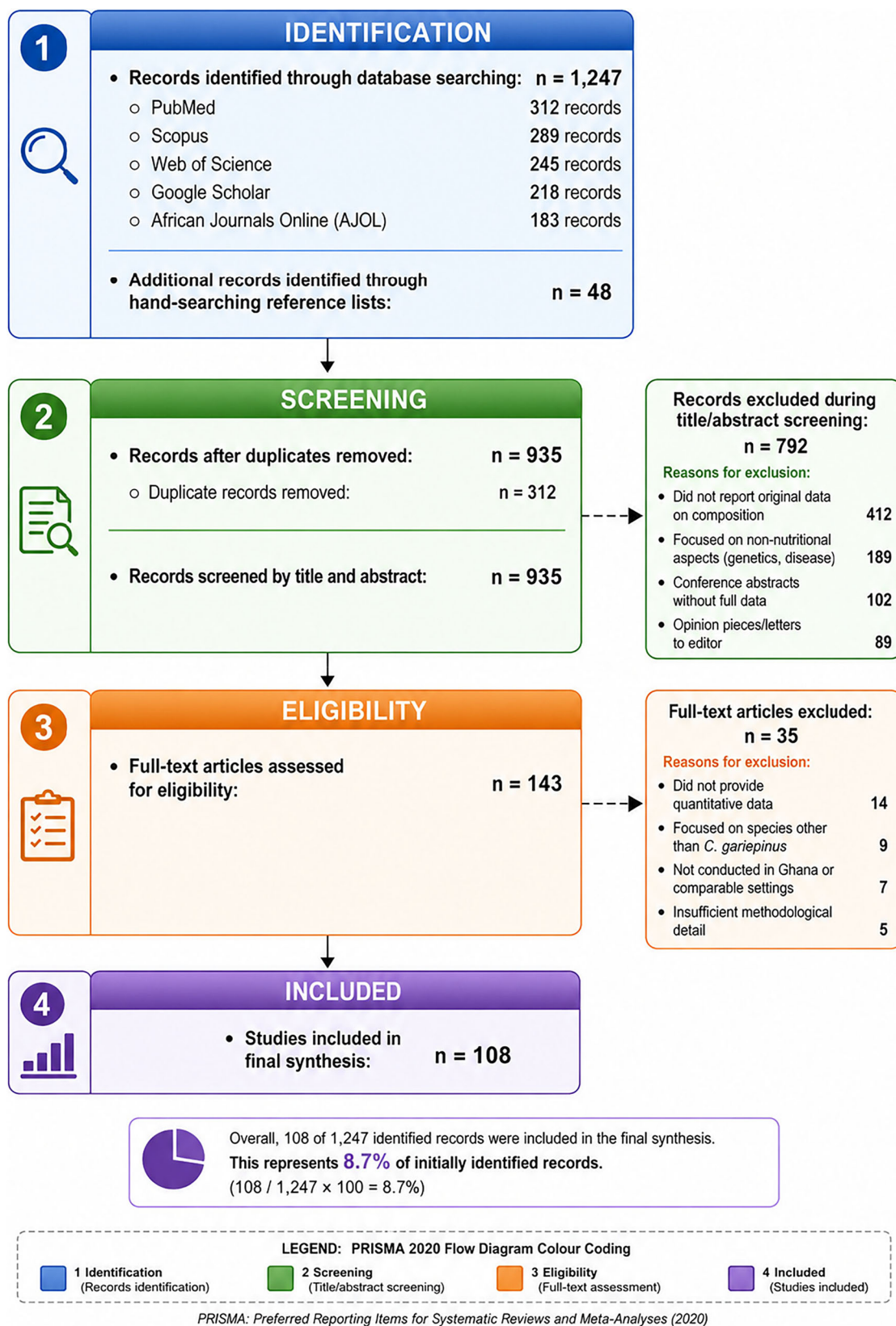


FIGURE 1 | PRISMA flow diagram of study selection process.

amino acids, fatty acids, minerals and vitamins. Data were compiled into a structured table. Because of heterogeneity in study designs, sample types and analytical methods, we performed a narrative synthesis rather than a meta-analysis. Findings are presented thematically under the main sections: proximate composition, amino acid profile, fatty acid composition, micronutrient content, influencing factors (feed, environment and processing) and food safety.

2.5 | Quality Assessment

The quality of included studies was assessed using a modified version of the Joanna Briggs Institute (JBI) checklist for analytical cross-sectional studies. Each study was independently rated on criteria, such as clear definition of the population, valid measurement of exposure and outcome and adequate statistical analysis. Studies that met at least 70% of the criteria were considered high quality; those meeting 50%–69% were moderate; and those below 50% were excluded. No study was excluded on quality grounds alone, but lower quality studies were given less weight in the synthesis. A summary of the quality assessment results is provided in Table S1.

The PRISMA guidelines were applied throughout the review process to ensure methodological rigour. Specifically, PRISMA informed (1) the development of the search strategy with clearly defined inclusion/exclusion criteria, (2) the documentation of the screening process with a flow diagram, (3) the systematic data extraction and synthesis approach and (4) the quality assessment of included studies. This structured approach enhanced the transparency and reproducibility of the review.

3 | Nutritional Value of African Catfish

3.1 | Proximate Composition

The proximate composition defines the fundamental nutritional matrix of a food item, quantifying its primary constituents: moisture, crude protein, total lipid (fat), ash (mineral content) and carbohydrates. For African catfish (*C. gariepinus*), this composition is indicative of its nutritional value but exhibits considerable variability, primarily dictated by dietary, biological and processing factors.

Moisture is the most abundant component, typically constituting between 72% and 78% of the fresh weight of catfish fillets (Akongyuure et al. 2015). This high-water content is a key contributor to the perishability of fresh fish and influences the concentration of other nutrients. Crude protein is the most significant nutritional attribute, with reported values generally ranging from 15% to 19% (Akongyuure et al. 2015; Siagian and Nugroho 2020). Extreme ranges from 10.4% to 49.2% cited in some literature (Ibhadon et al. 2015; Namaga et al. 2020) reflect analyses of different body parts (e.g., whole fish vs. fillet), sizes or methodological differences, but the consensus confirms catfish as an excellent source of high-quality protein.

The lipid content is the most variable proximate component. African catfish is often classified as a lean fish, with many studies

reporting lipid levels between 2.5% and 6.8% (Akongyuure et al. 2015; Taiwo et al. 2014). However, this is highly dependent on diet and life stage; studies employing high-energy feeds or analysing older fish report values reaching up to 15% (Abdel-Mobdy et al. 2021; Ningrum et al. 2023). This variability directly impacts the energy density and fatty acid profile of the fish. The ash content, representing the total mineral fraction, is relatively low and consistent, usually between 1.0% and 1.5% (Taiwo et al. 2014; Abdel-Mobdy et al. 2021). Carbohydrates are present in negligible amounts in fish muscle. The combined effect of these components yields a moderate energy value, approximately 110–135 kcal per 100 g serving, making it a nutrient-dense but not excessively calorific food source (Akongyuure et al. 2015; Osei Tutu et al. 2026; Mensah et al. 2026).

Conclusion for Section 3.1: The proximate composition of *C. gariepinus* positions it as a high-protein, moderately lean (but diet-dependent) food with a valuable nutrient-to-energy ratio. The observed variability underscores that its nutritional value is not a fixed property but a malleable outcome influenced by husbandry and processing. This variability, while presenting challenges for standardization, also offers opportunities for nutritional optimization through targeted interventions in feed formulation and culture management.

As shown in Table 1, the proximate composition of African catfish is distinct from that of other commonly consumed fish. Compared to Nile tilapia, catfish often has a comparable or slightly higher protein content and a generally higher, more variable lipid level, resulting in a greater energy density. This contrasts with the common perception of catfish as uniformly low-fat. When compared to fatty marine fish like mackerel and sardine, catfish typically has a lower lipid content and, consequently, a lower caloric value. However, the defining difference lies not just in the quantity but in the quality of this lipid, particularly the lower concentration of long-chain omega-3 fatty acids (eicosapentaenoic acid [EPA] and docosahexaenoic acid [DHA]), a point elaborated in Section 3.3.

3.2 | Amino Acid Profile

The nutritional value of dietary protein is fundamentally determined by its amino acid composition, particularly its content of the nine essential amino acids (EAAs) that cannot be synthesized by the human body and must be obtained from food. *C. gariepinus* provides a complete protein source, characterized by a balanced and abundant profile of all EAAs. This profile not only meets but also frequently exceeds the international reference patterns established by the Food and Agriculture Organization and World Health Organization (FAO/WHO), confirming its status as a high-quality protein with high biological value (Shadieva et al. 2020; Olopade et al. 2023). The biological value, a measure of how efficiently dietary protein can be utilized for growth and maintenance, is high for catfish protein due to this optimal amino acid balance and its excellent digestibility.

Quantitative analyses reveal a robust EAA profile. Lysine and leucine are notably abundant, with reported levels reaching up to 7.2 and 7.8 g per 100 g of protein, respectively (Shadieva et al. 2020). These amino acids are crucial for protein synthesis, tissue repair and metabolic regulation. Other EAAs, such as isoleucine,

TABLE 1 | Proximate composition of African catfish compared with tilapia and selected marine fish (per 100 g edible portion).

Species	Protein (%)	Lipid (%)	Moisture (%)	Ash (%)	Energy (kcal/100 g)	References
<i>Clarias gariepinus</i> (African catfish)	16.5–19.2	2.5–6.8	72–78	1.0–1.5	110–135	Akongyuure et al. (2015), Siagian and Nugroho (2020)
<i>Oreochromis niloticus</i> (Nile tilapia)	15.8–18.0	1.0–3.5	74–79	1.2–1.8	95–120	Akongyuure et al. (2015), Agbeko et al. (2018)
<i>Scomber</i> spp. (mackerel)	16.0–18.0	4.99–20.5	60–65	1.79–2.54	160–210	Moon et al. (2009), Olagunju et al. (2012), Shi et al. (2020)
<i>Sardinella</i> spp. (sardinella)	17.0–19.0	0.30–10.25	68–74	1.0–1.3	150–180	Muns-Pujadas et al. (2025)
<i>Thunnus albacares</i> (yellowfin tuna)	23.52–23.72	1.93–2.06	70–74	1.0–2.0	130–160	Peng and Chen (2013)

Note: Values represent ranges reported across multiple studies. Variability reflects differences in analytical methods, fish size, culture systems, feed composition and reporting basis (wet weight).

valine, threonine, phenylalanine and histidine, are present in significant quantities. Notably, sulphur-containing amino acids (methionine and cysteine), which are often limiting in plant-based proteins, are sufficiently present in catfish muscle, ensuring the protein's complementarity in mixed diets. Among non-EAAs, glutamic acid, aspartic acid and alanine dominate, contributing to the characteristic flavour (umami) and participating in various metabolic pathways. The overall amino acid index, a composite score reflecting conformity to the ideal protein standard, has been reported to reach 0.48 for catfish raised on high-protein feeds, significantly exceeding that of fish on nutrient-poor diets (Shadieva et al. 2020).

Conclusion for Section 3.2: The superior amino acid profile of *C. gariepinus* has direct and profound implications for human nutrition, especially in Ghanaian and similar contexts where protein-quality malnutrition remains a concern (Kumador et al. 2025; Mahama et al. 2025). The high levels of lysine, an amino acid typically deficient in cereal-based staple diets, make catfish an excellent dietary complement to grains like maize, effectively raising the biological value of the overall meal. The readily digestible and complete protein is particularly beneficial for populations with heightened physiological needs: It supports linear growth and cognitive development in children, and helps preserve lean muscle mass in the elderly, and aids in recovery during convalescence (Oluyemi et al. 2024). Therefore, beyond merely contributing to daily protein intake, the consumption of *C. gariepinus* ensures the provision of all necessary building blocks for protein synthesis, making it a strategic food for improving protein status and supporting the health of vulnerable demographic groups.

3.3 | Fatty Acid Composition

The lipid fraction of *C. gariepinus*, while variable in quantity, possesses a distinct fatty acid profile that determines its nutritional

character and health implications. This profile is not static but is profoundly influenced by dietary lipid sources, making it one of the most malleable aspects of the fish's composition. Broadly, the fatty acids in *C. gariepinus* are distributed across the three main classes: saturated (SFA), monounsaturated (MUFA) and polyunsaturated (PUFA) fatty acids. SFAs, primarily palmitic acid (C16:0), typically constitute a significant portion, often ranging from 30% to 40% of total fatty acids (Abdel-Mobdy et al. 2021). The MUFA fraction is dominated by oleic acid (C18:1n-9), which can represent 25%–35% of total fats, contributing to the relative stability and fluidity of the lipid depot (Effiong and Yaro 2019; Asiedu et al. 2026; Amjad et al. 2026). The PUFA component, generally comprising 20%–35%, includes both omega-6 (*n*-6) and omega-3 (*n*-3) families, with linoleic acid (LA, C18:2n-6) and alpha-linolenic acid (ALA, C18:3n-3) as the predominant representatives.

A critical nutritional distinction lies in the type of omega-3 PUFAs present. Unlike fatty marine fish (e.g., mackerel and salmon), which are rich in long-chain, highly unsaturated omega-3s, thus, EPA (C20:5n-3) and DHA (C22:6n-3), freshwater catfish typically contain very low concentrations of these specific compounds (Parzanini et al. 2020). Instead, its omega-3 content is largely in the form of the shorter-chain ALA. This compositional difference stems from the fish's diet and metabolic capacity. However, research demonstrates that this profile can be intentionally modulated. Strategic feed formulation using ingredients like fish oil, microalgae or flaxseed can significantly enhance the deposition of EPA and DHA in catfish fillets, thereby improving their nutritional value in terms of these cardioprotective and neurosupportive fatty acids (Rostika et al. 2023; Suja et al. 2012). Consequently, the fatty acid signature of farmed catfish serves as a direct biomarker of its dietary history.

Conclusion for Section 3.3: From a public health perspective in Ghana, the fatty acid composition of catfish presents a nuanced picture. Its high MUFA and overall PUFA content contribute

positively to dietary fat quality, especially when it replaces sources high in saturated fats. The presence of essential fatty acids (LA and ALA) is also beneficial. However, its relatively low EPA and DHA content means it cannot be considered a primary source of these critical long-chain omega-3s, which have well-established roles in preventing cardiovascular disease and supporting neurodevelopment (Gopal 2020). Therefore, although catfish is a valuable source of dietary lipids and essential fats, its role is complementary within a diverse diet that may also include fatty marine fish. This underlines the importance of a nutrition-sensitive approach to aquaculture, where feed formulation is guided not only by growth performance but also by the goal of optimizing the final product's fatty acid profile for human health.

