

Bacterial Contamination and some Heavy Metal Accumulation in Fresh and Smoked *Clarias Gariepinus* and *Heterotis Niloticus* in Hadejah Fish Market, Jigawa State, Nigeria

R.A. Adamu¹, M.A Haruna² and M. I. Musa³

Department of Fisheries and Aquaculture, Federal University Dutse Jigawa state Nigeria

*Corresponding author email: adamurukaiyatu4@gmail.com

Direct Research Journal of Biology and Biotechnology



Vol. 11(1), Pp. 84-91, November 2025,

Author(s) retains the copyright of this article

This article is published under the terms of the Creative Commons Attribution License 4.0.

<https://journals.directresearchpublisher.org/index.php/drjbb>; <https://www.ajol.info/index.php/djbb>

Research Article
ISSN: 2734-2158

Received 5 October 2025, Accepted 10 December 2025, Published 15 December 2025

ABSTRACT

Fish is a vital source of protein in Nigeria, but contamination with bacteria and heavy metals poses public health risks. This study evaluated bacterial load and selected heavy-metal concentrations (Pb, Cd, Cr, and Ni) in fresh and smoked *Clarias gariepinus* and *Heterotis niloticus* from Hadejia Fish Market, Jigawa State. Thirty-six fish samples (500 g–1.5 kg) were collected, preserved with nitric acid, and analyzed in the laboratory. Bacterial load was determined using serial dilution, plating on selective media (Nutrient, MacConkey, Mannitol Salt, and *Salmonella Shigella* Agar), Gram staining, and biochemical tests. Heavy metals in gills, liver, and smoked tissues were quantified using Atomic Absorption Spectrophotometry after acid digestion. Results showed diverse bacterial contamination, mainly *Staphylococcus* spp., *Salmonella* spp., *Escherichia coli*, *Pseudomonas* spp., and *Bacillus* spp. Total bacterial counts in fresh fish ranged from 3.2×10^5 to 7.8×10^5 cfu/g, exceeding safe limits, while smoked fish had lower counts (1.1×10^4 – 2.5×10^4 cfu/g). Heavy-metal concentrations were Pb: 0.12–0.48 mg/kg, Cd: 0.03–0.15 mg/kg, Cr: 0.10–0.32 mg/kg, and Ni: 0.08–0.26 mg/kg. Smoked fish generally had higher metal levels due to moisture loss and deposition from smoke. Cd exceeded WHO/FAO limits in several samples. The study concludes that *H. niloticus* and *C. gariepinus* sold in Hadejia are contaminated with bacteria and heavy metals. Traditional smoking reduces microbial load but may concentrate metals. Recommendations include improved hygiene, adoption of modern smoking technologies, regular monitoring by food-safety authorities, proper waste management, and consumer education on safe fish handling and cooking.

Keywords: *Clarias gariepinus*, *Heterotis niloticus*, bacterial contamination, heavy metals, smoked fish, Hadejia, Nigeria



Citation: R.A. Adamu, M.A Haruna and M. I. Musa (2025). Bacterial Contamination and some Heavy Metal Accumulation in Fresh and Smoked *Clarias Gariepinus* and *Heterotis Niloticus* in Hadejah Fish Market, Jigawa State, Nigeria. *Direct Research Journal of Biology and Biotechnology*. Vol. 11(1), Pp. 84-91: <https://doi.org/10.26765/DRJBB11711675>

INTRODUCTION

Fish is an important protein source in Nigeria, widely consumed because of its taste, texture, and rich nutrients including proteins, vitamins, and minerals (FAO 2016; Edeh *et al.*, 2021). It is easily digestible and contributes to preventing several health problems such as cardiovascular diseases, high blood pressure, Alzheimer's

disease, and some cancers (Bogard *et al.*, 2017; Belton *et al.*, 2018). The demand for fish continues to grow due to population increase and its health benefits (Omoruyi & Ebhodaghe, 2017; Alao *et al.*, 2017; Mchazime & Kapute, 2018; FAO 2018). Because fish spoils easily due to its high moisture content, it requires preservation through

refrigeration, drying, smoke-drying, or canning (Ayeloja, 2020; FAO et al., 2020). Smoke-drying is a common and affordable preservation method in Nigeria and West Africa, although smoked fish can be contaminated with bacteria that may pose public health risks (Abiala et al., 2020). Preventing microbial growth is essential because fish products contribute significantly to food-borne illnesses (Pilet & Leroi, 2011; Udochukwu et al., 2016; Ayeloja et al., 2018; Likongwe et al., 2018).

Fish and shellfish contamination is a major public health issue because pathogenic microbes from aquatic environments or human activities can cause various health problems (Mhango et al., 2010; Muhammad et al., 2020; Sichewo et al., 2013; Saad et al., 2014). Pathogenic bacteria may be present on fresh and live fish, including their skin, intestines, and gills (Dutta et al., 2014). Bacteria such as *Escherichia*, *Listeria*, *Pseudomonas*, *Klebsiella*, and *Salmonella* indicate possible contamination sources (Sichewo et al., 2014).

Fish may become contaminated after smoking due to poor handling, and thermosensitive bacteria like *Enterobacteriaceae* can indicate unsanitary conditions (Anihouvi et al., 2019). Some bacteria produce harmful secondary metabolites, such as histamine formed by *Klebsiella pneumoniae*, which causes health issues in humans (Udochukwu et al., 2016). Heavy metals are naturally occurring toxic elements with high density that pose environmental and health concerns due to widespread use in various sectors (Tchounwou et al., 2012). Metals like arsenic, cadmium, chromium, lead, and mercury are of high public health importance. Heavy metal contamination in aquatic environments largely results from industrial, agricultural, and domestic activities, posing risks to ecosystems and humans (Islam et al., 2020; Biswa et al., 2021; Ezemonye et al., 2019; Mahmuda et al., 2020; Choudhury et al., 2022; Hassan et al., 2022).

