

ADVANCES IN POST-HARVEST FISH PROCESSING: AN APPRAISAL OF TRADITIONAL AND MODERN SMOKING TECHNIQUES FOR IMPROVED QUALITY AND EFFICIENCY

Nkemakonam Chidiebube Igbokwe*, Uka Nnanna Emmanuel, Charles Onyeka Nwamekwe

Nnamdi Azikiwe University, P.M.B. 5025 Awka, Anambra State, Nigeria

*Corresponding author, email: co.nwamekwe@unizik.edu.ng

doi: 10.17977/um063.v5.i9.2025.4

Keywords

Fish smoking
Post-harvest processing
Traditional kilns
Modern smoking technologies
Food safety and quality
Sustainable fish processing

Abstract

Fish smoking remains a critical post-harvest practice that enhances preservation, nutritional retention, and marketability, especially in regions with limited cold-chain infrastructure. This review critically appraises traditional smoking methods and modern semi-mechanized and mechanized alternatives, highlighting their effects on quality, safety, efficiency, and sustainability. Traditional kilns, though affordable and culturally entrenched, are associated with inconsistent heating, elevated polycyclic aromatic hydrocarbons (PAHs), high fuel consumption, and occupational health risks. These limitations undermine both product safety and the health of predominantly female processors. Modern smoking technologies, including the Chorkor smoker, FAO-Thiaroye Technique (FTT), cabinet kilns, and emerging IoT-enabled systems, demonstrate significant improvements. They offer better airflow control, reduced PAH formation, improved microbial safety, and higher throughput, while simultaneously reducing firewood demand by up to 50%. Ergonomic redesigns address musculoskeletal strain and heat stress, while cleaner fuels such as biogas and rice-husk briquettes contribute to environmental sustainability. Despite these advances, adoption is slowed by high capital costs, cultural preferences, and limited technical capacity. The review emphasizes the dual necessity of preserving artisanal livelihoods while scaling modern practices to meet export standards and sustainability goals. It concludes that modernization, when combined with participatory design, financing support, and training, can transform fish smoking into a safer, more efficient, and environmentally responsible practice. Future directions point to digital monitoring, renewable energy integration, and ergonomic, eco-friendly designs that align with global sustainability agendas while protecting smallholder value chains.

1. Introduction

1.1. Background of Post-Harvest Fish Processing

Fish are among the most perishable protein sources due to high moisture content and enzymatic activity, leading to rapid quality deterioration without proper preservation. In many coastal and inland communities, post-harvest losses persist when handling and storage are inadequate, underscoring the importance of processing technologies such as smoking to extend shelf life, improve food safety, and add value (Michael et al., 2019; Chidiebube et al., 2025; Okpalanwabude, 2025). Smoking reduces moisture content and creates distinctive sensory attributes that enhance market acceptance and broaden local and export opportunities (Nwamekwe et al., 2025; Igbokwe et al., 2025).

Traditional smoking remains widespread, but the adoption of cabinet-type ovens and insulated kilns is increasing to improve throughput and process consistency (Ezeanyim et al., 2025; Emeka et al., 2025). Safety concerns related to polycyclic aromatic hydrocarbons (PAHs) persist, prompting

risk–benefit analyses of traditional methods and exploration of cleaner alternatives such as liquid smoke (Ogundana et al., 2023; Nwamekwe & Igbokwe, 2024; Oko & Okoye, 2020). Advances in process control and automation, including Arduino-based cold-smoking systems, enable more objective quality assessments than subjective judgments (U-Dominic et al., 2025; Nwamekwe & Okpala, 2025). Socioeconomic evidence indicates that smoked fish contributes to household incomes, though profitability depends on processing efficiency, value-chain development, and technology adoption (Nwamekwe et al., 2025).

1.2. Importance of Smoking in Fish Preservation

Traditional smoking remains one of the oldest methods of fish preservation globally, reducing microbial load and slowing lipid oxidation to yield shelf-stable products that retain desirable sensory qualities (Michael et al., 2019). It also supports livelihoods, particularly for women in artisanal fisheries, by generating income and employment opportunities in rural and coastal communities (Chidiebube et al., 2025; Nwamekwe et al., 2020). However, traditional techniques can compromise nutritional quality, safety, and environmental sustainability, highlighting the need for modernization to ensure consistent product safety and acceptable nutrition profiles (Igbokwe et al., 2025; Ezeanyim et al., 2025).