3.4 | Micronutrient Composition

3.4.1 | Mineral Content

C. gariepinus serves as a significant dietary source of essential macrominerals and trace elements, contributing to the prevention of micronutrient deficiencies that are prevalent in many regions, including sub-Saharan Africa. The mineral profile is particularly notable for its richness in phosphorus and calcium, which are crucial for skeletal health, cellular function and energy metabolism. Quantitative analyses report substantial concentrations, with calcium levels reaching up to 304.82 mg/100 g and phosphorus up to 279.45 mg/100 g in edible flesh (Abdel-Mobdy et al. 2021). The bioavailability of these minerals, especially when consuming fish with bones as is common in traditional preparations, enhances their nutritional impact. Furthermore, catfish provides appreciable amounts of potassium, which is vital for maintaining fluid balance and nerve function and sodium, though at moderate levels that align with dietary recommendations for cardiovascular health (Rosa et al. 2007).

The trace mineral composition of catfish is equally nutritionally relevant. Iron content is particularly noteworthy, with studies reporting levels as high as 17.03 mg/100 g (Abdel-Mobdy et al. 2021). A substantial portion of this iron is in the haem form, which is significantly more bioavailable than the non-haem iron found in plant sources, making catfish a potent food for combating iron-deficiency anaemia. Zinc, essential for immune function, protein synthesis and wound healing, is present in meaningful quantities, typically ranging from 1.0 to 1.6 mg/100 g (Abdel-Mobdy et al. 2021). Other essential trace elements, including copper, magnesium and selenium, are also present, completing a diverse mineral portfolio. The established hierarchy of minerals in catfish flesh is generally potassium (K) > phosphorus (P) > sodium (Na) > magnesium (Mg) > calcium (Ca) > zinc (Zn) > iron (Fe) > copper (Cu) > manganese (Mn), illustrating the relative abundance of each (Rosa et al. 2007).

However, the mineral content is subject to considerable variability influenced by environmental and dietary factors. The mineral composition of the water in culture systems and the specific formulation of aquafeeds directly affect the elemental deposition in fish tissues. For instance, studies from other regions, such as Nigeria, report potassium levels as high as 427.8 mg/100 g and phosphorus at 275.4 mg/100 g, confirming the potential for variation (Taiwo et al. 2014). Although similar ranges are

expected in Ghanaian catfish, comprehensive and localized profiling remains a critical research gap. This variability underscores that the mineral density of catfish is not a guaranteed constant but an attribute that can be optimized. Compared to Nile tilapia, catfish often exhibits a higher content of phosphorus and iron but may be lower in sodium and selenium, highlighting their complementary roles in a diverse diet (Abdel-Mobdy et al. 2021). Filling the data gap with Ghana-specific mineral analyses is therefore essential for accurately assessing its contribution to national nutrient intake and for designing targeted nutritional interventions. The quantitative mineral content of *C. gariepinus* in comparison to dietary benchmarks and tilapia is presented in Table 2.

Conclusion for Section 3.4.1: The mineral composition of *C. gariepinus* demonstrates its potential as a significant contributor to dietary mineral intake in Ghana. The high levels of bioavailable iron and phosphorus are particularly valuable for addressing common nutrient deficiencies. However, the variability observed across studies and the limited Ghana-specific data highlight the need for comprehensive local mineral profiling. Such data would enable accurate assessment of catfish's contribution to national nutrient intake and inform targeted nutritional interventions.

3.4.2 | Vitamin Content

Beyond its mineral density, *C. gariepinus* contributes a range of essential vitamins to the human diet, encompassing both fat-soluble and water-soluble groups. These micronutrients play critical roles in vision, immune function, neurological health and antioxidant defence. However, comprehensive quantitative data on the vitamin profile of *C. gariepinus*, particularly from Ghanaian stocks, is notably sparse compared to information on macronutrients and minerals. Existing literature, primarily from research in other regions, provides a foundational understanding but underscores a significant knowledge gap that limits precise nutritional evaluation and dietary planning.

The fat-soluble vitamins present in catfish tissues include vitamins A, D and E. Vitamin A, primarily as retinol, is vital for vision and cellular differentiation. Analyses of farmed catfish have detected vitamin A in muscle tissue, with reported levels around 12.3 µg/100 g and notably higher concentrations in the liver, which is a traditional but less commonly consumed part (Merdzhanova et al. 2018). Vitamin D₃ (cholecalciferol), essential for calcium homeostasis and bone health, is also present, with content influenced by exposure to sunlight or fortified feeds. Vitamin E (α-tocopherol), a potent antioxidant that protects cellular lipids from oxidation, is naturally associated with the fish's own lipid reserves. Its concentration, reported at approximately 1.76 mg/100 g in muscle tissue, is directly influenced by dietary lipid sources and the overall unsaturation of the fatty acid profile (Merdzhanova et al. 2018). The presence of these vitamins enhances the nutritional value of catfish, particularly when consumed whole or with organs, though their levels are susceptible to degradation during processing.

Water-soluble vitamins, particularly the B-complex group, are equally important. Catfish provides B vitamins such as thiamine

TABLE 2 | Selected micronutrient content of *Clarias gariepinus* compared with *Oreochromis niloticus* and recommended dietary allowance (RDA) per 100 g edible portion.

Nutrient	<i>Clarias gariepinus</i>	<i>Oreochromis niloticus</i>	RDA (adults)	References
Calcium (mg)	304.82	120–180	1000	Akongyuure et al. (2015), Agbeko et al. (2018), Abdel-Mobdy et al. (2021)
Phosphorus (mg)	279.45	160–210	700	Akongyuure et al. (2015), Abdel-Mobdy et al. (2021)
Iron (mg)	17.03	0.8–1.5	8 (men); 18 (women)	Abdel-Mobdy et al. (2021)
Zinc (mg)	1.2–1.5	0.9–1.3	8 (women); 11 (men)	Abdel-Mobdy et al. (2021)
Vitamin A (µg RE)	25–130	20–35	700 (women); 900 (men)	Merdzhanova et al. (2018)
Vitamin D (µg)	2.4–4.8	3.5–6.0	15	Tirakomonpong et al. (2022)
Vitamin B ₁₂ (µg)	1.5–2.5	1.0–2.0	2.4	Akongyuure et al. (2015)

(B₁), riboflavin (B₂), niacin (B₃) and cobalamin (B₁₂). Vitamin B₁₂ is of special significance due to its role in red blood cell formation and neurological function; it is naturally abundant in animal tissues and not available from plant sources. The provision of B₁₂ through catfish consumption is therefore crucial in diets with limited animal-source foods. Vitamin C (ascorbic acid) levels are generally low, as is typical in raw muscle tissue of most animals (Shadyeva et al. 2022). A critical consideration for all vitamins, especially the water-soluble B vitamins and ascorbic acid, is their sensitivity to heat, light and oxidation. The predominant processing method in Ghana, thus, traditional smoking, can lead to significant losses of these thermolabile nutrients, thereby altering the final vitamin content of the product as consumed (Olopade et al. 2023; Abrokwa et al. 2026). Consequently, although catfish is a source of multiple vitamins, comprehensive local profiling and an understanding of processing impacts are urgently needed to accurately quantify its contribution to vitamin intake in the Ghanaian population.

Conclusion for Section 3.4.2: *C. gariepinus* provides a range of essential vitamins, particularly fat-soluble vitamins A, D and E and water-soluble B vitamins, including B₁₂. However, the limited comprehensive data from Ghanaian sources and the vulnerability of these vitamins to processing losses, especially during traditional smoking, represent significant knowledge gaps. Addressing these gaps through systematic local profiling and processing studies is essential for accurately assessing catfish's contribution to vitamin intake and for designing interventions to maximize its nutritional benefits.

4 | Factors Influencing the Chemical Composition

The chemical composition of African catfish is not intrinsic but is dynamically shaped by a series of modifiable factors spanning production and post-harvest stages as summarized in Figure 2. Figure 2 provides a conceptual framework illustrat-

ing the three principal categories of factors that influence the nutritional composition of *C. gariepinus*. The figure shows how on-farm determinants (feed formulation and farming systems) interact with post-harvest modifiers (processing and preservation methods) to shape the final consumer nutrient profile.

4.1 | Feed and Diet

Diet is the most critical and manipulable factor determining the chemical composition of farmed *C. gariepinus*. As the primary source of nutrients for growth, the formulation of aquafeeds directly and profoundly influences the deposition of protein, lipids, vitamins and minerals in the fish's edible tissues. The macronutrient ratio of the diet, thus, specifically the balance between protein, lipid and carbohydrate, serves as the foundational blueprint for body composition. High-protein feeds (often exceeding 40%–50% crude protein) are directly correlated with enhanced muscle protein synthesis, leading to higher carcass protein content, improved fillet yield and firmer flesh texture (Shadieva et al. 2020; Wedekind 1995). Concurrently, dietary lipids serve as a dense energy source. When optimized, carbohydrates can provide a protein-sparing effect, allowing dietary protein to be directed towards growth rather than energy metabolism, with studies indicating an optimal carbohydrate-to-lipid ratio near 5.29 for *Clarias fngerlings* (Otchoumou et al. 2011). The choice of lipid source, however, is of paramount importance, as it dictates not just the quantity but the specific fatty acid profile of the stored fat.

The influence of feed extends precisely to the amino acid and micronutrient profile. The amino acid composition of catfish muscle closely mirrors the pattern of amino acids provided in the diet. High-quality, balanced protein sources in feed result in a correspondingly complete and abundant EAA profile in the fish, elevating its biological value for human consumers (Shadieva et al. 2020). For instance, diets rich in lysine and methionine

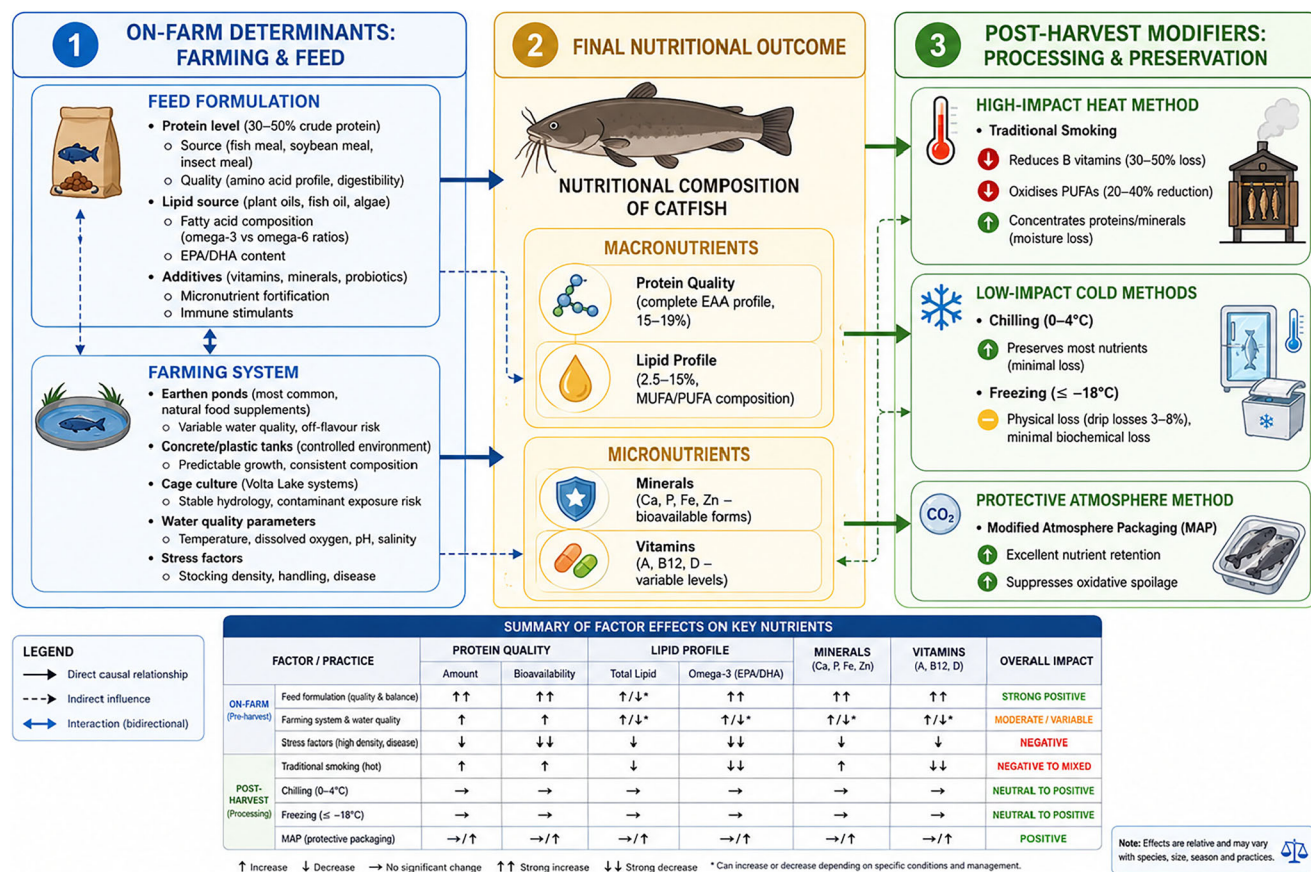


FIGURE 2 | Schematic overview of factors influencing nutritional composition of *Clarias gariepinus*. DHA, docosahexaenoic acid; EAA, essential amino acid; EPA, eicosapentaenoic acid; MUFA, monounsaturated fatty acid; PUFA, polyunsaturated fatty acid.

will enhance the levels of these often-limiting EAAs in the fillet. This presents a significant opportunity for nutrition-sensitive formulation. The exploration of locally available, sustainable feed ingredients such as soybean meal, groundnut oilcake, cassava leaf meal and insect meal (e.g., black soldier fly larvae) is a major research focus (Moazzam et al. 2026; Maranga et al. 2025). The goal is to develop cost-effective feeds that not only support efficient growth but also ensure the resulting fish product has a superior nutritional composition, thereby closing the loop between sustainable aquaculture and improved human nutrition (Adéyemi et al. 2020).

Most distinctly, dietary lipids are the principal architects of the fish's fatty acid profile. The classic adage 'you are what you eat' is literally true in aquaculture; the fatty acid deposited in catfish adipose tissue and muscle lipids largely reflects the fatty acid composition of the dietary oil source (Mukhopadhyay and Mishra 1998). Feeding plant oils like soybean or palm oil will produce fillets rich in omega-6 LA and saturated or monounsaturated fats, respectively. Conversely, incorporating marine fish oil, microalgae or flaxseed can significantly elevate the content of the nutritionally prized long-chain omega-3 fatty acids, EPA and DHA, in the final product (Rostika et al. 2023; Suja et al. 2012). However, this nutritional enhancement can involve trade-offs. Some studies note that while oils like flaxseed successfully increase omega-3 content, they may also impart different sensory characteristics or reduce the oxidative stability of the fillet compared to more conventional lipid sources (Faukner et al. 2013).

Therefore, feed formulation must strategically balance the objectives of optimizing growth performance, tailoring nutritional output for human health and maintaining desirable product quality and stability.