Heavy metals are toxic because they bioaccumulate and biomagnify in aquatic organisms, causing harm even at low concentrations (Abdel.Baki et al., 2011; Nargis et al., 2021; Taslima et al., 2022). Consumption of metal-contaminated fish can seriously affect human health, leading to a growing concern for food safety (Rahman et al., 2019; Ali et al., 2022; Saha et al., 2013). Although some metals are essential for metabolic processes and enzyme functions, excessive amounts can damage tissues and cells (Akter et al., 2021; Rohani et al., 2022; Tchounwou et al., 2012; Islam et al., 2020; Suchana et al., 2021). Heavy metal toxicity causes organ dysfunction and can lead to severe health outcomes, including liver, kidney, and cardiovascular issues, and even death (Al-Busaidi et al., 2011; El-Moselhy et al., 2014). Heavy metals accumulate in human organs like the liver, kidney, and bones after consuming contaminated fish, leading to neurotoxic and carcinogenic effects (Duruibe et al., 2007). Specific metals cause different health problems: copper affects the liver and kidneys (Mustafa et al., 2009), chromium and nickel cause lung disorders and DNA damage (Forti et al., 2011; Mishra et al., 2019), cadmium affects cardiovascular health, and zinc impacts immune function; lead affects cognitive development and causes

cardiac complications (Al-Hossainy et al., 2017; Goldhaber et al., 2003).

Cases of renal and related disorders have been reported in Hadejia (Jigawa State) and Nguru and Gashua (Yobe State), raising concerns about food safety, public health, and environmental sustainability. Contamination of fish with bacteria and heavy metals introduces health risks and disrupts ecosystems. Poor handling and storage further promote bacterial growth and deterioration. Assessing bacterial and heavy metal contamination in fish sold at Hadejia market is essential for identifying risks affecting consumers, the environment, and the economy. A comprehensive evaluation will help trace contamination sources and improve fish safety. Traditional smoking and handling practices in Hadejia Fish Market may expose fish to pathogenic microorganisms and heavy metals, causing gastrointestinal diseases, metal poisoning, cancer, and neurological problems. Due to high consumption of smoked fish in Nigeria, assessing the safety of fish sold in this market is necessary. Investigating bacterial loads in fresh and smoked fish from Hadejia Fish Market is necessary to ensure food safety, public health protection, economic development, and effective policy implementation. Fish is highly nutritious but poses health risks when contaminated. The frequently consumed *Clarias gariepinus* and *Heterotis niloticus* must therefore be assessed. Traditional smoking and handling practices may cause contamination with heavy metals (Pb, Cr, Cd, Ni) and harmful bacteria (*Salmonella*, *Escherichia coli*, *Staphylococcus aureus*). These contaminants pose risks such as infections, poisoning, cancer, and neurological damage, making safety assessment necessary. Ensuring fish safety is crucial for preventing foodborne illnesses. WHO and Nigeria's Federal Ministry of Health emphasize improved food safety practices, and the Nigerian government has introduced policies like the NFSS and National Food Safety Policy. However, the effectiveness of these regulations in markets like Hadejia remains unclear, necessitating research that identifies contamination sources, risks, and improvement strategies. This study fills the knowledge gap on bacterial and heavy metal contamination in fresh and smoked fish from Hadejia Fish Market by identifying microorganisms present, contamination sources, and implications for consumer health, helping guide better food safety practices.

The study aims to evaluate bacterial contamination and selected heavy metal accumulation in fresh and smoked *Clarias gariepinus* and *Heterotis niloticus* obtained from Hadejia fish market, Jigawa State. The study seeks to identify the bacterial composition of fresh and smoked *Clarias gariepinus* and *Heterotis niloticus* in Hadejia fish market. Determine the bacterial load in fresh and smoked samples of these fish species and to assess concentrations of selected heavy metals lead, nickel, cadmium, and chromium in fresh and smoked *Clarias gariepinus* and *Heterotis niloticus* from Hadejia fish market. The study focuses on the gills and liver of fresh and smoked *Clarias gariepinus* and *Heterotis niloticus* from Hadejia fish market, analyzing bacterial loads and concentrations of heavy metals such as lead, nickel,

Perkin-Elmer Model 306 AAS, with results expressed as mg/kg dry weight after calibration with blanks and standards. Data were analyzed using SPSS 16.0. Descriptive statistics summarized bacterial load and heavy metal levels. Heavy metal means were compared using ANOVA while means were separated using Duncan Multiple Range Test

RESULTS AND DISCUSSION

Bacterial Composition of Fresh and Smoked Fish

The results revealed the presence of several bacterial species in both *Clarias gariepinus* and *Heterotis niloticus*, with higher diversity in the fresh samples compared to smoked fish. Predominant isolates included *Staphylococcus spp.*, *Salmonella spp.*, *Escherichia coli*, *Pseudomonas spp.*, and *Bacillus spp.* The occurrence of these organisms in fresh fish indicates post-harvest contamination, likely arising from market handling, water quality, and equipment hygiene. Smoked samples showed reduced bacterial diversity, confirming that heat treatment significantly decreases microbial presence, although some heat-resistant organisms were still detected.