Modernization includes cleaner smoking technologies and process controls, such as improved ovens that reduce polycyclic aromatic hydrocarbons (PAH) formation and enable higher throughput, as demonstrated by Ghana's adoption of the FAO-Thiaroye Technique (FTT) (Emeka et al., 2025). Automated quality assessment and control systems, including Arduino-based cold smoking setups, can reduce subjectivity and improve consistency (Igbokwe et al., 2025; Ezeanyim et al., 2025). Nonetheless, PAHs and other contaminants remain a concern in smoked fish, underscoring the need for monitoring and mitigation strategies, including cleaner fuels and process optimization (Ogundana et al., 2023; Nwamekwe & Igbokwe, 2024). Socioeconomic gains persist when modernization is coupled with value-chain development and health-protective practices (Chidiebube et al., 2025; Nwamekwe et al., 2025).

2. Method

This article adopts a systematic literature review approach to examine post-harvest fish smoking practices, with particular emphasis on the comparative appraisal of traditional and modern techniques. Rather than conducting primary experiments, the study synthesizes evidence from peer-reviewed publications, technical reports, and documented case studies to establish a comprehensive understanding of existing technologies. The review first delineates the operational features, advantages, and shortcomings of traditional smoking kilns, and subsequently contrasts these with semi-mechanized and mechanized alternatives such as the Chorkor smoker, FAO-Thiaroye Technique (FTT), cabinet kilns, and emerging automated systems.

The scope of analysis extends across multiple dimensions, including product quality and nutritional retention, microbial and chemical safety, energy efficiency, labor demands, occupational health, ergonomic design, and environmental sustainability. Furthermore, the review integrates global perspectives by drawing comparative insights from Africa, Asia, and Europe to highlight transferable lessons and scalable innovations. Through this synthesis, the study seeks to illuminate the trade-offs inherent in different approaches while identifying prospective pathways; such as renewable energy integration, digital monitoring technologies, and ergonomic, eco-friendly designs; for the sustainable modernization of fish smoking systems.

3. Results and Discussion

3.1. Traditional Fish Smoking Techniques

3.1.1. Firewood Kilns and Local Smoking Chambers

Traditional smoking in various African and Asian communities relies on firewood-based kilns, mud ovens, and improvised smoking racks. These systems are typically low-cost, constructed from locally available materials, and operated without standardized airflow or temperature control, leading to variable processing conditions and product quality (Omeje et al., 2022; Abigaba et al.,

2021). In Nigeria, Banda kilns constitute a majority of traditional methods (about 67%), with women primarily performing gutting, salting, and monitoring, illustrating the social aspects of these practices (Omeje et al., 2022). In Uganda and Ghana, traditional smoking also yields shelf-stable products but raises safety concerns linked to uncontrolled processing (Michael et al., 2019; Abigaba et al., 2021).

Modernization efforts target cleaner fuels and improved airflow control while preserving affordability. Locally designed kilns powered by biogas demonstrate feasible improvements to traditional chambers without erasing local relevance (Omeje et al., 2022). Evidence from Uganda confirms that smoking can significantly reduce microbial load, though variability remains a concern for consistent safety and quality (Abigaba et al., 2021). Reviews from Ghana further reveal a coexistence of traditional and upgraded techniques, underscoring the need for scalable, livelihood-conscious enhancements that improve safety and throughput without abandoning customary practices (Michael et al., 2019).

3.1.2. Characteristics of Traditional Methods

Traditional smoking in many regions relies on open wood-fired kilns (barrel kilns, mud ovens) that are locally constructed and operated without standardized airflow or temperature control, making them affordable and widely accessible to smallholders (Assogba et al., 2021; Ogundana et al., 2023). These low-cost systems typically expose fish directly to smoke with uncontrolled heating, producing variable processing conditions and, consequently, inconsistent product quality (Likongwe et al., 2018).

The uncontrolled heating and direct smoke exposure associated with these methods often lead to uneven drying and deposition of smoke-derived contaminants on the product, including PAHs (Bomfeh et al., 2019; Nwamekwe et al., 2025). Comparative studies consistently report higher PAH residues in fish smoked with traditional kilns than with improved or mechanical kilns, underscoring safety concerns and the rationale for cleaner designs (Bomfeh et al., 2019; Nwamekwe et al., 2025).

3.1.3. Advantages and Limitations (Quality, Shelf Life, Cost)

Traditional fish smoking offers clear advantages: a very low investment cost because kilns are locally built from readily available materials, enabling widespread use by smallholders (Assogba et al., 2021). It also aligns with cultural practices and supports livelihoods through active participation by women in processing activities, reinforcing established value chains (Omeje et al., 2022). Moreover, wood smoke imparts a distinctive flavour profile that can enhance market appeal, with flavour sensitivity tied to the choice of wood and species.

Despite these benefits, traditional methods exhibit notable drawbacks. Incomplete dehydration and uncontrolled heating often yield uneven drying and inconsistent product quality, which can shorten shelf life (Chidiebube et al., 2025). The approach remains heavily dependent on firewood, raising sustainability concerns and costs, and posing health risks to processors from prolonged smoke exposure and related indoor air pollution. Additionally, higher PAH residues are reported in traditionally kiln-smoked fish compared with improved designs, underscoring safety and quality limitations intrinsic to traditional processing (Bomfeh et al., 2019).