Conclusion for Section 4.1: Feed formulation is the most powerful and manipulable determinant of catfish nutritional composition. The choice of protein sources determines amino acid profiles, whereas lipid sources directly dictate fatty acid composition. This presents a significant opportunity for nutrition-sensitive aquaculture, where feed is designed not only for growth but also to optimize the nutritional quality of the final product for human consumers. However, balancing nutritional enhancement with product quality and stability requires careful consideration.

4.2 | Aquaculture Environment

The aquaculture environment constitutes a dynamic and powerful determinant of the chemical composition of *C. gariepinus*, acting through its influence on fish physiology, metabolism and feed utilization. Water quality parameters, including temperature, dissolved oxygen, pH and salinity, directly regulate enzymatic activity, metabolic rate and overall homeostasis. For instance, suboptimal dissolved oxygen levels induce physiological stress, diverting energy from growth and nutrient deposition towards basic maintenance and stress response, which can ultimately result in reduced protein synthesis and altered body composition

(Ajiboye and Aremu 2015; Adil et al. 2025a; Adil et al. 2025b). Similarly, water temperature affects metabolic efficiency; temperatures outside the species' optimal range can depress feed intake and conversion, leading to poorer growth and lower flesh quality (Tunde et al. 2016). These biochemical pathways underscore that the environment is not merely a backdrop for culture but an active participant in shaping the final nutritional product.

Sources of variability among studies: The broad nutrient ranges reported in Tables 1 and 2 reflect multiple sources of variation that must be considered when interpreting compositional data. Analytical methods vary considerably across studies, with differences in sample preparation (whole fish vs. fillet), moisture determination (oven-drying vs. freeze-drying) and fat extraction (Soxhlet vs. Bligh–Dyer methods) contributing to reported variability. Fish size and age also play critical roles, as larger, older fish tend to have higher lipid content and lower moisture percentages. Culture systems (ponds vs. tanks vs. cages) influence feed efficiency and environmental stress, which in turn affect protein deposition and lipid metabolism. Feed composition, particularly protein and lipid levels, is perhaps the most significant source of variation, as discussed in Section 4.1. Additionally, whether data are reported on a wet- or dry-weight basis substantially affects comparability, yet this distinction is not always clearly specified in primary studies. The limited number of Ghana-specific studies further compounds these variability issues, as many reported values are derived from studies in other countries with different production systems and environmental conditions.

The choice of culture system fundamentally structures the environmental conditions experienced by the fish and, consequently, influences nutrient composition. In Ghana, the primary systems are earthen ponds, concrete or plastic-lined tanks and cage cultures. Earthen ponds, the most common small-scale system, offer a complex environment where natural food webs can supplement formulated feeds, potentially contributing to a more diverse micronutrient intake. However, they often exhibit less stable water quality, with risks of nutrient runoff, algal blooms and the development of off-flavour compounds like geosmin, which, while not directly altering nutrition, can affect palatability (Ansah et al. 2013; Wairimu et al. 2019). Tank systems provide superior environmental control, enabling consistent water quality management. This controlled setting typically yields more predictable growth and a consistent chemical composition, as variables affecting metabolism are minimized (Hasselberg et al. 2020). Cage culture in large water bodies like the Volta Lake exposes fish to natural currents and a more stable hydrological regime, but water quality is dependent on the broader lake conditions, including potential exposure to agricultural or industrial contaminants (Karikari et al. 2022). Each system presents a distinct trade-off between environmental control, natural nutrient input and potential stressors.

Chronic exposure to suboptimal environmental conditions triggers a sustained stress response with direct compositional consequences. Elevated levels of stress hormones such as cortisol can promote catabolism, breaking down muscle protein and mobilizing lipid stores for energy, thereby negatively impacting fillet yield and lipid content (Matea and Avenant-Oldewage 2026). Furthermore, stressful environments often suppress appetite, reducing total nutrient intake. The metabolic energy that should

be allocated for the biosynthesis of proteins and the deposition of high-quality lipids is instead redirected towards overcoming osmotic imbalance, detoxification or immune function. This not only reduces growth efficiency but can also alter the biochemical priorities of nutrient utilization, potentially affecting the ratio of saturated to unsaturated fats or the retention of certain minerals. Therefore, optimal environmental management is a prerequisite for achieving the genetic and dietary potential for high-quality flesh. It ensures that the nutritional value engineered through feed formulation is fully and efficiently expressed in the harvested fish, making environmental stewardship an integral component of nutrition-sensitive aquaculture.

Critical analysis of conflicting findings: The literature on aquaculture environment effects presents some conflicting findings that warrant discussion. For example, although Ajiboye and Aremu (2015) reported significant effects of water level on growth and nutrient utilization, other studies have found minimal impacts of environmental parameters within acceptable ranges on final fillet composition (Matea and Avenant-Oldewage 2026). These discrepancies may arise from differences in experimental design, species, life stage or the specific environmental parameters studied. Some studies have reported that catfish reared in ponds have higher lipid content than those reared in tanks, whereas others have found no significant difference or even the opposite trend. Such conflicting results likely reflect the complex interactions between environment, feed and genetics and highlight the need for carefully controlled studies that isolate specific environmental variables.

4.3 | Processing and Preservation

The post-harvest phase is a critical determinant of the final nutritional quality of *C. gariepinus*, as processing and preservation methods directly and often irreversibly alter its chemical composition. These techniques aim to extend shelf life and ensure safety but achieve this through mechanisms such as heat, dehydration, oxidation and microbial inhibition that can concurrently degrade sensitive nutrients. The predominant method in Ghana, traditional smoking, along with other common practices like chilling and freezing, thus represents a final filter through which the carefully modulated composition of the farmed fish is passed before consumption.

Traditional smoking is a dual-purpose technique of drying and cooking that imparts characteristic flavour while reducing microbial load. From a nutritional standpoint, it has complex and predominantly negative effects. The application of heat leads to the significant degradation of heat-labile, water-soluble vitamins, most notably thiamine (B₁), riboflavin (B₂) and vitamin C (Olopade et al. 2023). Concurrently, the process not only drives off moisture, concentrating other nutrients like protein and minerals on a wet-weight basis, but also exposes the lipid fraction to high temperatures and smoke constituents. This promotes the oxidation of PUFAs, reducing the availability of essential fatty acids and generating potentially harmful lipid oxidation products (Bouriga et al. 2020; Tenyang et al. 2017; Ampah et al. 2026; Osei Tutu et al. 2026). Furthermore, the combustion of wood fuel can deposit carcinogenic polycyclic aromatic hydrocarbons (PAHs) on the fish surface, introducing a food safety hazard that over-

shadows nutritional content (Essumang et al. 2013). Although fat-soluble vitamins (A, D and E) may appear more stable or even concentrated due to moisture loss, the net nutritional impact of traditional smoking is a reduction in the overall vitamin profile and lipid quality.

Chilling (0–4°C) and freezing ($\leq -18^{\circ}\text{C}$) are physiochemical preservation methods that better retain the intrinsic nutritional composition of fresh catfish. By drastically slowing enzymatic activity and microbial growth, these cold-chain techniques minimize the breakdown of proteins, lipids and vitamins over days (chilling) or months (freezing) (Duarte et al. 2020; Acheampong et al. 2025). However, they are not without compositional consequences. Freezing, in particular, causes the formation of ice crystals within muscle cells. Upon thawing, this can lead to drip, which is loss of the exudate of water containing dissolved nutrients, including minerals, free amino acids and water-soluble vitamins, thereby diminishing their content in the edible portion (Sáez et al. 2015; Acheampong et al. 2025; Osei Tutu et al. 2026). Repeated freeze–thaw cycles exacerbate this physical damage and nutrient loss. Although super-chilling (just below the freezing point of tissue) has shown promise in further inhibiting biochemical spoilage while minimizing ice crystal formation, its application is limited by infrastructure (Zhu et al. 2016; Kortei et al. 2026; Nyasordzi 2025; Javed et al. 2025). Modified atmosphere packaging (MAP), which replaces air with gas mixtures like CO_2 and N_2 , extends shelf life by suppressing microbial and oxidative spoilage, thereby better preserving nutrients compared to air-packed storage during chilled distribution (Shariat et al. 2013; Zhu et al. 2016; Hauzoukim and Mohanty 2020).

Every preservation method involves a trade-off. Traditional smoking ensures accessibility and cultural preference at a cost to micronutrients and lipid health. Cold-chain methods offer superior nutrient retention but require capital-intensive infrastructure and consistent energy. The choice of processing, therefore, directly dictates which nutrients are delivered to the consumer, establishing that the optimization of chemical composition is a challenge that spans the entire continuum from feed formulation to the final prepared product. The direct effects of these prevalent preservation techniques on the nutrient profile of catfish are consolidated in Table 3 and Figure 3. Figure 3 illustrates the technological spectrum of catfish processing and preservation methods, ranging from traditional techniques to advanced technologies. The figure positions each method along axes of technological sophistication, infrastructure requirements, nutritional preservation capacity and cost, enabling readers to understand the trade-offs involved in processing decisions.

Conclusion for Section 4.3: Processing methods fundamentally alter the nutritional profile of *C. gariepinus*. Traditional smoking, while culturally preferred and economically accessible, results in significant losses of heat-sensitive vitamins and promotes lipid oxidation. Cold-chain methods better preserve nutritional quality but require infrastructure investment. The choice of processing method represents a critical trade-off between preservation effectiveness, nutritional retention and economic accessibility. Optimizing the nutritional contribution of catfish to Ghanaian diets requires promoting improved processing technologies that better preserve nutritional integrity while maintaining cultural acceptability.

5 | Comparison With Other Commonly Consumed Fish

Placing the chemical composition of *C. gariepinus* in context requires comparison with other fish that dominate Ghanaian markets, namely, Nile tilapia (*Oreochromis niloticus*) and key marine species such as mackerel (*Scomber* spp.) and sardines (*Sardinella* spp.). This comparison reveals distinct nutritional signatures and highlights the complementary roles different fish can play in a balanced diet. Relative to Nile tilapia, its primary freshwater aquaculture counterpart, catfish often exhibits a comparable or slightly higher crude protein content (16.5%–19.2% vs. 15.8%–18.0%) but demonstrates greater variability and generally higher lipid levels (2.5%–15% vs. 1.0%–3.5%), leading to a higher energy density (Akongyuure et al. 2015; Namaga et al. 2020). Mineral profiles differ meaningfully: catfish tends to be richer in phosphorus and iron, whereas tilapia may contain higher levels of sodium and selenium (Abdel-Mobdy et al. 2021). Their amino acid profiles are both complete and of high biological value, making both excellent protein sources. The most cited distinction is in fatty acid ecology; both are low in long-chain marine omega-3s, but some studies suggest tilapia may have a more favourable omega-3 to omega-6 ratio than catfish, though this is heavily dictated by their respective diets (Onwenwaori et al. 2024).

The contrast with marine fish is more pronounced, particularly regarding lipid composition. Fatty marine species, like mackerel and sardines, are nutritional powerhouses of long-chain omega-3 PUFAs, thus EPA and DHA, which are linked to cardiovascular and cognitive health (Parzanini et al. 2020). Catfish lipid, in contrast, is predominantly composed of MUFAs, like oleic acid and shorter-chain PUFAs such as linoleic (omega-6) and alpha-linolenic (omega-3) acids (Ullah et al. 2022). Consequently, while marine fish provide 5–20 times more EPA and DHA per serving, catfish offers a lipid profile that is still beneficial, being rich in MUFAs and containing essential fatty acids, albeit of a different type. Furthermore, marine fish often have higher overall ash content, reflecting a different mineral composition influenced by seawater.

Limitations of the available evidence: The comparison presented in this section is constrained by several limitations in the available evidence. First, most studies comparing catfish with other species have been conducted outside Ghana, primarily in Nigeria, Egypt and Southeast Asia, and may not reflect local production conditions. Second, the limited number of Ghana-specific studies means that many comparisons rely on data from studies with different methodologies, reporting bases and sampling protocols. Third, the lack of standardized analytical methods across studies complicates direct comparisons. Fourth, seasonal variations in fish composition are rarely captured in the available data. These limitations underscore the need for Ghana-specific, systematically designed comparative studies.

Therefore, the unique advantages of *C. gariepinus* lie not in mimicking marine fish but in providing a locally sustainable, affordable and nutrient-dense package. Its strengths are its reliable yield of high-quality, digestible protein, its significant contributions of bioavailable iron and phosphorus and its provision of a suite of B vitamins (Hasselberg et al. 2020). Although it

TABLE 3 | Preservation methods for *Clarias gariepinus* and their nutritional and sensory implications.

Preservation method	Advantages	Limitations	Nutritional impact	Sensory impact	References
Traditional smoking	Extends shelf life (weeks); imparts characteristic smoky flavour; widely accessible; low cost	Nutrient loss (heat-sensitive vitamins); risk of polycyclic aromatic hydrocarbon (PAH) contamination; inconsistent product quality; labour-intensive	Reduces vitamin A, thiamine and riboflavin; promotes oxidation of unsaturated fatty acids	Strong smoky flavour; darkened colour; firmer texture; may develop bitter taste if over-smoked	Tiwo et al. (2019), Daramola et al. (2014), Salaudeen and Osibona (2018)
Chilling (0–4°C)	Slows microbial growth; maintains freshness for several days; preserves nutrients better than smoking	Short shelf life; requires reliable electricity and an uninterrupted cold chain	Minimal nutrient losses; good retention of protein, vitamins and fatty acids	Fresh-like flavour; firm texture; natural appearance	Duarte et al. (2020), Zhu et al. (2016), Walayat et al. (2023)
Freezing ($\leq -18^{\circ}\text{C}$)	Provides long-term storage (months); maintains nutritional quality; facilitates regional and international trade	High energy requirements; inadequate cold-chain infrastructure in many regions; texture deterioration after repeated freeze–thaw cycles	Preserves protein and fatty acids; minimal nutrient losses under stable frozen storage	Fresh-like flavour; possible drip loss and softer texture after thawing	Duarte et al. (2020), Zhu et al. (2016), Walayat et al. (2023)
Modified atmosphere packaging (MAP)	Extends shelf life; maintains freshness; suppresses microbial growth; preserves sensory quality	Requires specialized packaging materials and gas mixtures; relatively expensive; dependent on refrigeration	Minimal nutrient loss; maintains fatty acid profile and vitamin content	Retains natural colour, mild flavour and fresh texture	Hauzoukim and Mohanty (2020), Velu et al. (2013), Hyun and Lee (2018)
Irradiation	Effectively inactivates pathogens; extends shelf life; can reduce reliance on refrigeration during distribution	Limited availability of irradiation facilities; high implementation cost; consumer concerns regarding irradiation	Slight thiamine losses at higher doses; proteins, lipids and other macronutrients remain largely unaffected	Minor sensory changes; occasional faint irradiation-related odour at high doses	Mohamed et al. (2023), Mshelia et al. (2023)