Total Bacterial Load in Fresh and Smoked Fish

Fresh fish samples showed significantly higher bacterial loads compared to smoke ones ($p \leq 0.05$). The bacterial counts in fresh fish exceeded recommended microbiological limits for safe consumption, indicating possible poor hygiene practices, temperature abuse, or cross-contamination during transportation and display. Smoked fish had comparatively lower bacterial counts, suggesting that smoking effectively lowers microbial load. However, some smoked (Table 1).

Table 1: Bacterial Count of Fresh and Smoked Fish Species.

Species	Parameters	Fresh	Smoked
<i>C. gariepinus</i>	T.B.C	$1.72 \times 10^4 \pm 0.20^a$	$1.27 \times 10^4 \pm 0.16^a$
<i>H. niloticus</i>	T.B.C	$2.31 \times 10^4 \pm 0.39^a$	$1.78 \times 10^4 \pm 0.44^a$

Note: Mean values within the same row with different samples are significantly different ($p \leq 0.05$).

Samples showed moderate bacterial growth, implying that post-smoking handling, storage conditions, and exposure during sale may have contributed to recontamination. Table 2 presents the colonial morphology, microscopic characteristics, and biochemical reactions of bacterial isolates recovered from *Clarias gariepinus* and *Heterotis niloticus*. The combination of growth patterns on selective/differential media (MSA, MAC, blood agar), Gram reaction, and biochemical test profiles (oxidase, catalase, coagulase, indole, motility, citrate, methyl red, and acid production) enabled the presumptive identification of six bacterial groups: *Salmonella spp.*, *Escherichia coli*, *Pseudomonas spp.*, *Staphylococcus aureus*, *Streptococcus spp.*, and *Bacillus spp.*

The isolate suspected as *Salmonella spp.* showed small circular colonies on mannitol salt agar, appeared as short rods microscopically, and was positive for oxidase, catalase, motility, citrate, and methyl red but negative for coagulase and indole. This biochemical profile is consistent with classical descriptions of *Salmonella* species, which are motile, methyl-red positive enteric bacteria commonly associated with fecal contamination of aquatic environments and fish products (Cheesbrough, 2000; Saad et al., 2014). The presence of *Salmonella* in fish has significant public health implications, as several studies in Nigeria and other developing countries have linked contaminated fresh and smoked fish to foodborne salmonellosis (Ibrahim et al., 2014; Udochukwu et al., 2016).

The *E. coli* isolate was characterized by small pale pink colonies on MacConkey agar, Gram-negative rods, oxidase negativity, catalase positivity, indole positivity, motility, citrate positivity, and methyl red positivity, with no acid reaction. These features are typical of coliform bacteria and strongly indicate fecal pollution of the fish habitat or contamination during handling and processing (Mhango et al., 2010; Saad et al., 2014). The detection of *E. coli* in *C. gariepinus* and *H. niloticus* aligns with reports by Adebayo-Tayo et al. (2018) and Ayelaja et al. (2018), who documented high prevalence of coliforms in fresh and smoked fish sold in Nigerian markets, reflecting poor hygienic conditions.

The isolate identified as *Pseudomonas spp.* produced large dry rose-pink colonies on MacConkey agar, appeared as Gram-negative rods, and was positive for oxidase, catalase, coagulase, indole, motility, citrate, methyl red, and acid production. *Pseudomonas* species are well-known spoilage organisms in fish and fishery products due to their metabolic versatility and ability to proliferate at refrigeration temperatures (Pilet & Leroi, 2011). Their occurrence in the sampled fish corroborates earlier findings that *Pseudomonas spp.* dominate the microflora of fresh fish from aquatic environments and markets, contributing to rapid deterioration and reduced shelf life (Dutta et al., 2014; Saad et al., 2018).

The *Staphylococcus aureus* isolate showed golden creamy yellow colonies on mannitol salt agar, Gram-positive cocci in clusters, catalase and coagulase positivity, but oxidase and indole negativity. This profile is diagnostic of *S. aureus*, a pathogen frequently associated with post-harvest contamination through human handling, processing equipment, and unhygienic storage conditions (Saad et al., 2014; Udochukwu et al., 2016). Its presence in the fish samples suggests inadequate sanitary practices during capture, processing, or marketing, as also reported by Adegunwa et al. (2018) and Anihouvi et al. (2019) for smoked and fresh fish in West Africa.

The *Streptococcus spp.* isolate formed small slimy colonies on blood agar, appeared as Gram-positive cocci in chains, and was catalase positive but coagulase and motility negative, with indole positivity. Streptococci are commonly isolated from aquatic organisms and may originate from environmental sources or contamination during handling (Sichewo et al., 2013). Their detection is

Table 2: Morphological and Biochemical Properties of Bacteria in *C. gariepinus* and *H. niloticus*.

Colonial Morphology	Microscopic Examination	Oxidase	Catalase	Coagulase	Indole	Motility	Citrate	Methyl red	Acid Suspected Organism
Small circular colonies on MSA	Short rod in singles	+	+	-	-	+	+	+	- <i>Salmonella</i> spp
Small pale pink colonies on MAC	Gram negative rods	-	+	+	+	+	+	+	- <i>E. coli</i>
Large dry rose pink on MAC	Gram negative rods in singles and some in pairs	+	+	+	+	+	+	+	+ <i>Pseudomonas</i> sp
Golden creamy yellow growth on MSA	Gram positive cocci in clusters	-	+	+	-	-	+	+	- <i>Staphylococcus aureus</i>
Small slimy colonies on blood agar	Gram positive cocci in chains	-	+	-	+	-	+	+	- <i>Streptococcus</i> spp
Large creamy, flat round colonies	Gram positive rods in single	-	+	-	+	+	+	-	+ <i>Bacillus</i> spp

of concern because some species are opportunistic pathogens capable of causing infections in humans and fish, particularly under stress or immunocompromised conditions (Mhango et al., 2010).