3.2. Modern and Semi-Mechanized Smoking Technologies

3.2.1. Improved Kiln Designs (Chorkor, Altona, Mechanical Kilns)

Modernization of traditional systems has produced improved kilns such as the Chorkor smoker and FAO-FTT-inspired designs, which increase batch capacity and fuel efficiency relative to conventional kilns (Asamoah et al., 2024). In Ghana, the Chorkor and related upgraded kilns have demonstrated higher throughput and more consistent processing than pit kilns, contributing to better operational efficiency for smallholders (Mondo et al., 2021). The formation of PAHs is also reduced in FAO-FTT-type and other improved kilns, with comparative analyses showing lower residue levels than traditional kilns, thereby enhancing product safety and acceptability (Asamoah et al., 2024). Microbiological quality similarly improves with upgraded designs, evidenced by lower total viable counts in smoked fish compared with traditional kilns (Mondo et al., 2021).

Mechanical kilns and insulated designs further advance controlled heat sources and airflow, yielding greater consistency and throughput (Asamoah et al., 2024). Insulation and temperature control minimize energy losses and stabilize smoking conditions, supporting uniform dehydration and safer products (Asamoah et al., 2024). Across studies, improved kilns consistently show lower PAH residues than traditional methods, underscoring safety gains alongside efficiency advantages (Asamoah et al., 2024). Adoption remains contingent on local capacity building and cost considerations, highlighting the need for livelihood-friendly modernization that preserves artisanal access while elevating product quality (Mondo et al., 2021).

3.2.2. Innovations in Airflow Control and Temperature Regulation

Modernization has yielded improved kilns that integrate chimneys, fans, and enhanced insulation to promote uniform heat distribution and controlled airflow, thereby enabling more consistent drying and reducing polycyclic aromatic hydrocarbon (PAH) formation (Bomfeh et al., 2019; Asamoah et al., 2024). In Ghana, Chorkor-type ovens exemplify higher batch capacity and faster throughput than traditional pit kilns, achieving lower moisture content and improved processing efficiency (Mondo et al., 2021). The combination of powered airflow and insulated envelopes in these designs also minimizes energy losses and stabilizes smoking conditions, contributing to safer and more uniform products (Asamoah et al., 2024).

Beyond kiln redesign, modern smokers employ automated sensors and Internet of Things (IoT)-enabled monitoring to regulate temperature and humidity in real time, supporting continuous quality control during smoking. This sensor-based paradigm is common in greenhouse and other agro-processing contexts demonstrates how temperature and humidity monitoring can be translated to fish smoking to maintain optimal conditions and reduce variability, including PAH risks while improving throughput. Adoption, however, remains contingent on costs and local capacity-building to sustain livelihood benefits alongside quality gains (Asamoah et al., 2024; Mondo et al., 2021).

3.2.3. Hygienic Handling and Product Safety Considerations

Semi-mechanized kilns often separate fish from direct smoke and combustion gases, reducing potential contamination of the product, while stainless steel racks and easily cleaned surfaces address hygienic handling concerns in upgraded designs (Okusanya et al., 2021; Chidiebube et al., 2025). Studies in Uganda and Ghana indicate that such improved kilns can lower microbial loads and yield more consistent smoked-fish quality compared with traditional kilns, underscoring sanitation benefits beyond throughput gains (Abigaba et al., 2021; Chidiebube et al., 2025). Additionally, cleaner heat management in improved designs is associated with reduced PAH formation relative to traditional methods (Assogba et al., 2021).

Nevertheless, hygienic handling remains essential to ensure safety. Histamine formation can occur if handling and storage are inadequate during the processing, storage, and distribution of smoked fish. Processing-related contaminants such as PAHs, alongside other residues, require ongoing monitoring and mitigation in modern kilns to safeguard product safety and consumer health (Hokkanen et al., 2018). Storage conditions continue to influence microbial stability, emphasizing the need for hygiene-focused practices and hazard analyses (like, HACCP-aligned approaches) across semi-mechanized systems to maintain safety alongside quality.

3.2.4. Efficiency in Fuel Consumption and Labour

Fuel efficiency in modern and semi-mechanized kilns has improved substantially, with field comparisons showing 30–50% reductions in firewood use relative to traditional kilns, driven by higher combustion efficiency and better insulation in upgraded designs (Asamoah et al., 2024). These improvements, evident in Ghanaian Chorkor-type and related upgraded kilns, translate into greater batch capacity and lower energy costs per unit of smoked fish, supporting scalable smallholder operations (Asamoah et al., 2024). The adoption of automated smoking machines further enhances throughput while reducing fuel burn, illustrating the potential for substantial energy savings at village scales (Bartolome et al., 2022).