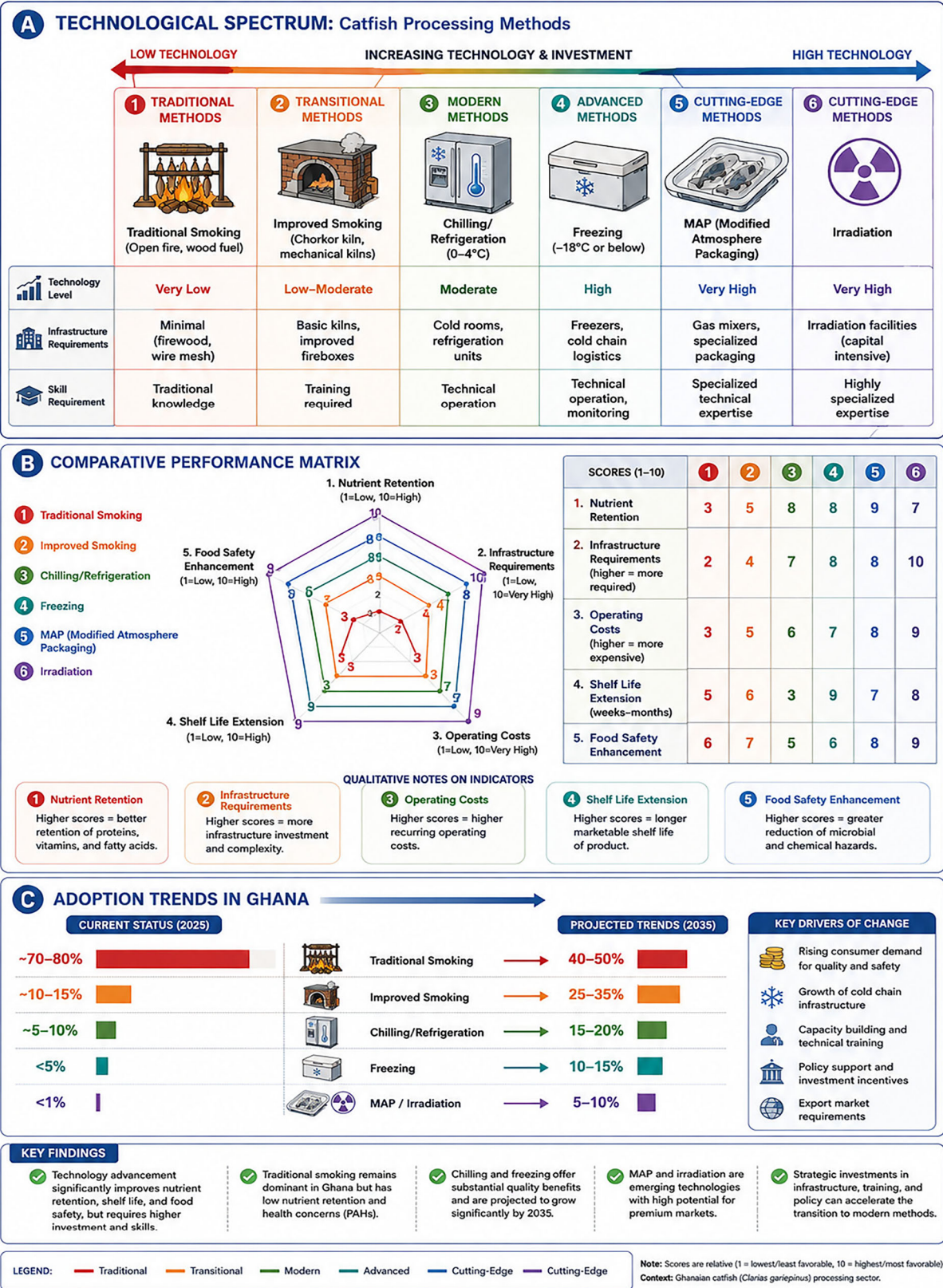


FIGURE 3 | Technological transitions in catfish processing and preservation. PAH, polycyclic aromatic hydrocarbons. (A) The technological spectrum of catfish processing methods. (B) Comparative performance matrix of the processing methods. (C) The adoption trends of the processing methods in Ghana.

should not be relied upon as a primary source of EPA and DHA, its consumption supports dietary diversity and addresses specific nutrient gaps common in Ghanaian diets, such as protein quality and iron deficiency. In a holistic dietary framework, catfish, tilapia and marine fish are not mutually exclusive but rather complementary. Marine fish supply critical long-chain omega-3s, whereas farmed freshwater catfish deliver consistent, affordable access to essential proteins and minerals, underscoring their vital role in a nutrition-secure food system.

6 | Implications for Human Nutrition in Ghana

The detailed chemical composition of *C. gariepinus* translates into direct and significant implications for addressing persistent nutritional challenges in Ghana. As a locally farmed and widely consumed animal-source food, catfish can be strategically leveraged to improve dietary quality and combat specific nutrient deficiencies prevalent among various demographic groups. Its rich profile of high-quality protein, bioavailable minerals and essential vitamins positions it as a functional food capable of contributing to multiple public health objectives, particularly for vulnerable populations, including children, pregnant and lactating women and the elderly.

The most substantial contribution lies in protein and EAA provision. The complete and digestible protein in catfish, rich in lysine and other EAAs, serves as a critical complement to Ghana's predominantly cereal-based staples. Regular consumption can help ameliorate protein-energy malnutrition and support healthy linear growth in children, whose requirements for amino acids like lysine for tissue synthesis are particularly high (Oluyemi et al. 2024; Khan et al. 2025; Javeria et al. 2026; Ozmen et al. 2025). For pregnant women, this high-quality protein supports foetal development, while for the elderly, it aids in the preservation of lean muscle mass, combating sarcopenia. Furthermore, the mineral density of catfish addresses key micronutrient gaps. Its haem iron content is especially valuable for preventing and treating iron-deficiency anaemia, a condition with high prevalence among women of reproductive age in Ghana (Wegmüller et al. 2020). The substantial phosphorus and calcium content support bone health and adequate zinc intake from catfish consumption bolsters immune function and wound healing, contributing to overall resilience against disease (Hasselberg et al. 2020).

Critical analysis of implications: Although the nutritional benefits of catfish are substantial, several factors moderate its potential impact on public health in Ghana. The significant nutrient losses during traditional smoking mean that the nutritional value of catfish as actually consumed may be considerably lower than that of fresh fish. This is particularly relevant for heat-sensitive vitamins and omega-3 fatty acids. Additionally, the low EPA/DHA content of catfish means that it cannot replace marine fish in the diet for these critical nutrients. The variability in composition across production systems and feed types also means that the nutritional benefits are not uniformly distributed; consumers may receive widely different nutritional value depending on the source of their fish. Finally, food safety concerns, particularly PAH contamination from traditional smoking, may pose health risks that offset some nutritional benefits. These considerations

highlight the need for integrated approaches that address both nutritional enhancement and food safety.

However, a nutritionally informed perspective requires acknowledging both strengths and limitations. Although catfish provides beneficial monounsaturated and polyunsaturated fats, its low content of the long-chain omega-3 fatty acids EPA and DHA means it cannot singularly fulfil recommendations for these cardioprotective and neurodevelopmental nutrients. Therefore, its role is optimally realized within a diversified diet that also includes marine fish or other sources of EPA and DHA. Additionally, the substantial nutrient losses incurred during traditional smoking, particularly of heat-sensitive B vitamins, must be recognized as a mitigating factor that reduces the potential nutritional yield (Olopade et al. 2023). This underscores the necessity of pairing production with improved post-harvest handling. Ultimately, enhancing the role of catfish in Ghanaian nutrition demands an integrated, nutrition-sensitive approach across the value chain; thus, from formulating feeds to optimize nutrient deposition to adopting processing methods that better preserve nutritional integrity, ensuring that this viable and sustainable food resource delivers its full potential to support national health and food security goals.

7 | Food Safety and Quality Assurance

Note on integration of this section: Although this food safety section is detailed, it is directly relevant to the nutritional quality of catfish because microbial contamination can lead to spoilage that degrades nutrient content and chemical contaminants can pose health risks that offset nutritional benefits. The section has been structured to highlight these connections, particularly how traditional smoking methods, while used for preservation, introduce PAH contaminants that affect both safety and nutritional quality through lipid oxidation and vitamin degradation.

7.1 | Microbial Hazards in Catfish Value Chains

Microbial hazards remain one of the most significant challenges affecting the safety and quality of *C. gariepinus* in Ghana. Contamination can occur at multiple points along the value chain, from production to processing, transport and retail. The main sources of microbial risk are poor water quality in ponds, inadequate hygiene during handling and unsanitary conditions in processing and marketing environments. Aboagye et al. (2020) found that fish value chains have insufficient food safety practices, with stakeholders scoring poorly in handling (mean scores of 41.2%–63.0%). Amoah et al. (2024) specifically identified that 23% of smoked catfish samples were contaminated, with *Escherichia coli* present in 35.2% of those samples. Yeboah et al. (2019) further confirmed higher pathogen levels in fish from wastewater-fed ponds, particularly in fish gut and skin. The evidence suggests systemic contamination risks across production, processing and marketing environments, highlighting the need for improved hygiene and monitoring practices.

At the production stage, ponds and cages are often located in water bodies that receive agricultural runoff, untreated wastewater or effluents from nearby communities. Such conditions

increase the likelihood of contamination with *E. coli*, *Salmonella* spp. and *Aeromonas* spp., which are frequently reported in aquaculture systems in West Africa (Aboagye et al. 2020). Uchechukwu and Okoli (2019) found diverse microbial communities in earthen ponds, including *Klebsiella pneumoniae*, *Salmonella enteritidis* and *E. coli*. Yeboah et al. (2019) specifically noted that wastewater-fed ponds exceeded permissible *E. coli* limits by 2–3 log units. Atawodi et al. (2025) further identified pathogens like *Staphylococcus aureus*, *E. coli*, *Salmonella typhi* and *K. pneumoniae* in both water and fish samples. These findings consistently demonstrate that improper water management in aquaculture can lead to significant microbial contamination, posing serious health risks, especially when fish are consumed raw or undercooked.

Processing practices further contribute to microbial contamination. Traditional smoking, although effective in reducing microbial load, often involves the use of unclean facilities and cross-contamination from handling and storage in unhygienic environments. Empirical evidence demonstrates that smoked catfish can harbour dangerous pathogens like *Vibrio cholerae*, *S. aureus*, *E. coli* and *S. typhi* (Daramola et al. 2014). Traditional smoking techniques, while reducing initial microbial loads, do not eliminate contamination risks (Salaudeen and Osibona 2018). Ambient temperature storage accelerates bacterial and fungal proliferation, with studies showing microbial populations can increase dramatically within days (Nguyen et al. 2018). Fungi like *Penicillium* and *Aspergillus* species were consistently identified in smoked catfish by Onyia et al. (2011). Proper sanitation, controlled temperature and improved processing practices are critically recommended to mitigate these microbial hazards.

Transport and retail stages also present risks. Fish transported in unrefrigerated vehicles or displayed in open-air markets are exposed to fluctuating temperatures, dust and vectors, such as flies. These conditions accelerate microbial growth and further compromise safety. Studies reveal alarming microbial contamination rates: Sahu et al. (2016) found *S. aureus* in 100% of retail shop samples, *E. coli* in 83.33% of retail samples and *Clostridium* in 100% of retail samples. Grema et al. (2020) identified systemic food safety risks, including lack of cold chain, poor hygiene practices and absence of fish inspection. Nguyen et al. (2018) demonstrated that microbiological quality of catfish becomes unacceptable within 3–4 days of refrigerated storage, highlighting the vulnerability of these products to microbial growth. Environmental factors like unrefrigerated transport, open-air markets and inadequate sanitation dramatically accelerate these contamination risks.

Addressing microbial hazards in Ghana's catfish sector requires improvements in hygiene practices, investment in infrastructure and adoption of internationally recognized food safety standards. The implementation of hazard analysis and critical control point (HACCP) systems in fish processing and distribution has been shown to effectively identify and control contamination points, thereby enhancing product safety and marketability (Unnevehr and Hoffmann 2015). Training farmers, processors and traders in safe handling practices is equally critical, as poor hygiene and inadequate processing methods are major contributors to microbial contamination in aquaculture products (Aheto et al. 2019). Furthermore, investment in cold chain facilities can reduce

post-harvest losses and microbial risks, ensuring that catfish contributes positively to food and nutrition security in Ghana (Overå et al. 2022). Table 4 summarizes food safety hazards in the *C. gariepinus* value chain.

7.2 | Chemical Contaminants and Residues

Chemical contaminants and residues represent another critical food safety concern in the catfish value chain in Ghana. These hazards arise mainly from aquaculture inputs, environmental pollution and processing practices. If left unmonitored, they pose risks to consumer health and reduce the competitiveness of catfish in both domestic and export markets.

Catfish aquaculture in Ghana and other developing regions faces significant risks from unregulated chemical and antibiotic use, with widespread potential for harmful residues and antimicrobial resistance. Olatoye and Basiru (2013) found that 95% of farmers administer drugs without veterinary prescription, with 61.3% of catfish liver and 52.5% of muscle samples containing detectable antimicrobial residues. Ogunnowo et al. (2025) found antibiotics exceeding maximum residue limits in catfish samples, with tetracycline at 0.2 µg/g beyond safe levels. Okocha et al. (2018) highlighted that antimicrobial residues can lead to antimicrobial resistance, hypersensitivity reactions and potential carcinogenic effects. Agoba et al. (2017) confirmed that in Ghana, some farmers still use antibiotics like tetracycline in fish feed, whereas Chuah et al. (2016) note that 90% of global aquaculture occurs in developing countries lacking robust regulatory frameworks. Okocha et al. (2021) further emphasize that most fish are 'indiscriminately dosed' with antibiotics, predisposing consumers to significant food safety and antimicrobial resistance risks. The evidence strongly suggests an urgent need for comprehensive monitoring and farmer education to mitigate these public health threats.

Environmental pollution is another important contributor. Aquaculture ponds and cages often draw water from rivers and lakes that receive effluents from mining, agriculture and domestic waste. Multiple studies across Africa and Asia document metal bioaccumulation, particularly in bottom-dwelling catfish species (Blankson et al. 2024; Bagumire et al. 2008). Metals like lead, cadmium and mercury accumulate most significantly in fish liver and gill tissues, with concentrations often exceeding recommended safety limits (Onyidoh et al. 2017). Although most studies suggest current contamination levels pose minimal immediate health risks, they unanimously recommend continuous monitoring of aquaculture environments (Yeboah et al. 2019). The primary contamination sources include agricultural runoff, industrial effluents and domestic waste, highlighting the critical need for comprehensive environmental management in aquaculture regions.