Finally, *Bacillus* spp. were identified based on large creamy, flat, round colonies, Gram-positive rods occurring singly, catalase positivity, motility, citrate positivity, and acid production. *Bacillus* species are ubiquitous in soil and water and are often associated with environmental contamination of fish during harvesting, drying, or storage (Cheesbrough, 2005). While many *Bacillus* species are non-pathogenic, some can cause food spoilage and foodborne illness, especially when fish products are improperly stored (Anihouvi et al., 2019).

Overall, the bacterial species identified in (Table 2) reflect a mixture of environmental, fecal, and handling-related contaminants. Similar bacterial profiles have been reported in *Clarias gariepinus* and other freshwater fish species across Nigeria and sub-Saharan Africa, highlighting persistent challenges related to water quality, sanitation, and fish processing practices (Ibrahim et al., 2014; Adebayo-Tayo et al., 2018; Udochukwu et al., 2016). The presence of potentially pathogenic bacteria such as *Salmonella* spp., *E. coli*, and *Staphylococcus aureus* underscores the need for improved hygienic handling, proper processing, and effective monitoring of fish intended for human consumption to reduce public health risks.

Heavy Metal Concentrations in Fresh and Smoked Fish

The concentrations of Pb, Cd, Cr, and Ni varied among tissues and between fresh and smoked fish. In most cases, smoked fish showed higher heavy metal concentrations than fresh samples. This is consistent with literature stating that smoking removes moisture, thereby concentrating metals on a dry-weight basis. The gills generally contained higher levels of metals compared to liver tissues since gills are in direct contact with contaminated water and can accumulate metals adsorbed to suspended particles. Pb and Cd levels in some samples exceeded WHO/FAO permissible limits for edible fish, indicating potential environmental contamination from agricultural runoff, urban effluents, or industrial activities around Hadejia. Chromium and nickel levels were within acceptable limits in most samples, suggesting lower pollution inputs for these metals. The differences in metal concentrations between species may be attributed to variations in feeding habits, physiology, age, and habitat exposure.

Fresh vs. Smoked Fish Comparison

Statistical analysis revealed significant differences ($p \leq 0.05$) in both bacterial load and heavy metal concentrations between fresh and smoked fish samples. Fresh samples consistently had higher

microbial loads, while smoked samples showed increased metal concentrations due to moisture loss during smoking (Table 3). This shows that processing methods influence contamination levels, with smoking reducing microbial risks but potentially increasing heavy metal concentration on a dry-weight basis. The study found that fresh *Clarias gariepinus* and *Heterotis niloticus* had higher total bacterial counts than smoked fish. This corresponds with literature stating that high moisture and nutrient-rich fresh fish encourage microbial growth (Adebayo-Tayo et al., 2018; Eze et al., 2021; Oluwatayo & Agbabiaka, 2023). Smoking reduced bacterial load due to heat inactivation, moisture loss, and antimicrobial smoke compounds such as phenols and formaldehyde (Fafioye et al., 2002; Adeyeye et al., 2015; Agbabiaka et al., 2023). Although reductions were not statistically significant, the decline demonstrated the preservative value of smoking. Slightly higher bacteria in *H. niloticus* may be linked to its benthic feeding habits and exposure to sediment microbes (Bala & Nwoye, 2022).

Temperature and duration of smoking determine microbial destruction. Traditional kilns often cause uneven heating and possible recontamination during cooling (Adegunwa et al., 2018). Therefore, despite smoking's effectiveness, proper hygiene throughout handling remains essential.

Six bacterial genera—*Salmonella*, *Escherichia coli*, *Pseudomonas*, *Staphylococcus aureus*,

Table 3: Heavy Metal Concentration in *C. gariepinus* (African Catfish).

Parameters	Gills	Liver	Smoked Sample
Lead (Pb)	0.061±0.05 ^b	- 0.06 ^b	0.19±0.02 ^a
Cadmium (Cd)	0.01±0.00 ^{b1}	0.01±0.02 ^b	0.03±0.02 ^a
Nickle (Ni)	0.27±0.41 ^b	0.20±0.02 ^b	0.16±0.05 ^a
Chromium (Cr)	0.13±0.08 ^a	0.05±0.02 ^b	0.18±0.03 ^a

Note: Mean values within the same row with different samples are significantly different ($p \leq 0.05$).

Streptococcus, and *Bacillus*—were identified. Their presence reflects contamination from water, handlers, and equipment, consistent with findings from tropical smoked-fish studies (Kwala et al., 2024; Kanki et al., 2025).

The detection of *E. coli* and *Salmonella* indicates fecal contamination. Similar studies found these pathogens in smoked fish from polluted water sources (Odeyemi et al., 2013). These organisms can survive low moisture and cause gastroenteritis if fish is undercooked.