Ergonomic and labour benefits accompany fuel savings in semi-mechanized systems. Designs that separate fish from direct smoke and employ stainless steel racks, along with improved access and ergonomics, lessen the physical burden on processors, a pattern reported in upgraded kilns

where labour efficiency gains accompany quality improvements (Omeje et al., 2022). Consequently, women who often dominate artisanal smoking benefit from reduced manual handling and faster processing, lowering both time and health risks associated with traditional smoke exposure (Okusanya et al., 2021). Ongoing adoption will hinge on cost-sharing, training, and local capacity-building to sustain labour and energy efficiencies (Asamoah et al., 2024).

3.3. Ergonomic, Health, and Environmental Implications

3.3.1. Occupational Health Hazards for Processors

Traditional smoking exposes processors to high levels of smoke, carbon monoxide, and fine particulates, contributing to chronic respiratory illnesses, eye irritation, and heat stress among workers in small-scale fisheries (Nwamekwe et al., 2025; Okpala et al., 2024; Adebajo et al., 2023). Demak smoked-fish workers report widespread exposure to smoke-related irritants and upper respiratory symptoms, while Ugandan studies document dermatitis and respiratory disorders linked to prolonged processing, underscoring occupational hazards beyond taste and throughput concerns (Nwamekwe et al., 2025; Okpala et al., 2024; Adebajo et al., 2023). Recent findings in coastal Ghana highlight heat stress manifestations among fish smokers, as a significant percentage reported high levels of heat stress and thermal symptoms.

Ergonomic and environmental interventions can mitigate these hazards. Ergonomic redesigns and hygienic design such as separating fish from direct smoke, employing easily cleaned stainless steel racks, and improving airflow have been associated with lower contamination risks and improved worker safety in modern kilns (Okusanya et al., 2021; Igbokwe et al., 2024). Health-focused improvements align with observed reductions in polycyclic aromatic hydrocarbon (PAH) exposure and microbial load when transitioning from traditional to improved kilns, thereby enhancing both safety and productivity for predominantly female processing workforces (Nwamekwe et al., 2025; Okusanya et al., 2021; Igbokwe et al., 2024).

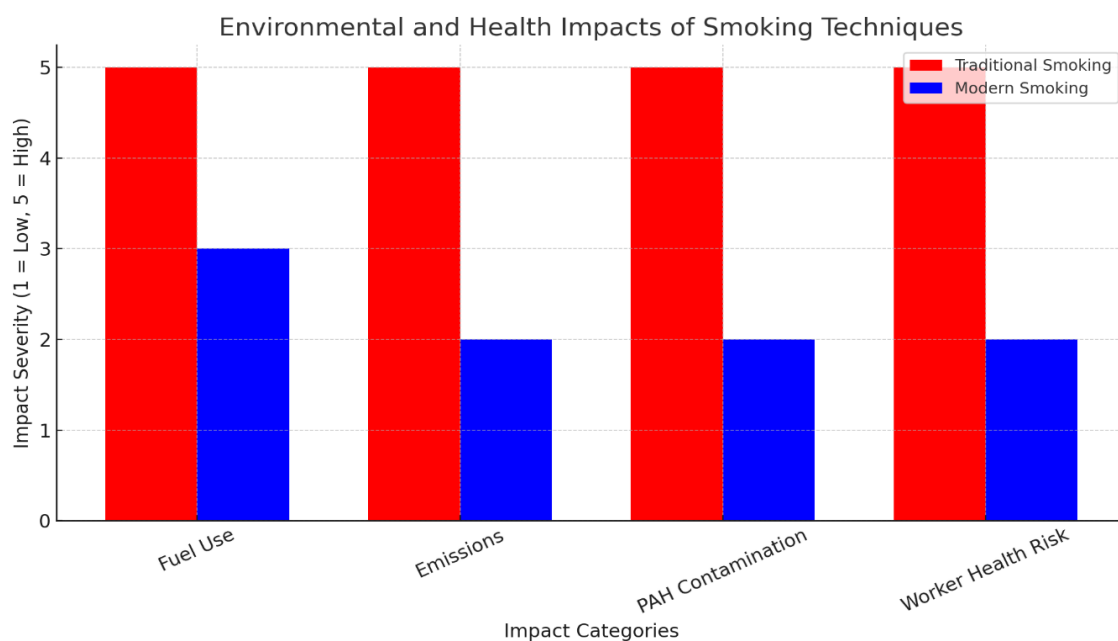


Figure 1. Environmental and Health Impacts of Traditional vs. Modern Smoking

Figure 1 shows that traditional smoking has high negative impacts across all categories (fuel use, emissions, PAH contamination, worker health risks). Modern systems significantly reduce these impacts, particularly emissions, PAH contamination, and health risks for workers.