Processing and preservation practices may also introduce chemical hazards. Traditional smoking, for example, exposes fish to PAHs, some of which are classified as carcinogens. Analyses of smoked catfish in Ghana have found PAH concentrations above internationally recommended safety limits, making this a barrier to accessing export markets (Essumang et al. 2013). The type of fuelwood used, smoking duration and lack of

TABLE 4 | Food safety hazards in the *Clarias gariepinus* value chain.

Hazard type	Source(s)	Health risks	Control measures	References
Microbial contamination (<i>Salmonella</i> , <i>Escherichia coli</i> , <i>Listeria monocytogenes</i>)	Poor water quality, unhygienic handling, contaminated equipment, inadequate storage and temperature abuse	Foodborne illnesses, diarrhoea, gastroenteritis, septicæmia, listeriosis	Good aquaculture practices (GAP), hazard analysis and critical control point (HACCP) systems, proper sanitation, potable water, maintenance of the cold chain	Aboagye et al. (2020), Amoah et al. (2024), Aheto et al. (2019)
Chemical residues (antibiotics, pesticides, feed additives)	Unregulated use of veterinary drugs, pesticides and chemical additives in aquaculture production	Antimicrobial resistance, allergic reactions, disruption of gut microbiota, chronic toxic effects	Regulation of veterinary drug use, adherence to withdrawal periods, residue monitoring programmes, farmer education and training	Olatoye and Basiru (2013), Ogunnowo et al. (2025)
Heavy metals (mercury, lead, cadmium)	Contaminated water bodies, industrial effluents, agricultural runoff, mining activities	Neurotoxicity, kidney and liver damage, developmental disorders, carcinogenic effects following long-term exposure	Routine water quality monitoring, industrial effluent treatment, environmental regulation, aquaculture site selection and zoning	Naangmenyele et al. (2021), Blankson et al. (2024)
Polycyclic aromatic hydrocarbons (PAHs)	Traditional smoking using wood, charcoal and open-fire kilns	Exposure to carcinogenic compounds, increased long-term cancer risk, respiratory hazards	Improved smoking technologies (e.g., Chorkor and mechanical kilns), alternative fuels, standardized smoking conditions, routine PAH monitoring	Essumang et al. (2013), Asamoah et al. (2021)
Parasites (<i>Clonorchis</i> spp., <i>Opisthorchis</i> spp.)	Infected wild broodstock, contaminated pond water, poor pond management practices	Intestinal infections, hepatobiliary disease, liver fluke infections	Proper pond management, use of certified disease-free seed, biosecurity measures, thorough cooking before consumption	FAO (2020)

standardized practices contribute to the variability and risk of PAH contamination.

Traditional fish smoking practices in Ghana introduce significant PAH contamination in catfish, posing potential health risks and export market barriers. Multiple studies confirm PAH levels frequently exceed international safety limits (Essumang et al. 2013; Asamoah et al. 2021). Key contamination factors in smoked catfish production are closely linked to the type of fuelwood used, the duration of smoking and the smoking method applied. Hardwoods such as acacia and mangrove generate higher levels of PAHs, which pose health risks when consumed (Essumang et al. 2013). Extended smoking periods further increase PAH accumulation in fish tissues, intensifying contamination levels (Abiona et al. 2020). In addition, traditional smoking kilns are associated with substantially higher PAH concentrations compared to improved smoking techniques, underscoring the importance of adopting safer processing technologies (Bomfeh et al. 2019). Critically, some studies found PAH levels 3–33 times above European Union regulatory limits, with potential long-term carcinogenic risks (Agyei et al. 2025; Yusuf et al. 2015). Adopting improved smoking technologies and standardized practices could mitigate these contamination risks.

Addressing chemical contamination in the catfish sector requires a multi-pronged approach. Strengthening regulatory frameworks and enforcing monitoring of aquaculture inputs, together with routine testing of fish for chemical residues, is essential. Training farmers on the responsible use of chemicals and encouraging adoption of safer processing technologies can also reduce risks. Investment in improved smoking kilns, water treatment systems and feed quality assurance will contribute to safer and more competitive catfish products.

7.3 | Quality Standards and Certification

To ensure the safety and quality of catfish, it is important to adopt recognized standards and certification systems. These frameworks provide a structured way to manage risks and verify that products are safe to eat, which is essential for building consumer trust and accessing formal markets.

One key system is HACCP. This is a step-by-step approach that identifies potential hazards (like microbial or chemical contamination) at critical stages of production and processing. It then puts controls in place to prevent or eliminate these hazards (Unnevehr and Hoffmann 2015). Although HACCP is used by some large processors in Ghana, most small-scale operators find it difficult to implement due to a lack of training, resources and infrastructure (Unnevehr 2022).

Another important framework is the International Organization for Standardization (ISO) certification, particularly ISO 22000 for food safety management. This standard integrates HACCP principles into a broader management system, requiring companies to demonstrate they can consistently control food safety hazards (Panghal et al. 2018). However, the high cost and technical expertise required for ISO certification are major barriers for small and medium-sized businesses in Ghana and across Africa (Kussaga et al. 2014).

Finally, Codex Alimentarius standards, developed by the United Nations, serve as international benchmarks for food safety and quality. These guidelines cover everything from acceptable levels of contaminants to hygiene and labelling practices (FAO/WHO 2020). For Ghana, complying with Codex standards is a necessary step if catfish producers wish to export to regulated markets like the European Union, where these benchmarks are often used as a reference (Henson and Humphrey 2010).

The adoption of these standards is a clear indicator of a product's safety and quality. Promoting their use through training, financial incentives and public–private partnerships is vital for enhancing the reputation and competitiveness of Ghanaian catfish both at home and abroad. The key hazards and control points within the catfish value chain are mapped in Figure 4. Figure 4 provides a comprehensive mapping of food safety hazards and critical control points across the catfish value chain in Ghana. The figure illustrates how risks emerge at different stages, from production through processing, distribution and retail, and identifies specific interventions that can prevent or mitigate these hazards.

8 | Research Gaps and Future Prospects

Despite the established importance of *C. gariepinus* in Ghanaian aquaculture and nutrition, significant gaps persist in the scientific understanding of its chemical composition and the factors that modulate it. Addressing these knowledge deficits is essential for moving from general appreciation to evidence-based optimization, enabling a truly nutrition-sensitive approach to production and consumption. The current fragmentation of data and the lack of targeted, locally relevant studies hinder the ability to fully harness this species for public health.

A primary and fundamental gap is the lack of comprehensive, Ghana-specific nutrient profiling. Existing data are often skewed towards proximate composition (moisture, protein and fat), with much less detailed and consistent information on the full spectrum of micronutrients. There is a pressing need for systematic analyses to quantify the complete vitamin profile (particularly vitamins A, D, E and B₁₂) and a detailed mineral audit (including iron, zinc, selenium and iodine) in catfish raised under prevailing Ghanaian farming conditions (Hasselberg et al. 2020; Asiedu et al. 2026). Furthermore, detailed characterization of the fatty acid profile, specifically the levels of EPA and DHA and the complete amino acid spectrum across different production systems is required. Such high-resolution compositional data are the indispensable foundation for accurate dietary assessments, nutrient database development and targeted nutritional interventions.

Distinguishing Ghanaian data from external evidence: A critical limitation of the current review is that much of the cited evidence originates from studies conducted outside Ghana, including Nigeria, Egypt, Indonesia, Bangladesh and other regions. Although these studies provide valuable insights into the nutritional composition and factors affecting *C. gariepinus*, they may not fully represent Ghanaian conditions due to differences in climate, water quality, feed ingredients, farming practices and processing methods. Ghana-specific studies are particularly



FIGURE 4 | Food safety hazards and control points in the catfish value chain. HACCP, hazard analysis and critical control point; PAH, polycyclic aromatic hydrocarbons.

sparse for detailed micronutrient profiling, fatty acid analysis and vitamin content. Where data are available from Ghana, they are often limited to proximate composition. This geographic bias in the evidence base means that conclusions about the nutritional composition of Ghanaian catfish must be interpreted with caution. Future research should prioritize Ghana-specific studies that use standardized methods and clearly report all relevant parameters to enable accurate assessment of the nutritional contribution of locally produced catfish.

Second, research on the impact of local inputs and practices on final nutrient composition remains underdeveloped. Although the use of local agro-industrial by-products (e.g., cassava leaf meal and palm kernel cake) as alternative feed ingredients is studied for growth performance, research rarely tracks how these ingredients affect the nutritional quality of the fillet for human consumers, thus its fatty acid profile, amino acid balance or micronutrient density (Kwasek et al. 2020; Adéyemi et al. 2020). Concurrently, there is a critical lack of quantitative data on nutrient retention through indigenous processing methods. Although smoking is ubiquitous, studies precisely quantifying the losses of heat-sensitive vitamins (B_1 , B_2 and C) and the oxidation of PUFAs across different smoking temperatures, durations and kiln types (traditional vs. improved) are scarce (Bomfeh 2021). Research is needed to model how processing transforms the compositional profile of the farmed fish into that of the consumed product.

Third, methodological and translational gaps must be closed. The absence of standardized protocols for sampling and analysis leads to high variability in reported values, complicating comparisons and meta-analyses. Developing and advocating for standardized methods is crucial for generating reliable, comparable data. Finally, there is an almost complete absence of dietary intervention studies investigating the direct impact of catfish consumption on nutritional status biomarkers in Ghanaian populations. Robust evidence demonstrating improvements in iron status (ferritin levels), vitamin B_{12} sufficiency, or growth parameters in children following regular catfish consumption would provide powerful validation for its role in nutrition programming (Byrd et al. 2022). Filling these interconnected gaps, thus from foundational composition data to human efficacy trials, is imperative to build a robust, evidence-based framework for leveraging *C. gariepinus* as a keystone in Ghana's strategy for improved nutrition and food security. Table 5 summarizes the research gaps and priorities for *C. gariepinus* in Ghana.

9 | Conclusion and Recommendations

This review, conducted following PRISMA guidelines, consolidates current knowledge on the chemical composition of the African catfish (*C. gariepinus*), elucidating its substantial nutritional value and the critical factors that determine its final quality as a food commodity in Ghana. The evidence confirms that catfish

TABLE 5 | Research gaps and priorities for *Clarias gariepinus* in Ghana.

Research area	Current knowledge	Identified gap	Future research priorities	References
Nutritional composition	Proximate composition (protein, fat, moisture) has been fairly well documented	Limited data on detailed micronutrient and bioactive compound profiles	Comprehensive profiling of vitamins, minerals, fatty acids and bioactive peptides under different production systems and environmental conditions	Langi et al. (2024), Hasselberg et al. (2020)
Feed and diet effects	Some studies link feed type to variation in lipid content	Lack of systematic feeding trials using locally available feed resources	Development of cost-effective, nutrition-sensitive feed formulations using agro-industrial by-products and underutilized resources	Da et al. (2012), Adéyemi et al. (2020), Kwasek et al. (2020)
Processing and preservation	Traditional smoking is well documented and widely practiced	Limited evaluation of nutrient losses, safety risks and quality changes in modern preservation techniques	Comparative studies on nutrient retention and safety in freezing, modified atmosphere packaging (MAP), irradiation and combined preservation methods	Bomfeh (2021), Bomfeh et al. (2019), Bai et al. (2023)
Food safety	Known hazards include PAHs, microbial contamination and heavy metals	Weak monitoring systems and limited quantitative data on contaminant residues	Development of surveillance systems, quantitative risk assessment models and rapid detection technologies	Gbogbo et al. (2018), Essumang et al. (2013)
Consumer behaviour	Some surveys exist on smoked fish preferences in local markets	Lack of detailed sensory evaluation and willingness-to-pay studies	Studies on urban vs. rural consumption patterns, value-added products and market segmentation	Johnson et al. (2025), Gosh (2024)
Policy and sustainability	Aquaculture policies exist, but enforcement remains inconsistent	Limited integration of food safety, gender and sustainability considerations in aquaculture policy	Research on policy effectiveness, gender dynamics in value chains and climate-smart aquaculture strategies	Overå et al. (2022), Zornu et al. (2023), Asiedu et al. (2017)

is a rich source of high-quality, complete protein with an EAA profile that meets human nutritional requirements, alongside a variable but significant lipid content and a valuable array of bioavailable minerals such as iron, zinc, phosphorus and calcium. Its fatty acid profile, while distinct from marine species and dominated by monounsaturated and shorter chain polyunsaturated fats, contributes beneficially to dietary fat quality. However, the synthesis also reveals that this nutrient profile is not a fixed attribute but a dynamic outcome, highly responsive to pre- and post-harvest conditions.

The composition of catfish is profoundly shaped by a triad of influential factors. Diet is the principal lever, with feed formulation directly dictating growth, protein deposition and, most notably, the fatty acid signature of the fillet. The aquaculture environment, encompassing water quality and system type, modulates metabolic efficiency and stress, thereby influencing nutrient utilization and flesh quality. Finally, processing, particularly the traditional smoking methods prevalent in Ghana, acts as a final transformative filter, often reducing heat-sensitive vitamins and altering lipid quality through oxidation, despite achieving preservation. Therefore, the nutritional potential inherent in the species can only be fully realized through intentional management of this entire chain, from feed formulation to post-harvest handling.

For Ghana, *C. gariepinus* represents more than a viable aquaculture product; it is a strategic, locally sustainable food resource with a demonstrated role in enhancing dietary quality. Its consistent availability and rich nutrient density make it a key food for addressing protein and specific micronutrient deficiencies, particularly among vulnerable groups. To maximize this potential, future efforts must be guided by a nutrition-sensitive approach. This necessitates targeted research to fill critical data gaps on Ghana-specific nutrient profiles and processing losses, alongside the promotion of improved feeds and processing technologies. By integrating nutritional objectives into aquaculture development and food safety policy, Ghana can harness the full capacity of *C. gariepinus* to strengthen food and nutrition security, contributing meaningfully to improved public health outcomes.

Summary of conclusions by section:

- Section 3.1 (Proximate Composition): *C. gariepinus* provides high-quality protein (15%–19%) with a variable lipid content (2.5%–15%) influenced by diet and culture conditions, positioning it as a nutrient-dense food source with a valuable nutrient-to-energy ratio.
- Section 3.2 (Amino Acid Profile): The species offers a complete EAA profile that meets FAO/WHO requirements, with particularly high levels of lysine, making it an excellent complement to cereal-based diets and supporting growth, muscle maintenance and recovery.
- Section 3.3 (Fatty Acid Composition): The lipid profile is dominated by MUFAs and PUFAs but contains low levels of long-chain omega-3s (EPA/DHA), distinguishing it from marine fish and highlighting the need for dietary diversity.
- Section 3.4 (Micronutrient Composition): Catfish provides bioavailable minerals (particularly iron, zinc, phosphorus and

calcium) and essential vitamins (A, D, E and B-complex), though comprehensive Ghana-specific data are lacking.