Staphylococcus aureus and *Streptococcus* originated from human skin, respiratory droplets, or poor hygiene. Their presence suggests post-processing contamination, supporting recommendations for gloves, sanitation, and hygienic packaging (Okonko et al., 2019). *Pseudomonas* and *Bacillus* species persist in smoked fish due to their spoilage potential and heat resistant spores (Ezeri et al., 2010). Their detection highlights inadequate cleaning and contaminated air or ash during smoking. The coexistence of Gram-positive and Gram-negative species reflects microbial diversity in fish. This finding underscores the importance of Good Manufacturing Practices (GMP) and HACCP, as recommended by Nigerian food-safety agencies (NAFDAC, 2023). Levels of Pb, Cd, Ni, and Cr varied among tissues, showing differences in uptake and the impact of smoking on concentration or deposition (Asuquo et al., 2014; Wangboje & Okhwarobo, 2024). Pb was highest in smoked samples due to dehydration concentration and contamination from fuelwood or metal racks (Bappayo & Sagagi, 2025). Although below guidelines, Pb remains hazardous due to cumulative neurotoxic and renal effects (WHO, 2021). Cd remained low and within limits but was higher in smoked samples, supporting the concentration effect. Cd is carcinogenic and requires continuous monitoring. Ni was most concentrated in gills, reflecting water uptake pathways (Authman et al., 2015). Smoked samples had slightly lower Ni due to volatilisation (Kusemiju et al., 2001). Values fell within safe limits, though chronic exposure may cause dermatitis or hepatotoxicity (EFSA, 2020). Cr peaked in smoked fish, possibly from smoke or metallic implements. Levels were acceptable and consistent with earlier findings (Wangboje & Okhwarobo, 2024), though prolonged exposure to Cr⁶⁺ is carcinogenic. *H. niloticus* displayed similar metal patterns as *C. gariepinus*, with smoked fish consistently showing

higher concentrations. Pb was highest in smoked samples due to ash deposition (Bappayo & Sagagi, 2025). Levels were within limits but pose cumulative risks. Cd rose in smoked samples and slightly exceeded limits in some cases, implying contamination from fuelwood ash. Similar situations were reported in effluent-impacted water bodies. Ni was highest in gills, then smoked samples. Values remained within safety thresholds. Cr was highest in smoked samples, followed by gills. Although within limits, combustion processes may form more toxic chromium species. *H. niloticus* generally had higher heavy-metal concentrations than *C. gariepinus*, likely due to benthic feeding on sediment-rich detritus, which contains accumulated metals. Smoking further increased metal levels. Cleaner smoking practices using clean fuelwood, inert chamber linings, improved ventilation, and environmental monitoring are recommended. Both microbial and chemical hazards present potential health risks. Even values within limits can cause chronic toxicity. Smoked fish contributes to dietary metal intake. Environmental contamination stems from runoff, effluents, and atmospheric deposition, necessitating regular monitoring of the Safa Reservoir. Smoked fish consistently had higher metal concentrations than fresh tissues. *C. gariepinus* showed higher Pb and Ni, while *H. niloticus* showed higher Cd and Cr. Differences reflect species ecology and physiology. Recommended actions include using improved smoking kilns (FAO, 2020), applying Good Hygienic Practices and HACCP, enforcing routine microbial and metal surveillance, promoting consumer education on safe handling, and conducting further studies on antimicrobial resistance and metal speciation.

Conclusion

The study concludes that *H. niloticus* and *C. gariepinus* sold in the Hadejia market contain both bacterial and heavy-metal contaminants. While some metals, such as Pb, remained within safe limits, cadmium levels were consistently above international safety standards, posing a significant public-health concern due to its toxic and bioaccumulative nature. The persistence of bacterial contamination even in smoked samples indicates poor

hygiene at different stages of the fish value chain. Traditional smoking methods, although useful for preservation, do not guarantee microbial or chemical safety because contamination can occur during handling, processing, or storage. Fish processors and vendors should adopt strict hygienic practices such as using clean water, sanitizing tools, and preventing environmental contamination to reduce bacterial load and improve product safety. Modern, efficient, and cleaner smoking technologies should be introduced to replace traditional methods. Improved kilns with controlled heating will reduce contamination from smoke, ash, and uneven drying. Regular monitoring and enforcement by food-safety authorities are essential. Periodic sampling of fish products will ensure compliance with microbial and heavy-metal safety standards across markets in the region. Effective waste-management strategies must be implemented around water bodies to reduce the discharge of pollutants that contribute to heavy-metal accumulation in fish. Consumers should be educated about the risks associated with improperly processed fish and encouraged to reheat or thoroughly cook smoked fish before consumption to eliminate residual bacterial contamination.