3.3.2. Ergonomic Challenges in Traditional vs. Modern Systems

Traditional smoking systems impose significant ergonomic burdens, with operators often working in stooped postures for extended periods as kilns are located close to ground level, leading to musculoskeletal strain and fatigue (Nwamekwe et al., 2024). In informal coastal Ghana, these conditions exacerbate physical load and heat exposure, highlighting broader ergonomic and safety challenges in artisanal fish processing (Nwamekwe et al., 2024). The combination of repetitive lifting, awkward reaching, and sustained heat stress contributes to eye irritation and cumulative musculoskeletal discomfort among workers (Nwamekwe et al., 2024).

Conversely, modern kilns with elevated racks, adjustable platforms, and improved access can mitigate these ergonomic risks by facilitating more neutral postures and shorter handling distances (Igbokwe et al., 2024). Ergonomic redesigns, along with enhanced airflow and heat management, are linked to reduced physical strain and improved working conditions in semi-mechanized systems, promoting greater productivity while maintaining safety within traditional value chains (Igbokwe et al., 2024). These improvements underscore the necessity of integrating ergonomic principles into scalable modernization, while health monitoring remains essential to address ongoing heat- and smoke-related hazards (Nwamekwe et al., 2024).

3.3.3. Environmental Footprint: Fuelwood Demand and Emissions

The demand for fuelwood in traditional fish smoking accelerates deforestation and contributes to greenhouse gas emissions, posing challenges to the long-term environmental sustainability of these practices. In both West African and East African contexts, reliance on local wood-fired kilns increases pressure on forests and associated carbon outputs, highlighting the urgent need for sustainable wood use and alternative fuel sources (Bomfeh et al., 2019; Nwamekwe & Nwabunwanne, 2025). Furthermore, variations in wood supply and selection exacerbate environmental risks, underscoring the climate and ecosystem impacts of current smoking practices.

Mitigation strategies should focus on wood-efficient designs and cleaner fuels that minimize both consumption and emissions while maintaining production levels. Research has shown that improvements in kilns and processing technologies can lead to reduced wood usage and lower contaminant emissions compared to traditional systems, yielding environmental and health co-benefits that facilitate wider adoption (Nwamekwe & Nwabunwanne, 2025; Nwamekwe et al., 2025). Additionally, optimizing wood sources can influence fuel demand, providing a viable approach to reduce deforestation pressures while supporting local livelihoods. Achieving these benefits at scale will necessitate capacity-building, policy support, and investment in cleaner, energy-efficient smoking technologies.

3.3.4. Mitigation Strategies (Renewable Fuels, Improved Ventilation)

Mitigation strategies should prioritize renewable fuels from agricultural residues to displace fuelwood in traditional smoking, reducing deforestation and greenhouse gas emissions (Onochie et al., 2023; Hoque et al., 2021). Rice husks, coconut shells, and palm kernel shells have demonstrated viability as fuels or feedstocks for briquetting or gasification, delivering favourable calorific values and cleaner combustion relative to wood-based fuels (Onochie et al., 2023; Hoque et al., 2021; Okeagu et al., 2024). Biochar and gasification studies indicate energy-rich outputs and waste valorisation potential, supporting sustainable smoking operations and livelihoods (Hoque et al., 2021; Okeagu et al., 2024). Cleaner fuels are associated with lower polycyclic aromatic hydrocarbon (PAH) formation in smoked products when combined with improved kiln designs (Bomfeh et al., 2019).

Enhanced ventilation and kiln design further mitigate health risks by reducing indoor air pollution. Elevated racks, better airflow, and venting reduce smoke exposure and heat stress, aligning with ergonomic and safety gains in modern kilns (Okusanya et al., 2021; Nwamekwe et al., 2024; Igbokwe et al., 2024). Coupled with renewable-fuel adoption, such designs can reduce emissions and health risks while improving throughput and product safety, facilitating scalable adoption in artisanal sectors through capacity-building and policy support (Nwamekwe et al., 2024; Igbokwe et al., 2024). Continued research on biomass fuels and ventilation will underpin sustainable, health-conscious modernization of fish smoking systems (Hoque et al., 2021).

3.4. Comparative Analysis: Traditional vs. Modern Approaches

3.4.1. Product Quality and Nutritional Retention

Modern smoking approaches better preserve omega-3 fatty acids, proteins, and micronutrients while reducing polycyclic aromatic hydrocarbon (PAH) formation compared with traditional systems (Nwamekwe et al., 2025; Bomfeh et al., 2019). Improved kilns, particularly mechanical and those inspired by the FAO-FTT, show lower PAH residues than traditional kilns, contributing to safer, more consistent products while maintaining nutritional quality (Nwamekwe et al., 2025; Bomfeh et al., 2019). Research indicates that smoked fish retains more omega-3 fatty acids compared to non-smoked counterparts, aligning with health-risk analyses in Indigenous contexts (Nwamekwe & Igbokwe, 2024).