- Section 4 (Influencing Factors): Feed formulation is the most critical factor determining nutritional composition, followed by aquaculture environment and post-harvest processing methods, all of which present opportunities for nutritional optimization.
- Section 5 (Comparison): Catfish complements rather than replaces marine fish and tilapia, offering reliable protein and minerals, whereas marine fish provide superior long-chain omega-3s.
- Section 6 (Implications): Catfish can contribute significantly to addressing protein-energy malnutrition, iron deficiency and other nutrient gaps in Ghana, particularly when produced and processed with nutrition-sensitive approaches.
- Section 7 (Food Safety): Microbial contamination, chemical residues and PAHs from traditional smoking pose food safety risks that can offset nutritional benefits, requiring improved practices and monitoring.
- Section 8 (Research Gaps): Priority areas include Ghana-specific nutrient profiling, feed optimization using local ingredients, processing impact studies and dietary intervention trials.

Recommendations:

1. Strengthen Ghana-specific nutrient databases: Conduct systematic, standardized analyses of the complete nutrient profile (proximate, amino acids, fatty acids, vitamins and minerals) of *C. gariepinus* from different production systems and regions in Ghana.
2. Develop nutrition-sensitive feed formulations: Invest in research to develop cost-effective feeds using local ingredients that optimize both growth performance and nutritional quality (particularly fatty acid profiles and micronutrient content) for human consumers.
3. Adopt improved processing technologies: Promote the adoption of improved smoking kilns and cold-chain infrastructure that better preserve nutritional quality while reducing food safety risks (PAHs, microbial contamination).
4. Strengthen food safety systems: Implement HACCP-based approaches and strengthen regulatory monitoring of microbial contamination, chemical residues and PAHs in the catfish value chain.
5. Integrate nutritional objectives into aquaculture policy: Ensure that aquaculture development plans explicitly include nutritional outcomes as objectives, not just production targets.
6. Conduct dietary intervention studies: Undertake research to quantify the impact of catfish consumption on nutritional status biomarkers in vulnerable populations to provide evidence for nutrition programming.
7. Develop standardized methods: Establish and advocate for standardized sampling, analytical and reporting protocols

to enable reliable comparisons across studies and meta-analyses.

Author Contributions

Amy Atter: conceptualization, project administration, methodology, writing – original draft, writing – review and editing, resources, visualization, validation, software. **Crossby Osei Tutu:** conceptualization, project administration, methodology, writing – original draft, writing – review and editing, resources, visualization, validation, software. **Naomi Taye:** methodology, investigation, writing – review and editing, resources, validation. **Bernard Kwabena Asiedu:** methodology, investigation, writing – review and editing, resources, validation. **Reuben Acheampong:** methodology, investigation, writing – review and editing, resources, validation. **Hayford Ofori:** methodology, investigation, writing – review and editing, resources, validation. **Stephen Nketia:** methodology, investigation, writing – review and editing, resources, validation. **Richard Yaw Otwey:** methodology, investigation, writing – review and editing, resources, validation. **Christopher Galley:** methodology, investigation, writing – review and editing, resources, validation. **Frank Peget:** methodology, investigation, writing – review and editing, resources, validation. **Jackline Boateng:** methodology, investigation, writing – review and editing, resources, validation. **Patricia Mensah:** methodology, investigation, writing – review and editing, resources, validation. **Stacy Ayitey:** methodology, investigation, writing – review and editing, resources, validation. **Eric Dogbey:** methodology, investigation, writing – review and editing, resources, validation. **Seth Agyakwah:** methodology, investigation, writing – review and editing, resources, validation. **Wisdom Amod-Awua:** methodology, investigation, writing – review and editing, resources, validation.

Funding

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data associated with the work are included/referenced in the article.

References

- Abdel-Mobdy, H. E., H. A. Abdel-Aal, S. L. Souzan, and A. G. Nassar. 2021. "Nutritional Value of African Catfish (*Clarias gariepinus*) Meat." *Asian Journal of Applied Chemistry Research* 8, no. 2: 31–39. <https://doi.org/10.9734/ajacr/2021/v8i230190>.
- Abiona, O. O., A. O. Adegunwa, S. H. Awojide, W. B. Agbaje, and A. S. Tayo. 2020. "Impact Assessment of Smoking Duration on Polycyclic Aromatic Hydrocarbons (PAH's) Contaminations of *Clarias gariepinus*." *UNIOSUN Journal of Engineering and Environmental Sciences* 2, no. 2. <https://doi.org/10.36108/ujees/0202.20.0201>.
- Aboagye, E., K. Tano-Debrah, and A. P. Kunadu. 2020. "Microbial Quality of Fish Along With the Tilapia, African Catfish and Sardinella Artisanal Value Chains in Kpong and James Town, Ghana." *International Journal of Bonorowo Wetlands* 10, no. 1: 1–17. <https://doi.org/10.13057/bonorowo/wl100101>.
- Abrokwa, T. O., C. Osei Tutu, P. T. Akonor, F. K. Saalia. 2026. "Drying kinetics and model evaluation of banana puree during foam mat drying." *Translational Food Sciences* 2026: vxag018. <https://doi.org/10.1093/trfood/vxag018>.
- Acheampong, R., C. Osei Tutu, P. T. Akonor, et al. 2025. "Effect of Conventional and Emerging Thawing Technologies on Drip Loss, Microstructure and Post-thaw Quality of Frozen Fruits and Vegetables:

a Review." *Applied Food Research* 5, no. 2: 101323. <https://doi.org/10.1016/j.afres.2025.101323>.

Adéyemi, A. D., A. P. P. Kayodé, I. B. Chabi, O. B. O. Odouaro, M. J. Nout, and A. R. Linnemann. 2020. "Screening Local Feed Ingredients of Benin, West Africa, for Fish Feed Formulation." *Aquaculture Reports* 17: 100386. <https://doi.org/10.1016/j.aqrep.2020.100386>.

Adil, M., G. Xinbo, J. Cai, et al. 2025. "Data-independent Acquisition-mass Spectrometry Proteomic Insights Into Nutritional Metabolism of *Litopenaeus vannamei* Exposed to *Lactococcus Lactis* D1813, Varied Salinity, and Dissolved Oxygen." *International Journal of Food Science and Technology* 60, no. 1: vvaf067. <https://doi.org/10.1093/ijfood/vvaf067>.

Adil, M., G. Xinbo, J. Cai, M. Waseem, M. F. Manzoor, and C. Osei Tutu. 2025. "Investigating the Role of *Lactococcus Lactis* D1813, Salinity, and Dissolved Oxygen on the Nutritional, Chromatic, and Textural Profile of *Litopenaeus vannamei*." *Food Chemistry: X* 27C, no. 2025: 102404. <https://doi.org/10.1016/j.fochx.2025.102404>.

Agbeko, E., R. Asmah, F. A. Anani, and E. T. Mensah. 2018. *A Training Manual for Grow out Pond Culture of African Catfish: A Comprehensive Guide to Small-Scale African Catfish Farming in Ghana*. Western Region Coastal Foundation (WRCF).

Agoba, E. E., F. Adu, C. Agyare, and V. E. Boamah. 2017. "Antibiotic Use and Practices in Selected Fish Farms in the Ashanti Region of Ghana." *Journal of Infectious Diseases and Treatment* 3, no. 02: 2472–2493.

Agyei, T. A., S. K. Amponsah, J. O. Akowuah, and A. Addo. 2025. "Polycyclic Aromatic Hydrocarbon Profiles and Carcinogenic Risks Associated With Smoked Catfish and Rabbit Meat: A Comparative Study of Traditional and Improved Smoking Methods." *Journal of Food Quality* 2025, no. 1: 8759400.

Aheto, D. W., E. Acheampong, and J. O. Odoi. 2019. "Are Small-Scale Freshwater Aquaculture Farms in Coastal Areas of Ghana Economically Profitable?" *Aquaculture International* 27, no. 3: 785–805. <https://doi.org/10.1007/s10499-019-00363-9>.

Ajiboye, O., and A. Q. Aremu. 2015. "Effects of Water Level on Growth, Nutrient Utilization and Survival of African Catfish, *Clarias gariepinus*." *International Journal of Agricultural Sciences and Natural Resources* 2, no. 4: 109–112. <https://doi.org/10.1006/JFBI.2001.1845>.

Akongyuure, D. N., E. D. Abarike, S. A. Atindana, et al. 2015. "Chemical Composition and Sensory Evaluation of Wild and Cultured *Oreochromis niloticus* and *Clarias gariepinus* in Northern Ghana." *Journal of Ghana Science Association* 16, no. 2: 79–89.

Amjad, A., A. Syed, M. Waseem, et al. 2026. "Effect of Apple Peel Powder and Pomace Extract on Hyperlipidemic Health Indices of Albino Wistar Rats." *Journal of the Science of Food and Agriculture* 106: 1195–1205. <https://doi.org/10.1002/jsfa.70242>.

Amoah, B. D., A. Mensah, L. Darko, et al. 2024. "Microbial Load and Antibiotic Resistance Pattern of Microflora Isolated From Smoked Catfish and Mackerel Sold in Ghanaian Markets: A Potential Health Threat." *International Journal of Pathogen Research* 13, no. 5: 1–11. <https://doi.org/10.9734/ijpr/2024/v13i5304>.

Ampah, J., E. J. S. Blessie, A. H. Andoh-Odoom, C. Osei Tutu, B. K. Asiedu, and G. O. Sampson. 2026. "Thin Layer Drying Characteristics and Chemical Properties of Two Local Plantain Varieties." *International Journal of Food Science and Technology* 61, no. 1: vvag090. <https://doi.org/10.1093/ijfood/vvag090>.

Amponsah, S. K., S. Agodzo, E. Agbeko, and E. A. Osei. 2021. "Impact of Tank Geometry on Production of African Catfish (*Clarias gariepinus*)." *African Journal of Agricultural Research* 17, no. 1: 165–172. <https://doi.org/10.5897/ajar2020.15239>.

Ansah, Y. B., E. A. Frimpong, and S. Amisah. 2013. "Characterisation of Potential Aquaculture Pond Effluents, and Physico-Chemical and Microbial Assessment of Effluent-Receiving Waters in Central Ghana." *African Journal of Aquatic Science* 38, no. 2: 185–192. <https://doi.org/10.2989/16085914.2013.767182>.

- Asamoah, E. K., F. K. E. Nunoo, S. Addo, J. O. Nyarko, and G. Hyldig. 2021. "Polycyclic Aromatic Hydrocarbons (PAHs) in Fish Smoked Using Traditional and Improved Kilns: Levels and Human Health Risk Implications Through Dietary Exposure in Ghana." *Food Control* 121: 107576. <https://doi.org/10.1016/j.foodcont.2020.107576>.
- Asiedu, B., S. Iddrisu, and P. Failler. 2023. "Yesterday, Today, and Tomorrow's Fish Consumption: Analysis of Present and Prospective Fish Consumption in Ghana by 2030." *Cogent Food & Agriculture* 9, no. 1: 2224603. <https://doi.org/10.1080/23311932.2023.2224603>.
- Asiedu, B., F. Nunoo, and S. Iddrisu. 2017. "Prospects and Sustainability of Aquaculture Development in Ghana, West Africa." *Cogent Food & Agriculture* 3, no. 1: 1349531. <https://doi.org/10.1080/23311932.2017.1349531>.
- Asiedu, B. K., C. Osei Tutu, P. T. Akonor, et al. 2026. "Momoni as a Model for African Fermented Fish: Nutritional Composition, Bioactive Metabolites and Safety Perspectives." *Journal of Food Composition and Analysis* 149C, no. 2026: 108612. <https://doi.org/10.1016/j.jfca.2025.108612>.
- Asiedu, B. K., C. Osei Tutu, E. O. Afoakwa, P. T. Akonor, A. S. Budu, and F. K. Saalia. 2026. "Effect of Manual Depulping and Roasting on Functional, Rheological and Sensory Characteristics of Cocoa Liquor." *Applied Food Research* 6, no. 1: 102033. <https://doi.org/10.1016/j.afres.2026.102033>.
- Atawodi, J. C., P. O. Somdare, E. Okolo, and H. Bala. 2025. "Assessment of Bacterial Contamination in Farmed Catfish and Wild Caught (*Clarias gariepinus*) (Burchell, 1822) and Water Sources in Zaria, Nigeria." *Journal of Science Research and Reviews* 2, no. 2: 43–52. <https://doi.org/10.70882/josrar.2025.v2i2.60>.
- Bagumire, A., W. K. Rumbeiha, E. C. D. Todd, C. Muyanja, and G. W. Nasinyama. 2008. "Analysis of Environmental Chemical Residues in Products of Emerging Aquaculture Industry in Uganda as Case Study for Sub-Saharan Africa." *Food Additives and Contaminants: Part B* 1, no. 2: 153–160. <https://doi.org/10.1080/02652030802482491>.
- Bai, L., M. Liu, and Y. Sun. 2023. "Overview of Food Preservation and Traceability Technology in the Smart Cold Chain System." *Foods* 12, no. 15: 2881. <https://doi.org/10.3390/foods12152881>.
- Bakhsh, N. M., N. M. H. Ghazali, N. M. K. Yar, et al. 2023. "The Role of Fish in Global Food and Nutrition Security: Current Aspects and Future Prospect." *University of Sindh Journal of Animal Sciences (USJAS)* 7, no. 04. <https://doi.org/10.57038/usjas.v7i04.6643>.
- Blankson, E. R., N. K. Ohene-Opong, B. A. Awuah, D. Oduro, J. Ewool, and F. Gbogbo. 2024. "Heavy Metal Bioaccumulation in Highly Consumed Pelagic and Benthic Fish and Associated Health Risk." *Biological Trace Element Research* 202, no. 8: 3781–3788. <https://doi.org/10.1007/s12011-023-03943-2>.
- Bomfeh, K. 2021. "The Shift From a Traditional to an Improved Fish Smoking Oven in Ghana: Implications for Food Safety and Public Health." *Afrika Focus* 34, no. 1: 155–166. <https://doi.org/10.1163/2031356X-34010009>.
- Bomfeh, K., L. Jacksens, W. K. Amoa-Awua, et al. 2019. "Reducing Polycyclic Aromatic Hydrocarbon Contamination in Smoked Fish in the Global South: A Case Study of an Improved Kiln in Ghana." *Journal of the Science of Food and Agriculture* 99, no. 12: 5417–5423. <https://doi.org/10.1002/jsfa.9802>.
- Bouriga, N., S. Bejaoui, B. Jemmali, J. P. Quignard, and M. Trabelsi. 2020. "Effects of Smoking Processes on the Nutritional Value and Fatty Acid Composition of Zander Fish (*Sander lucioperca*)." *Grasas y Aceites* 71, no. 1: e340.
- Byrd, K. A., J. Shieh, S. Mork, et al. 2022. "Fish and Fish-Based Products for Nutrition and Health in the First 1000 Days: A Systematic Review of the Evidence From Low and Middle-Income Countries." *Advances in Nutrition* 13, no. 6: 2458–2487. <https://doi.org/10.1093/advances/nmac102>.
- Chuah, L. O., M. E. Effarizah, A. M. Goni, and G. Rusul. 2016. "Antibiotic Application and Emergence of Multiple Antibiotic Resistance (MAR) in Global Catfish Aquaculture." *Current Environmental Health Reports* 3: 118–127. <https://doi.org/10.1007/s40572-016-0091-2>.
- Daramola, J. A., F. O. Alao, S. A. Osofero, and O. O. Wemimo. 2014. "Assessment of the Microbial and Sensory Qualities of Smoked African Catfish (*Clarias gariepinus*)." *Journal of Agriculture and Environmental Sciences* 3, no. 1: 11–22.
- Duarte, A. M., F. Silva, F. R. Pinto, S. Barroso, and M. M. Gil. 2020. "Quality Assessment of Chilled and Frozen Fish—Mini Review." *Foods* 9, no. 12: 1739. <https://doi.org/10.3390/foods9121739>.
- Effiong, M. U., and C. A. Yaro. 2019. "Fatty Acid Composition of Fillets of African Catfish, *Clarias gariepinus* Fed With Various Oil-Based Diets." *Aquaculture Studies* 20, no. 1: 29–35. https://doi.org/10.4194/2618-6381-v20_1_04.
- Essumang, D. K., D. K. Dodoo, and J. K. Adjei. 2013. "Effect of Smoke Generation Sources and Smoke Curing Duration on the Levels of Polycyclic Aromatic Hydrocarbon (PAH) in Different Suites of Fish." *Food and Chemical Toxicology* 58: 86–94.
- FAO/WHO. 2020. *Codex Alimentarius: International Food Standards*. Food and Agriculture Organization of the United Nations/World Health Organization. <https://www.fao.org/fao-who-codexalimentarius>.
- FAO. 2020. *The State of World Fisheries and Aquaculture 2020: Sustainability in Action*. Food and Agriculture Organization of the United Nations. <https://doi.org/10.4060/ca9229en>.
- Faukner, J., S. D. Rawles, A. Proctor, et al. 2013. "The Effects of Diets Containing Standard Soybean Oil, Soybean Oil Enhanced With Conjugated Linoleic Acids, Menhaden Fish Oil, or an Algal Docosahexaenoic Acid Supplement on Channel Catfish Performance, Body Composition, Sensory Evaluation and Storage Characteristics." *North American Journal of Aquaculture* 75, no. 2: 252–265.
- Gbogbo, F., A. Arthur-Yartel, J. A. Bondzie, et al. 2018. "Risk of Heavy Metal Ingestion From the Consumption of Two Commercially Valuable Species of Fish From the Fresh and Coastal Waters of Ghana." *PLoS ONE* 13, no. 3: e0194682.
- Gopal, T. S. 2020. "Foods From the Ocean for Nutrition, Health and Wellness." In *Nutritional and Health Aspects of Food in South Asian Countries*. Academic Press.
- Gosh, K. 2024. "Exploring the Influential Factors Shaping Consumer Behavior and Purchase Intentions of Catfish Products in the Southern USA." *Aquaculture* 592: 741225. <https://doi.org/10.1016/j.aquaculture.2024.741225>.
- Grema, H. A., J. K. P. Kwaga, M. Bello, and O. H. Umaru. 2020. "Understanding Fish Production and Marketing Systems in North-Western Nigeria and Identification of Potential Food Safety Risks Using Value Chain Framework." *Preventive Veterinary Medicine* 181: 105038. <https://doi.org/10.1016/j.prevetmed.2020.105038>.
- Hasselberg, A. E., I. Aakre, J. Scholtens, et al. 2020. "Fish for Food and Nutrition Security in Ghana: Challenges and Opportunities." *Global Food Security* 26: 100380.
- Hauzoukim, S. S., and B. Mohanty. 2020. "Modified Atmosphere Packaging of Fish and Fishery Products: A Review." *Journal of Entomology and Zoology Studies* 8, no. 4: 651–659.
- Henson, S., and J. Humphrey. 2010. "Understanding the Complexities of Private Standards in Global Agri-Food Chains as They Impact Developing Countries." *Journal of Development Studies* 46, no. 9: 1628–1646.
- Hyun, J. E., and S. Y. Lee. 2018. "Effect of Modified Atmosphere Packaging on Preserving Various Types of Fresh Produce." *Journal of Food Safety* 38, no. 1: e12376.
- Ibhadon, S., M. S. Abdulsalami, M. C. Emere, and V. Yilwa. 2015. "Comparative Study of Proximate, Fatty and Amino Acids Composition of Wild and Farm-Raised African Catfish *Clarias gariepinus* in Kaduna, Nigeria." *Pakistan Journal of Nutrition* 14, no. 1: 56–61.
- Javed, M. A., R. Suleman, M. Waseem, et al. 2025. "Novel Colocasia Esculenta Starch-Clove Extract Packaging Films for Enhanced Oxidative Stability, Microbial Quality, and Sensory Acceptability of Chicken."