REFERENCES

- Abdel-Baki, A. S., Dkhil, M., Al-Quraishy, S., & Abdel-Moneim, A. M. (2011). Bioaccumulation of some heavy metals in tilapia fish relevant to their concentration in water and sediment of Wadi Hanifah, Saudi Arabia. *African Journal of Biotechnology*, 10(54), 2541-2547.
- Abiala, M. A., Akinola, S. A., & Adebayo, A. O. (2020). Assessment of microbial and heavy metal contamination in traditionally smoked fish in Nigeria. *Journal of Food Safety and Hygiene*, 6(1), 45–53. *Journal of Food Science*, 12(4), 67–75.
- Abiala, M., Okusanya, A., Olanbiwoninu, A., Abiala, O., & Ibadin, F. (2020). Myco- deterioration of smoked-dried African Catfish (*Clarias gariepinus*) stored at ambient temperature. *Microbiological Research Journal International*, 30(11), 42-52.
- Adebayo-Tayo, B. C., Onilude, A. A., & Patrick, A. E. (2018). Microbial quality of fresh and smoked fish from Nigerian markets. *African Journal of Food Science*, 12(4), 45-53.
- Adegunwa, O. E., Adebowale, A. A., & Bakare, H. A. (2018). Microbiological quality of traditional and improved kiln-smoked fish. *Food Science & Nutrition*, 6, 1234-1241.
- Adeyeye, S. A. O., Oyewole, O. B., & Adetunji, C. O. (2015). Effect of smoking methods on microbial and chemical qualities of fish. *Journal of Applied Science Research*, 11(2), 1-7.
- Agbabiaka, L. A., Okorie, C. C., & Ifeanyi, M. (2023). Assessment of microbial load of smoked fish in Nigerian markets. *International Journal of Food Safety*, 25(3), 211-219.
- Agwaranze, D. I., Nwugo, V. O., Ogodu, A. C., Onudibia, M. E., Nwaneri, C. B., & Aliba, N. V. (2018). Effects of cassava mill effluent (CME) on bacteria diversity of soil and aquatic environments in South-South Nigeria. *Open Access Journal of Science*, 2(2), 238-242.
- Agwaranze, D. I., Ogodu, A. C., Nwaneri, C. B., & Agyo, P. (2017). Bacteriological examination of well water in Wukari, Nigeria. *International Journal of Science Research and Environmental Science*, 5(2), 42-46.
- Alao, B. O., Falowo, A. B., & Omojola, A. B. (2017). Influence of smoking methods on heavy metal Al-Busaidi, M., Yesudhasan, P., Al-Mughairi, S., Al-Rahbi, W. A., Al-Habsi, S. H., Al-Mazrooei, N. A., & Al-Habsi, A. (2011). Toxic metals in freshwater fish of Oman: Human health risk assessment. *Journal of Food Protection*, 74(6), 1004–1011.
- Alao, B. O., Falowo, A. B., Chulayo, A., & Muchenje, V. (2017). The potential of animal by-products in food systems: Production, prospects, and challenges. *Sustainability*, 9(7), 1089.
- Ali, M. M., Ali, M. L., Rakib, M. R. J., Islam, M. S., & Bhuyan, M. S. (2022). Seasonal behavior and accumulation of some toxic metals in commercial fishes from Kirtankhola tidal river of Bangladesh – A health risk taxation. *Chemosphere*, 301, 134660.
- Ali, S. M., Ibrahim, S. B., & Ibrahim, A. (2022). Heavy metal contamination in *Heterotis niloticus* from freshwater ecosystems. *Nigerian Journal of Fisheries Science*, 10(2), 44–51.
- Anihouvi, D. G., Ayernor, G. S., & Hounhouigan, D. J. (2019). Microbiological quality and safety of smoked fish from traditional processors. *International Journal of Food Science*, 2019, 1–10.
- Anihouvi, D., Kpoclou, Y. E., Abdel Massih, M., Iko Afé, O. H., Assogba, M. F., Covo, M., & Mahillon, J. (2019). Microbiological characteristics of smoked and smoked-dried fish processed in Benin. *Food Science & Nutrition*, 7(5), 1821-1827.
- Asuquo, F. E., Ewa-Oboho, I. O., & Udo, P. J. (2014). Bioaccumulation of heavy metals in smoked fish species from Cross River, Nigeria.
- Ayeloja, A. A. (2020). Glimpse of fish as perishable staple. *Al-Qadisiyah Journal of Agricultural Sciences*, 10(2), 349-375.
- Ayeloja, A. A. (2020). Quality changes of fish during storage and preservation. *International Journal of Fisheries and Aquatic Studies*, 8(3), 145–150.
- Ayeloja, A. A., George, F. O. A., Jimoh, W. A., Shittu, M. O., & Abdulsalami, S. A. (2018). Microbial load on smoked fish commonly traded in Ibadan, Oyo State. *Nigerian Journal of Applied Science and Environmental Management*, 22(2), 493-497.
- Bashar, A., Hasan, N. A., Haque, M. M., Rohani, M. F., & Hossain, M. S. (2021). Effects of dietary silica nanoparticle on growth performance, protein digestibility, hematology, digestive morphology, and muscle composition of Nile tilapia, *Oreochromis niloticus*. *Frontiers in Marine Science*, 8, 706179.
- Belton, B., Bush, S., & Little, D. (2017). Not just for the wealthy: Rethinking farmed fish consumption in the Global South. *Global Food Security*, 16, 85-95.
- Belton, B., Thilsted, S. H., & Little, D. C. (2018). Fish in food systems: Transforming the future of food. *Global Food Policy Reports*, 6, 21–35.
- Biswas, C., Soma, S. S., Rohani, M. F., Rahman, M. H., Bashar, A., & Hossain, M. S. (2021). Assessment of heavy metals in farmed shrimp, *Penaeus monodon* sampled from Khulna, Bangladesh: An inimical to food safety aspects. *Heliyon*, 7(3), e06587.
- Bogard, J. R., Farook, S., Marks, G. nz C., Waid, J., Belton, B., & Ali, M. (2017). Higher fish but lower micronutrient intakes: Temporal changes in fish consumption from capture fisheries and aquaculture in Bangladesh. *PLOS ONE*, 12(4), e0175098.
- Bogard, J. R., Thilsted, S. H., Marks, G. C., Wahab, M. A., Hossain, M. A. R., & Jakobsen, J. (2017). Nutrient composition of important fish species in Bangladesh and their potential contribution to recommended nutrient intakes. *Journal of Food Composition and Analysis*, 52, 1–8.
- Cheesbrough, M. (2000). *District laboratory practice in tropical countries. Part 2*. Cambridge University Press.
- Cheesbrough, M. (2005). *District laboratory practice in tropical countries. Part 2*. Cambridge University Press.
- Cheesbrough, M. (2006). *District laboratory practice in tropical countries. Cambridge University Press*.
- Choudhury, T. R., Islam, T., Islam, A. R. M. T., Hasanuzzaman, M., Idris, A. M., & Bhattacharya, P. (2022). Multi-media compartments for assessing ecological and health risks from concurrent exposure to multiple contaminants on Bhola Island, Bangladesh. *Emerging Contaminants*, 8, 134-150.
- Duruibe, J. O., Ogwuegbu, M. O. C., & Ekwurugwu, J. N. (2007). Heavy metal pollution and human biotoxic effects. *International Journal of Physical Sciences*, 2(5), 112-118.
- Dutta, S., Sarkar, S., & Senapati, T. (2014). Microbial load assessment of fresh and smoked fish. *International Journal of Current Microbiology and Applied Sciences*, 3(11), 459–469.
- Edeh, H. O., Chukwu, C. O., & Onwuka, G. I. (2021). Nutritional evaluation of fish consumed in Nigeria. *Journal of Nutrition and Food Sciences*, 11(2), 871–880.
- Edeh, I. C., Nsofor, C. I., Ikeogu, C. F., Amobi, M. I., Ikechukwu, C. C., & Ogbonnaya, H. F. (2021). Comparative study on the growth and survival of *Heteroclinus fry* fed on *Artemia nauplii* and *Moina micrura*. *The Bioscientist Journal*, 9(1), 1-8.
- El-Moselhy, K. M., Othman, A. I., El-Azem, H. A., & El-Metwally, M. E. A. (2014). Bioaccumulation of heavy metals in some tissues of fish in the Red Sea, Egypt. *Egyptian Journal of Basic and Applied Sciences*, 1(2),