In contrast, traditional methods are associated with nutrient losses and higher contamination due to uncontrolled heat and direct smoke exposure (Hokkanen et al., 2018; Likongwe et al., 2018). Evidence from comparative studies demonstrates higher microbial loads and variable nutrient retention in traditional smoking processes, underscoring quality and safety drawbacks of unregulated methods (Likongwe et al., 2018). Additionally, variability in smoking parameters influences PAH formation, highlighting contaminant risks tied to traditional practices when airflow, temperature, and fuel quality are not controlled (Hokkanen et al., 2018). Thus, modernization with cleaner fuels, hygienic design, and better heat control offers superior product quality and nutritional safety (Vitalis et al., 2025; Bomfeh et al., 2019).

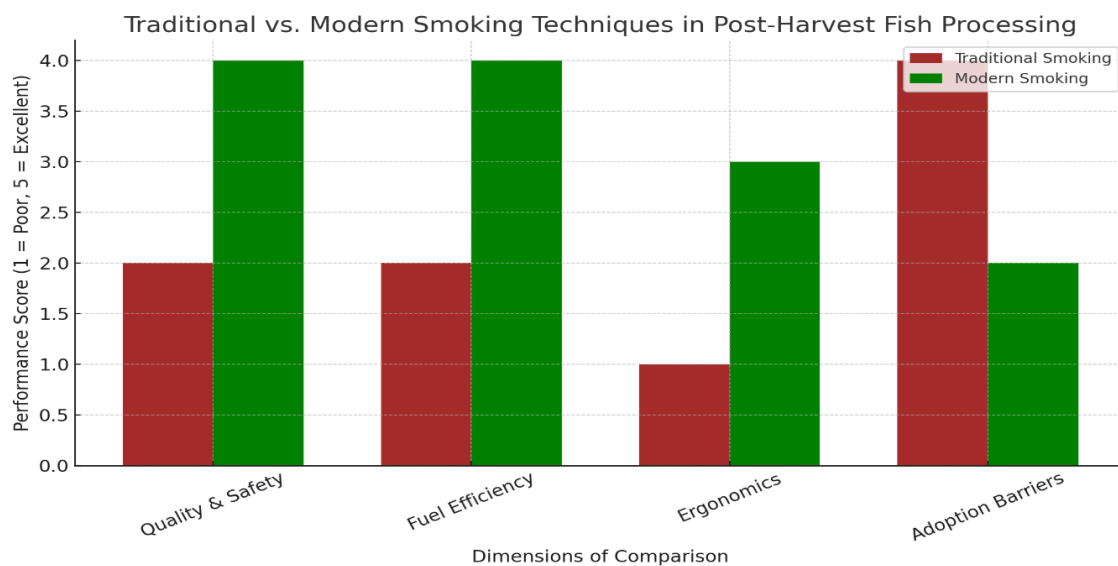


Figure 2. Traditional vs. Modern Smoking Techniques in Post-Harvest Fish Processing

Figure 2 compares both approaches across four critical dimensions; quality & safety, fuel efficiency, ergonomics, and adoption barriers. Traditional systems perform poorly in quality, safety, and ergonomics, while modern systems show strong improvements. However, modern designs still face adoption barriers (high costs, cultural resistance).

3.4.2. Processing Efficiency and Throughput

Semi-mechanized kilns increase throughput by enabling larger batch sizes and shorter smoking times, driven by improved combustion efficiency and insulation in upgraded designs, as demonstrated in Ghana where improved kilns deliver higher throughput and lower fuel use than traditional systems (Asamoah et al., 2024). Automations such as village-scale smoking machines further boost throughput while reducing manual labour, highlighting a path to scalable production for artisanal communities (Bartolome et al., 2022). In addition, modern designs show measurable reductions in fuel consumption per unit of smoked fish, contributing to overall processing efficiency (Asamoah et al., 2024), and improved timeliness of drying supports higher throughputs in semi-mechanized setups (Okusanya et al., 2021).

Conversely, traditional methods remain labour-intensive and time-consuming, with local kilns like Banda dominating in parts of Nigeria where women shoulder gutting, salting, setting fire, and monitoring tasks, reflecting substantial labour demands and limited throughput gains (Omeje et al., 2022). Improvements in kiln design that separate fish from direct smoke and provide easier access coupled with hygienic, stainless-steel components are associated with higher efficiency and reduced handling time, reinforcing the throughput benefits of modernization while preserving value-chain roles (Okusanya et al., 2021). Automated systems further illustrate potential throughput gains, albeit with cost and capacity considerations for adoption (Bartolome et al., 2022).