- Journal of Food Processing and Preservation* 2025: 5563606, 14 pages, 2025. <https://doi.org/10.1155/jfpp/5563606>.
- Javeria, A., R. Suleman, M. Waseem, et al. 2026. "Nutritional and Antioxidative Characterisation, Antimicrobial, and Sensory Stability of Ultrasound-assisted *Agaricus bisporus* (J. E. Lange) Imbach Dried Powder-based Biscuits." *International Journal of Food Science and Technology* 61, no. 1: vvag052. <https://doi.org/10.1093/ijfood/vvag052>.
- Johnson, A., A. Morey, B. Su, et al. 2025. "Evaluation of Texture, Sensory, and Fillet Color Traits in Channel Catfish (*Ictalurus punctatus*), Blue Catfish (*Ictalurus furcatus*), and the Hybrid Catfish (Channel Catfish ♀ × Blue Catfish ♂)." *Journal of the World Aquaculture Society* 56, no. 1: e13113.
- Karikari, A. Y., R. Asmah, W. W. Anku, S. Amisah, T. Trevor, and R. Lindsay. 2022. "Assessment of Cage Fish Farm Impacts on Physico-Chemical Parameters of the Volta Lake in Ghana." *Journal of Fisheries and Coastal Management* 3, no. 1: 22.
- Khan, W. A., M. Waseem, I. Yasmin, et al. 2025. "Effect of Dietary Proteins on Mayonnaise Techno-functionality and Rheology: a Review." *Food and Humanity* 5C, no. 2025: 100665. <https://doi.org/10.1016/j.foohum.2025.100665>.
- Koranteng, C. O., C. Gadegbeku, J. Owusu-Bempah, et al. 2026. "Rental compound housing: A culturally beneficial need sustaining livelihoods in urban spaces in Ghana." *Cities* 179: 107470. <https://doi.org/10.1016/j.cities.2026.107470>.
- Kortei, N. K., A. A. Aduko, L. Quansah, et al. 2026. "Mycoflora, Mycotoxin Exposure and Cancer Risk Assessment in Tuo-Zaafi, a Fermented Cereal Meal Consumed in northern Ghana." *Toxicology Reports* 16, no. 2026: 102253. <https://doi.org/10.1016/j.toxrep.2026.102253>.
- Kumador, D. K., A. Opoku-Mensah, V. Tackie-Ofosu, S. Mahama, J. Owusu-Bempah, and C. Osei Tutu. 2025. "Preterm Delivery in Ghana: Challenges and Implications for Maternal Mental Health Trajectories." *PLoS ONE* 20, no. 3: e0317147. <https://doi.org/10.1371/journal.pone.0317147>.
- Kussaga, J. B., L. Jacxsens, B. P. Tiisekwa, and P. A. Luning. 2014. "Food Safety Management Systems Performance in African Food Processing Companies: A Review of Deficiencies and Possible Improvement Strategies." *Journal of the Science of Food and Agriculture* 94, no. 11: 2154–2169.
- Kwasek, K., A. L. Thorne-Lyman, and M. Phillips. 2020. "Can Human Nutrition be Improved Through Better Fish Feeding Practices? A Review Paper." *Critical Reviews in Food Science and Nutrition* 60, no. 22: 3822–3835.
- Mahama, S., J. A. Ackom, B. A. Agyekum, C. Osei Tutu, D. K. Kumador, and J. Owusu-Bempah. 2025. "Beyond the Observed: Postpartum Posttraumatic Stress Symptoms and Mother-child Bonding in Ghana." *Midwifery* 148C, no. 2025: 104470. <https://doi.org/10.1016/j.midw.2025.104470>.
- Maranga, B. O., K. M. Omolo, R. N. Kagali, P. S. Orina, and D. N. Kyule. 2025. "Fatty Acid Composition of African Catfish (*Clarias gariepinus*) Fed on Black Soldier Fly Larvae (*Hermitia illucens*) Formulated Diets." *Aquaculture, Fish and Fisheries* 5, no. 3: e70078. <https://doi.org/10.1002/aff2.70078>.
- Matea, T. K., and A. Avenant-Oldewage. 2026. "Aspects of the Histopathology of *Clarias gariepinus* Infected With the Camallanid Parasite *Procamallanus* (*Procamallanus*) *Pseudolaeviconchus* Moravec and Van As, 2015." *Journal of Fish Diseases* 49, no. 5: e70107. <https://doi.org/10.1111/jfd.70107>.
- Mensah, P. O., C. Osei Tutu, P. T. Akonor, et al. 2026. "Development and Evaluation of Gluten-free Rice Bread Formulated With Hydrocolloid-protein Additive Systems." *Food and Humanity* 6, no. 2025: 100956. <https://doi.org/10.1016/j.foohum.2025.100956>.
- Merdzhanova, A., D. A. Dobрева, and V. Panayotova. 2018. "Comparison of Fatty Acids, Cholesterol, Fat Soluble Vitamins and Carotenoids Content of Skin and Edible Tissue of Farmed African Catfish (*Clarias gariepinus*, Burchell 1822)." *Ovidius University Annals of Chemistry* 29: 41–47.
- Moazzam, M., S. Ali, M. A. Khan, et al. 2026. "Impact of Soy Protein Concentrate and Storage on the Safety, Quality and Shelf Stability of Beef Patties." *Food Science & Nutrition* 14, no. 1: e71327. <https://doi.org/10.1002/fsn3.71327>.
- Mohamed, E. F. E., A. E.-S. E. Hafez, H. G. Seadawy, et al. 2023. "Irradiation as a Promising Technology to Improve Bacteriological and Physicochemical Quality of Fish." *Microorganisms* 11, no. 5: 1105. <https://doi.org/10.3390/microorganisms11051105>.
- Moon, S. K., S. N. Hong, I. S. Kim, and B. Y. Jeong. 2009. "Comparative Analysis of Proximate Compositions and Lipid Component in Cultured and Wild Mackerel *Scomber japonicus* Muscles." *Korean Journal of Fisheries and Aquatic Sciences* 42, no. 5: 411–416.
- Mshelia, R. D. Z., N. I. Dibal, and S. M. Chiroma. 2023. "Food Irradiation: An Effective but Under-Utilized Technique for Food Preservations." *Journal of Food Science and Technology* 60, no. 10: 2517–2525.
- Mukhopadhyay, P. K., and S. Mishra. 1998. "Effect of Feeding Different Lipid Sources on Growth, Feed Efficiency and Tissue Fatty Acid Composition of *Clarias batrachus* Fry and Fingerlings." *Journal of Applied Ichthyology* 14, no. 1–2: 105–107. <https://doi.org/10.1111/j.1439-0426.1998.tb00623.x>.
- Muns-Pujadas, L., M. Constenla, S. Dallarés, A. Soler-Membrives, F. Padrós, and R. Sala. 2025. "The Round Sardinella (*Sardinella aurita* Valenciennes, 1847) From the NW Mediterranean: A Healthy and Safe Choice for Human Consumption." *Mediterranean Marine Science* 26, no. 1: 16–29.
- Naangmenyele, Z., S. Ncube, F. J. Akpabey, S. Dube, and M. M. Nindi. 2021. "Bioaccumulation and Human Risk Assessment of Heavy Metals in *Oreochromis niloticus* and *Clarias gariepinus* Fish Species From the Gologing Reservoir, Ghana." *South African Journal of Chemistry* 75: 111–116. <https://doi.org/10.17159/0379-4350/2021/v75a13>.
- Namaga, W. M., B. Yahaya, and M. A. Salam. 2020. "Proximate Composition of Male and Female African Catfish (*Clarias gariepinus*) and Tilapia (*Tilapia zilli*) in Jega River, Kebbi State, Nigeria." *Journal of Fisheries, Livestock and Veterinary Science* 01, no. 02: 28–35. <https://doi.org/10.18801/jflvs.010220.04>.
- Nguyen, T. T., A. Adhikari, D. Bhattacharya, V. S. Chhetri, and K. Kharel. 2018. "Microbial Food Safety Risks Associated With Fresh and Thawed Catfish Fillets During Refrigerated Storage." *Food and Nutrition Sciences* 9, no. 11: 1261–1272.
- Ningrum, K. P., A. Rohman, and R. Martien. 2023. "Physicochemical Characterization and Fatty Acid Profiles of Catfish Oil (*Clarias gariepinus*)." *Journal of Food and Pharmaceutical Sciences* 11: 860–866. <https://doi.org/10.22146/jfps.7418>.
- Nyasordzi, J., S. Awude, N. K. Kortei, F. M. Kpodo, C. Osei Tutu, and T. Annan. 2025. "Evaluation of Safety and Health Risk Characterization of some Baby Foods in Ghana." *Scientific Reports* 15: 42289. <https://doi.org/10.1038/s41598-025-21731-x>.
- Ogunnowo, A. M., A. F. Popoola, O. P. Asanga, O. O. Ayanleye, B. O. Oyawaluja, and A. A. Adepoju-Bello. 2025. "Analysis of Antibiotic and Heavy Metal Residues in *Clarias gariepinus* (African Catfish)." *Nigerian Journal of Pharmaceutical Research* 21: 43–49. <https://doi.org/10.4314/njpr.v21i1.5>.
- Okocha, R. C., I. O. Olatoye, and O. B. Adediji. 2018. "Food Safety Impacts of Antimicrobial Use and Their Residues in Aquaculture." *Public Health Reviews* 39, no. 1: 21. <https://doi.org/10.1186/s40985-018-0099-2>.
- Okocha, R. C., I. O. Olatoye, P. I. Alabi, M. G. Ogunnoiki, and O. B. Adediji. 2021. "Aquaculture Management Practices Associated With Antimicrobial Residues in Southwestern Nigeria." *Aquaculture* 533: 736195. <https://doi.org/10.1016/j.aquaculture.2020.736195>.
- Olagunju, A., A. Muhammad, S. Bello, A. Mohammed, H. A. Mohammed, and K. Mahmoud. 2012. "Nutrient Composition of Tilapia Zilli, Hemi-Synodontis Membranacea, Clupea Harengus and *Scomber scombrus*