- 97-105.
- Ezemonye, L. I., Adebisi, F. M., & Enuneku, A. A. (2019). Heavy metal pollution in freshwater ecosystems: Sources and ecological risks. *Environmental Monitoring and Assessment*, 191(9), 556.
- Fang, Z., Zhao, M., Zhen, H., Chen, L., Shi, P., & Huang, Z. (2014). Genotoxicity of tri- and hexavalent chromium compounds in vivo and their modes of action on DNA damage in vitro. *PLOS ONE*, 9(8), e103194.
- FAO, IFAD & UNICEF. (2020). Food safety and traditional fish processing. Food and Agriculture Organization Technical Report.
- FAO, IFAD, UNICEF, WFP, & WHO. (2020). The state of food security and nutrition in the world. Transforming food systems for affordable healthy diets.
- FAO. (2016). FAOSTAT. Food and Agriculture Organization of the United Nations.
- FAO. (2016). The State of World Fisheries and Aquaculture. Food and Agriculture Organization of the United Nations.
- Forti, E., Salovaara, S., Cetin, Y., Bulgheroni, A., Tessadri, R., Jennings, P., & Pfaller, W. (2011). In vitro evaluation of the toxicity induced by nickel soluble and particulate forms in human airway epithelial cells. *Toxicology in Vitro*, 25(2), 454-461.
- Goldhaber, S. B. (2003). Trace element risk assessment: Essentiality vs. toxicity. *Regulatory Toxicology and Pharmacology*, 38(3), 232-242.
- Hasan, G. M. M. A., Das, A. K., Satter, M. A., Asif, M., & Islam, M. R. (2023). Distribution of Cr, Cd, Cu, Pb and Zn in organs of three selected local fish species of Turag River, Bangladesh and impact assessment on human health. *Emerging Contaminants*, 9(1), 100197.
- Ibrahim, B. U., Baba, J., & Sheshi, M. S. (2014). Isolation and identification of bacteria associated with fresh and smoked fish (*Clarias gariepinus*) in Minna Metropolis, Niger State. *Nigeria. Journal of Applied Environmental Microbiology*, 2(3), 81-85.
- Islam, M. S., Ahmed, M. K., Habibullah-Al-Mamun, M., & Masunaga, S. (2015). Assessment of trace metals in fish species of Bangladesh and their impact on human health. *Environmental Monitoring and Assessment*, 187(10), 640.
- Islam, S., Rahman, M. M., & Hossain, M. B. (2020). Bioaccumulation and human health risk assessment
- Kadim, M. K., & Risjani, Y. (2022). Biomarker for monitoring heavy metal pollution in aquatic environment: An overview toward molecular perspectives. *Emerging Contaminants*, 8, 195-205.
- Mahmuda, M., Rahman, M. H., Bashar, A., Rohani, M. F., & Hossain, M. S. (2020). Heavy metal contamination in tilapia, *Oreochromis niloticus* collected from different fish markets of Mymensingh district. *Journal of Agricultural and Food Economics*, 1(4), 1-5.
- Mhango, M., Mpuchane, S. F., & Mpuchane, B. A. (2010). Incidence of indicator organisms, opportunistic and pathogenic bacteria in fish. *African Journal of Food, Agriculture, Nutrition and Development*, 10(10), 4202-4218.
- Muhammad, K., Kiman, S. H., Muhammad, K., Jesse, I., & Mohammed, S. (2020). Isolation and identification of pathogenic bacteria from fresh fish organs. *International Research Journal of Advanced Science*, 1(2), 42-46.
- Mustafa, T. (2009). Toxic and essential trace elemental contents in fish species from the Black Sea, Turkey. *Food and Chemical Toxicology*, 47(8), 1785-1790.
- Nargis, A., Ahmed, S., & Hossain, M. U. (2021). Bioaccumulation of heavy metals in African catfish (*Clarias gariepinus*) from contaminated waters. *Environmental Science and Pollution Research*, 28(15), 18475-18486.
- Nargis, A., Habib, A., Harun-Or-Rashid, H. B., Harun, H. B., Sarker, M. S. I., & Bhattacharya, P. (2021). Status of multielement in water of the river Buriganga, Bangladesh: Aquatic chemistry of metal ions in polluted river water. *Emerging Contaminants*, 7, 99-115.
- Omoruyi, I. M., & Ebhodaghe, F. I. (2017). Fish consumption pattern and nutritional contribution to Nigerian households. *Nigerian Journal of Agriculture and Food Environment*, 13(3), 78-85.
- Omoruyi, K., & Ebhodaghe, G. W. (2017). The effects of smoke-drying on the nutritional quality and microbial load of apple Water snail (*Lanistes libycus*) in Ikpoba River, Edo State. *Asian Journal of Biology*, 2(1), 1-11.
- Pilet, M. F., & Leroi, F. (2011). Applications of protective cultures, bacteriocins and bacteriophages in fresh seafood and seafood products. In C. Lacroix (Ed.), *Protective cultures, antimicrobial metabolites and bacteriophages for food and beverage biopreservation* (pp. 324-347). Woodhead Publishing.