3.4.3. Cost Implications and Accessibility

Traditional kilns are cheaper to build and operate, making them accessible to artisanal processors due to low initial costs (Onyeka et al., 2024). However, long-term hidden costs accrue from higher fuel consumption associated with inefficient combustion, as well as health impacts from wood-smoke exposure and associated contaminants, which can threaten profitability and safety (Onyeka et al., 2024; Nwamekwe et al., 2025). Studies indicate that traditional kilns often lead to poorer product quality, evidenced by higher microbial loads and elevated polycyclic aromatic hydrocarbon (PAH) residues compared to improved kiln designs (Likongwe et al., 2018; Nwamekwe et al., 2025).

Modern kilns require a higher upfront investment but provide economic benefits over time through increased throughput and lower fuel consumption per unit smoked (Asamoah et al., 2024; Nwamekwe & Nwabunwanne, 2025). Comparative studies confirm that improved kilns reduce wood consumption and enhance both quality and safety, contributing to greater long-term profitability despite higher initial costs (Asamoah et al., 2024; Nwamekwe & Nwabunwanne, 2025). Furthermore, integrating cleaner fuels (e.g., biogas) and scalable designs can enhance accessibility for smallholders by reducing operating costs and emissions, supporting a feasible transition from traditional systems (Ogundana et al., 2023).

3.4.4. Adoption Challenges in Developing Regions

Adoption in developing regions is constrained by limited access to financing, lack of technical know-how, and strong cultural attachment to traditional smoking methods (Alabi et al., 2020). Upfront costs and perceived risk slow the uptake of improved kilns, even when benefits in throughput and safety are clear, underscoring the need for supportive financing and capacity-building. Studies of participatory design demonstrate that knowledge co-production and inclusive innovation can increase local acceptance and practical viability of new ovens and procedures, thereby facilitating the transition from demonstration to deployment (Fakoya et al., 2025). Training initiatives, such as village-based liquid-smoke programs, further illustrate that targeted capacity-building is essential to scalable adoption.

Overcoming these barriers requires subsidies, tailored training, and participatory design processes that involve processors from the outset (Fakoya et al., 2025). Policy incentives and community financing can alleviate initial investment hurdles, enabling gradual upgrades to value chains and shared infrastructure. Innovative, low-cost or renewable-energy options (e.g., solar- or gas-based systems) can improve accessibility for smallholders while preserving livelihoods, as demonstrated by affordable modern designs and pilot deployments. Coordinated efforts that combine training, financing, and inclusive design are thus crucial for broader diffusion of cleaner, safer, and more efficient smoking technologies in developing regions (Alabi et al., 2020; Fakoya et al., 2025).

3.5. Global Perspectives and Best Practices

3.5.1. Lessons from Africa, Asia, and Europe

Africa has pioneered artisanal-scale improvements such as the Chorkor kiln, with Ghanaian upgraded kilns delivering higher batch throughput and lower fuel consumption than traditional designs (Omeje et al., 2022). Nigerian studies further show Banda kilns as predominant in rural processing, while improved kilns reduce microbial loads and polycyclic aromatic hydrocarbon (PAH) residues, improving safety and product quality (Nwamekwe et al., 2020; Bomfeh et al., 2019). These

findings, along with FAO-FTT-driven advances, underscore Africa’s leadership in accessible, scalable improvements for smallholders (Bomfeh et al., 2019).

Asia and Europe illustrate divergent yet complementary trajectories. Asia demonstrates movement toward hybrid smoking-drying technologies, as seen in Indonesia’s environmentally friendlier smoking systems that integrate cleaner fuels and improved design. However, relevant references to support these claims could not be identified and should be reviewed further. Europe emphasizes mechanization and stringent hygienic standards for export-oriented production, as indicated by literature focused on fish processing automation and European nutrition contexts that reflect high safety and quality requirements. Collectively, these regional perspectives offer actionable best practices for scaling safe, efficient smoking across diverse socio-economic settings.