- Consumed in Zaria.” *World Journal of Life Sciences and Medical Research* 2, no. 1: 16.
- Olatoye, I. O., and A. Basiru. 2013. “Antibiotic Usage and Oxytetracycline Residue in African Catfish (*Clarias gariepinus* in Ibadan, Nigeria).” *World Journal of Fish and Marine Sciences* 5, no. 3: 302–309. <https://doi.org/10.5829/idosi.wjfm.2013.05.03.71214>.
- Olopade, O. A., H. E. Dienye, G. C. Denson, and V. C. Onyekwere. 2023. “Effects of Smoking Processes on the Nutritional Value of Cultured Catfish (*Clarias gariepinus*).” *Food and Environment Safety Journal* 22, no. 1: 71–78. <https://doi.org/10.4316/fens.2023.007>.
- Oluyemi, G., A. Oluchukwu, and V. Alabi. 2024. “Nutrient Digestibility of Non-Conventional Protein Sources Blend in African Catfish, *Clarias gariepinus* (Burchell, 1822) Post Juveniles Using Novel Aquafeed Formulation Software.” *Asian Journal of Fisheries and Aquatic Research* 26, no. 4: 100–106. <https://doi.org/10.9734/ajfar/2024/v26i4760>.
- Onwenwaori, K., A. O. Oko, and S. C. Eluu. 2024. “Comparative Study of the Proximate Compositions of Tilapia and Catfish From Wild and Pond-Bred Sources in Ebonyi State, Nigeria.” *Nigeria Agricultural Journal* 55, no. 2: 797–803.
- Onyia, L. U., O. A. Sogbesan, C. Milam, and A. I. Joseph. 2011. “Microbial Load Analysis of Fresh Mud Catfish (*Clarias anguillaris*) and Tilapia (*Oreochromis niloticus*) in Lake Gerio, Adamawa State, Nigeria Using Two Different Smoking Kilns.” *Journal of Environmental Issues and Agriculture in Developing Countries* 3, no. 1: 165–170.
- Onyidoh, E. H., I. Rasaq, I. F. Muhammad, and M. A. Muhammad. 2017. “Concentrations and Risk Evaluation of Selected Heavy Metals in Water and African Catfish *Clarias gariepinus* in River Kaduna, Nigeria.” *Greener Journal of Ecology and Ecosolution* 4, no. 1: 1–9.
- Osei Tutu, C., R. Acheampong, P. T. Akonor, et al. 2026. “Postharvest Strategies for Indigenous Fruits and Vegetables in West Africa: Linking Food Loss Reduction, Nutrient Retention and Diet Quality.” *Food and Energy Security* 15, no. 3: e70275. <https://doi.org/10.1002/fes3.70275>.
- Osei Tutu, C., J. Ampah, P. T. Akonor, et al. 2026. “Performance Evaluation of a Natural-convection Gas-fired Cabinet Dryer for Drying Two Banana Varieties in Ghana.” *Food Research International: Reports* 2026: 100008, <https://doi.org/10.1016/j.frinr.2026.100008>.
- Otchoumou, A. K., C. M. Blé, S. L. Niamké, et al. 2011. “Effect of Dietary Carbohydrate: Lipid Ratio on Growth Performance and Body Composition of African Catfish (*Heterobranchius longifilis*) Fingerlings.” *Israeli Journal of Aquaculture—Bamidgeh* 63, no. 2: 169–180.
- Overå, R., A. Atter, S. Amponsah, and M. Kjelleevold. 2022. “Market Women’s Skills, Constraints, and Agency in Supplying Affordable, Safe, and High-Quality Fish in Ghana.” *Maritime Studies* 21, no. 4: 485–500. <https://doi.org/10.1007/s40152-022-00279-w>.
- Ozmen, D., H. Demircan, R. M. Yildirim, et al. 2025. “Influence of Seed Concentration and Storage Time on the Rheological, Textural, and Microscopic Crystallization Attributes of Apis Mellifera Honey.” *Food Chemistry: X* 28C, no. 2025: 102634. <https://doi.org/10.1016/j.fochx.2025.102634>.
- Pal, J., B. N. Shukla, A. K. Maurya, H. O. Verma, G. Pandey, and A. Amitha. 2018. “A Review on Role of Fish in Human Nutrition With Special Emphasis to Essential Fatty Acid.” *International Journal of Fisheries and Aquatic Studies* 6, no. 2: 427–430.
- Panghal, A., N. Chhikara, N. Sindhu, and S. Jaglan. 2018. “Role of Food Safety Management Systems in Safe Food Production: A Review.” *Journal of Food Safety* 38, no. 4: e12464. <https://doi.org/10.1111/jfs.12464>.
- Parzanini, C., S. M. Colombo, M. J. Kainz, A. Wacker, C. C. Parrish, and M. T. Arts. 2020. “Discrimination Between Freshwater and Marine Fish Using Fatty Acids: Ecological Implications and Future Perspectives.” *Environmental Reviews* 28, no. 4: 546–559.
- Peng, S., and C. Chen. 2013. “Amino Acid and Fatty Acid Composition of the Muscle Tissue of Yellowfin Tuna (*Thunnus albacares*) and Bigeye Tuna (*Thunnus obesus*).” *Journal of Food and Nutrition Research* 1, no. 4: 42–45.
- Rosa, R., N. M. Bandarra, and M. L. Nunes. 2007. “Nutritional Quality of African Catfish *Clarias gariepinus* (Burchell 1822): A Positive Criterion for the Future Development of the European Production of Siluroidei.” *International Journal of Food Science & Technology* 42, no. 3: 342–351.
- Rostika, R., F. M. Pratiwy A. Andhikawati, B. Pasaribu, and B. P. Dewanti. 2023. “The Addition of Fish Oil to Commercial Feed as Omega-3 Fatty Acid Source in Biofloc *Clarias* sp. Culture System.” *Aquaculture, Aquarium, Conservation & Legislation* 16, no. 1: 55–65.
- Sáez, M. I., M. D. Suárez, S. Cárdenas, and T. F. Martínez. 2015. “Freezing and Freezing-Thawing Cycles on Textural and Biochemical Changes of Meagre (*Argyrosomus regius*, L.) Fillets During Further Cold Storage.” *International Journal of Food Properties* 18, no. 8: 1635–1647.
- Sahu, R. K., V. V. Deshmukh, C. D. Bhong, M. S. Vaidya, and S. Patil. 2016. “Microbial Hazard Analysis of Fish (*Catla catla*) at Various Stages of Supply Chain.” *Journal of Animal Research* 6, no. 4: 711.
- Salaudeen, M. M., and A. O. Osibona. 2018. “Impact of Smoking Techniques and Storage Conditions on Microbial Safety and Stability of Catfish (*Clarias gariepinus*).” *Ife Journal of Science* 20, no. 2: 345–353. <https://dx.doi.org/10.4314/jfs.v20i2.15>.
- Shadieva, L. A., E. M. Romanova, V. N. Lyubomirova, V. V. Romanov, and T. M. Shlenkina. 2020. “Effect of Feed Composition on the Nutritional Value of Meat of African Catfish.” *BIO Web of Conferences* 27: 00134. <https://doi.org/10.1051/bioconf/20202700134>.
- Shadyeva, L. A., E. M. Romanova, V. V. Romanov, and E. V. Spirina. 2022. “Vitamin Content in Meat When Growing African Catfish With Probiotics.” *IOP Conference Series: Earth and Environmental Science* 954, no. 1: 012069.
- Shariat, M., M. Raftari, and F. Abu Bakar. 2013. “Evaluation of Sensory and Biochemical Changes in Freshwater Catfish Stored Under Vacuum and Different Modified Atmospheres.” *Analytical Methods* 5, no. 1: 231–238.
- Shi, L., T. Yin, G. Xiong, et al. 2020. “Microstructure and Physicochemical Properties: Effect of Pre-Chilling and Storage Time on the Quality of Channel Catfish During Frozen Storage.” *LWT* 130: 109606.
- Siagian, E. R., and R. A. Nugroho. 2020. “Growth Performance and Carcass Composition of African Catfish, *Clarias gariepinus* Fed Different Protein and Energy Levels.” *Iranian Journal of Fisheries Sciences* 19, no. 4: 1828–1839.
- Suja, B., R. Lochmann, T. Sink, H. Phillips, and R. Chen. 2012. “Effect of Diets Supplemented With Soybean, Flaxseed, or Menhaden Fish Oil on the Growth, Feed Utilization, Immune Status, and Sensory Properties of Channel Catfish in a Recirculating System at 22°C.” *Journal of Applied Aquaculture* 24, no. 1: 16–31. <https://doi.org/10.1080/10454438.2012.651418>.
- Taiwo, O. E., K. Usman, T. H. Ogono, and R. O. Osoniyi. 2014. “Proximate and Lipid Profile Analysis of Cultured and Wild African Catfish, *Clarias gariepinus* [Burchell].” *Ife Journal of Science* 16, no. 1: 133–142.
- Tenyang, N., H. M. Womeni, B. Tiencheu, P. Villeneuve, and M. Linder. 2017. “Effect of Refrigeration Time on the Lipid Oxidation and Fatty Acid Profiles of Catfish (*Arius maculatus*) Commercialized in Cameroon.” *Grasas y Aceites* 68, no. 1: e177. <https://doi.org/10.3989/gya.0335161>.
- Tirakomonpong, N., P. Sridonpai, K. Judprasong, et al. 2022. “Effects of Different Cooking Methods on the Vitamin D Content of Commonly Consumed Fish in Thailand.” *Foods (Basel, Switzerland)* 11, no. 6: 819. <https://doi.org/10.3390/foods11060819>.
- Tiwo, C. T., F. Tchoumboungang, E. Nganou, P. Kumar, and B. Nayak. 2019. “Effect of Different Smoking Processes on the Nutritional and Polycyclic Aromatic Hydrocarbons Composition of Smoked *Clarias gariepinus* and *Cyprinus carpio*.” *Food Science & Nutrition* 7, no. 7: 2412–2418. <https://doi.org/10.1002/fsn3.1107>.
- Tunde, A. O., O. S. Oluwagbemiga, A. Babatunde, and O. O. Oluseyi. 2016. “The Growth Performance of African Catfish (*Clarias gariepinus*) Fed Commercially Prepared Imported Fish Feeds.” *International Journal*

of *Agricultural Economics* 1, no. 3: 57–61. <https://doi.org/10.11648/j.ijae.20160103.11>.

Uchechukwu, D. E., and M. T. Okoli. 2019. “Microbial Communities of Culture Water and African Catfish Reared in Different Aquaculture Systems in Nigeria Analyzed Using Culture Dependent Techniques.” *Asian Journal of Fisheries and Aquatic Research* 5, no. 1: 1–18. <https://doi.org/10.9734/ajfar/2019/v5i130066>.

Ullah, M. R., M. A. Rahman, M. N. Haque, M. R. Sharker, M. M. Islam, and M. A. Alam. 2022. “Nutritional Profiling of Some Selected Commercially Important Freshwater and Marine Water Fishes of Bangladesh.” *Heliyon* 8, no. 10: e10825. <https://doi.org/10.1016/j.heliyon.2022.e10825>.

Ulzen, J., R. C. Abaidoo, C. Masso, E. D. J. Owusu-Ansah, and N. Ewusi-Mensah. 2018. “Is there a need for *Bradyrhizobium yuanmingense* and *B. japonicum* reinoculation in subsequent cropping seasons under smallholder farmers’ conditions?” *Applied Soil Ecology* 128: 54–60.

Unnevehr, L., and V. Hoffmann. 2015. “Food Safety Management and Regulation: International Experiences and Lessons for China.” *Journal of Integrative Agriculture* 14, no. 11: 2218–2230. [https://doi.org/10.1016/S2095-3119\(15\)61112-1](https://doi.org/10.1016/S2095-3119(15)61112-1).

Unnevehr, L. J. 2022. “Addressing Food Safety Challenges in Rapidly Developing Food Systems.” *Agricultural Economics* 53, no. 4: 529–539. <https://doi.org/10.1111/agec.12724>.

Velu, S., F. Abu Bakar, N. A. Mahyudin, N. Saari, and M. Z. Zaman. 2013. “Effect of Modified Atmosphere Packaging on Microbial Flora Changes in Fishery Products.” *International Food Research Journal* 20, no. 1: 17–26.

Wairimu, T. O., K. Esther, C. C. Ngugi, B. M. Mwangi, and J. K. Nzeve. 2019. “Impact of Aquaculture Development on Water Quality of Fish Ponds in Gatundu North and South Sub-Counties, Kenya.” *International Journal of Fisheries and Aquatic Studies* 7, no. 4: 01–06.

Walayat, N., W. Tang, X. Wang, et al. 2023. “Quality Evaluation of Frozen and Chilled Fish: A Review.” *eFood* 4, no. 1: e67. <https://doi.org/10.1002/efd2.67>.

Wedekind, H. 1995. “Dietary Influences on Product Quality in African Catfish (*Clarias gariepinus*).” *Journal of Applied Ichthyology* 11, no. 3–4: 347–353. <https://doi.org/10.1111/j.1439-0426.1995.tb00038>.

Wegmüller, R., H. Bentil, J. P. Wirth, et al. 2020. “Anemia, Micronutrient Deficiencies, Malaria, Hemoglobinopathies and Malnutrition in Young Children and Non-Pregnant Women in Ghana: Findings From a National Survey.” *PLoS ONE* 15, no. 1: e0228258. <https://doi.org/10.1371/journal.pone.0228258>.

Yeboah, M. A., A. Philip, A. W. Nelson, A. Muspratt, and S. Aikins. 2019. “Safety Assessment on Microbial and Heavy Metal Concentration in *Clarias gariepinus* (African Catfish) Cultured in Treated Wastewater Pond in Kumasi, Ghana.” *Environmental Technology* 40, no. 3: 302–311. <https://doi.org/10.1080/09593330.2017.1388851>.

Yusuf, K. A., L. N. Ezechukwu, K. A. Fakoya, S. L. Akintola, J. I. Agboola, and T. O. Omoleye. 2015. “Influence of Fish Smoking Methods on Polycyclic Aromatic Hydrocarbons Content and Possible Risks to Human Health.” *African Journal of Food Science* 9, no. 3: 126–135. <https://doi.org/10.5897/AJFS2014.1227>.

Zhu, Y., L. Ma, H. Yang, Y. Xiao, and Y. L. Xiong. 2016. “Super-Chilling (−0.7°C) With High-CO₂ Packaging Inhibits Biochemical Changes of Microbial Origin in Catfish (*Clarias gariepinus*) Muscle During Storage.” *Food Chemistry* 206: 182–190. <https://doi.org/10.1016/j.foodchem.2016.03.053>.

Zornu, J., M. Oyih, M. Binde, et al. 2023. “Stakeholder Perspectives on the 2023 Ghana National Aquaculture Development Plan: An Integration Within the Ecosystem Approach Framework.” *Aquaculture, Fish and Fisheries* 3, no. 6: 459–471. <https://doi.org/10.1002/aff2.135>.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supplementary Material: aff270303-sup-0001-Tables.docx.