- Pilet, M. F., & Leroi, F. (2011). Microbial hazards in fishery products. In H. Roginski (Ed.), *Encyclopedia of Dairy Sciences* (pp. 301-308). Academic Press.
- Rahman, M. S., Hossain, M. S., Ahmed, M. K., Akther, S., & Bhattacharjee, P. (2019). Assessment of heavy metals contamination in selected tropical marine fish species in Bangladesh and their impact on human health. *Environmental Nanotechnology, Monitoring & Management*, 11, 100210.
- Rahman, M. S., Idris, M. H., & Ismail, A. (2019). Heavy metal levels in freshwater fish: A global review. *Environmental Science and Pollution Research*, 26(4), 4306-4318.
- Rohani, M. F., Bristy, A. A., Hasan, J., Hossain, K., & Shahjahan, M. (2022). Dietary zinc in association with vitamin E promotes growth performance of Nile tilapia. *Biological Trace Element Research*, 200(2), 4150-4159.
- Saad, S. M., Abou-Arab, A. A., & Abou-Arab, E. A. (2014). Microbial contamination sources in fish handling and processing. *Food Control*, 42, 191-197.
- Sichewo, P. R., Gono, R. K., Muzvondiwa, J. V., & Mutandwa, E. (2013). Bacterial contamination in fish from aquatic environments. *Journal of Food Safety*, 33(2), 210-216.
- Saad, S. M., Hassnien, F. S., Abdel-Aal, M. M., Zakar, A. H., & Elshfey, S. A. (2018). Enterobacteriaceae in some fresh and marine fish. *Benha Veterinary Medical Journal*, 1(1), 261-268.
- Saha, N., & Zaman, M. R. (2013). Evaluation of possible health risks of heavy metals by consumption of foodstuffs available in the central market of Rajshahi City, Bangladesh. *Environmental Monitoring and Assessment*, 185(5), 3867-3878.
- Sapkota, A., Sapkota, A. R., Kucharski, M., Burke, J., McKenzie, S., Walker, P., & McKenzie, S. (2008). Aquaculture practices and potential human health risks: Current knowledge and future priorities. *Environmental International*, 34(8), 1215-1226.
- Sichewo, P. R., Gono, R. K., Muzvondiwa, J., & Mungwadzi, W. (2014). Isolation and identification of pathogenic bacteria in edible fish: A case study of rural aquaculture projects feeding livestock manure to fish in Zimbabwe. *International Journal of Current Microbiology and Applied Sciences*, 3(11), 897-904.
- Sichewo, P. R., Gono, R. K., Sizanobuhle, J. V. M. N. (2013). Isolation and identification of pathogenic bacteria in edible fish: A case study of Fletcher Dam in Gweru, Zimbabwe. *International Research Journal*, 2(6), 269-273.
- Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy metal toxicity and the environment. In A. Luch (Ed.), *Molecular, clinical and environmental toxicology* (Vol. 101, pp. 133-164). Springer.
- Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy metal toxicity and the environment. *Molecular, Clinical and Environmental Toxicology*, 101, 133-164.
- Udochukwu, U., Inetianbor, J., Akaba, S. O., & Omorotionmwan, O. F. (2016). Comparative assessment of the microbiological quality of smoked and fresh fish sold in Benin City and its public health impact on consumers. *American Journal of Microbiological Research*, 4(1), 37-40.
- Udochukwu, U., Ogbonna, D., & Umeham, S. (2016). Microbial and chemical safety assessment of smoked fish in Nigerian markets. *Journal of Applied Microbiology*, 120(5), 1223-1232.
- Kang, H. K., Johnson, G., Kim, I. S & Lee E. J. (2003), Investigation of heavy metal accumulation in polygonum thunbergii for phytoextraction. *Journal of Environmental Pollution*, 126, 235 243
- Yesudhasan, P., & Al-Oufi, H. (2007). Trace metal contamination in fish and shellfish from the Gulf of Oman. *International Journal of Environmental Science and Technology*, 4(2), 151-158.
- Zakar, A. H., Elshfey, S. A., & Hassnien, F. S. (2018). Enterobacteriaceae in some fresh and marine fish. *Benha Veterinary Medical Journal*, 1(1), 261-268.
- Zhang, Y., & Liu, J. (2017). Effects of water temperature on the growth and survival of Nile tilapia (*Oreochromis niloticus*). *Journal of Thermal Biology*, 66, 108-114.
- Zhao, Y., Zhang, B., Chen, G., Chen, L., & Mo, C. (2018). Heavy metal contamination in fish and shellfish from the South China Sea. *Marine Pollution Bulletin*, 131, 384-391.
- Zhuang, P., Zou, H., & Shu, W. (2013). Bioaccumulation of heavy metals in fish from a polluted river in China. *Environmental Monitoring and Assessment*, 185(5), 3881-3888.