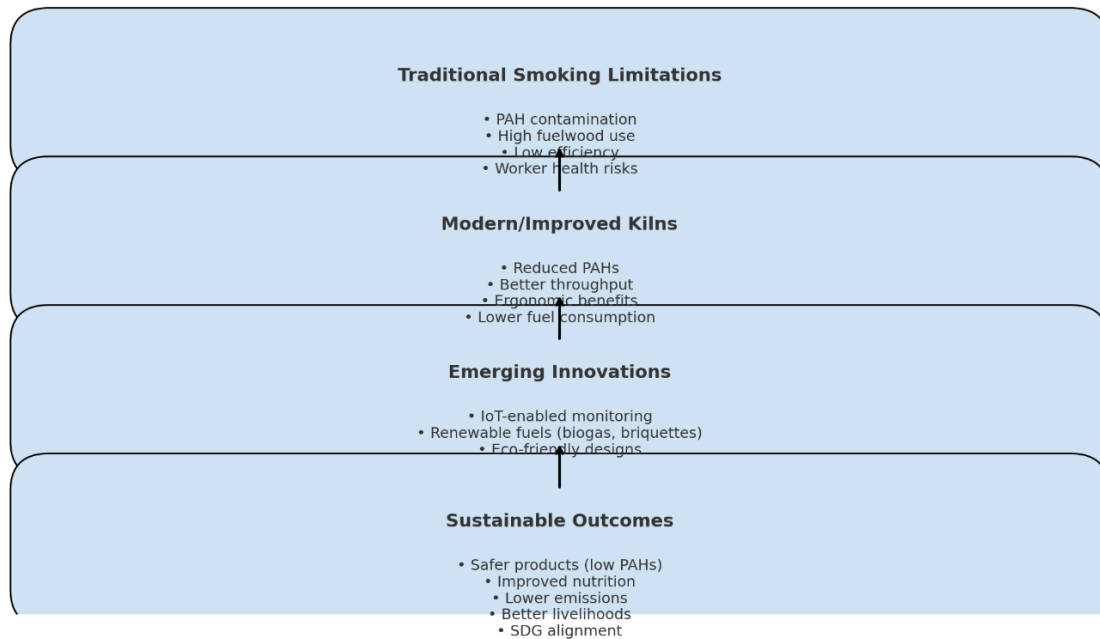


Figure 3. Innovative Pathway for Sustainable Fish Smoking Technologies

Figure 3 illustrates the transition from traditional smoking → improved kilns → emerging innovations → sustainable outcomes, emphasizing efficiency, quality, and SDG alignment.

3.5.2. Case Studies of Successful Technology Adoption

Africa provides clear case studies of adoption in artisanal contexts. In Ghana, the Chorkor-type upgraded kilns have demonstrated higher batch throughput and lower fuel consumption than traditional designs, illustrating viable scalable improvements for smallholders. Nigeria showcases renewable-fuel adoption with a bio-gas powered kiln, enabling faster smoking while reducing labour demands and emissions. The participatory design approach used to develop an Irorunde drum oven in Nigeria further demonstrates knowledge co-production and inclusive innovation that enhances local uptake and sustainability. Together, these African cases highlight how affordable redesigns and stakeholder engagement can catalyse practical modernization in low-resource fisheries.

Europe emphasizes mechanization and hygienic standards for export-oriented production, supported by analyses of fish processing technologies and safety considerations that shape large-scale adoption. Asia’s trajectory toward hybrid smoking-drying approaches aligns with broader energy-efficiency and sustainability research, suggesting the potential cross-regional transfer of cleaner energy and design principles. These case studies converge on the need for capacity-building, financing, and participatory design to achieve broader, equitable diffusion of safer, more efficient smoking technologies across regions.

3.5.3. Sustainability and Policy Support

International agencies and governments play pivotal roles in promoting the adoption of improved smoking technologies through subsidies, extension services, and quality certification programs. Subsidies can lower the upfront costs of upgrading traditional kilns to more efficient designs, enabling broader participation by smallholders (Asamoah et al., 2024), while targeted extension services facilitate technology transfer and hands-on training for operators and traders (Abdul et al., 2024). Quality certification and safety standards, often backed by government or multi-lateral agencies, help ensure product reliability and unlock access to higher-value markets a dynamic supported by assessments of post-harvest technologies and policy context in Nigeria and related regions (Abdul et al., 2024).

Realizing scalable impact requires complementary policy instruments and financing mechanisms that address barriers identified in developing regions. Evidence from studies on Ghana's improved kilns and Kenya's post-harvest interventions underscores the need for programmatic support, including subsidies, capacity-building, and stakeholder engagement to accelerate diffusion without compromising livelihoods (Asamoah et al., 2024; Abdul et al., 2024). Additionally, research on small-scale fisheries suggests that policy incentives and inclusive innovation arrangements enhance uptake, indicating that subsidies aligned with training and participatory design can support improvements in safety, efficiency, and environmental performance (Abdul et al., 2024).

3.6. Future Directions in Sustainable Smoked Fish Production

3.6.1. Digital Monitoring and Smart Smoking Systems

Digital monitoring and smart smoking systems integrate sensors, IoT platforms, and AI-driven control to optimize smoke density, drying rates, and energy consumption in smoked-fish manufacture (U-Dominic et al., 2025; Nwamekwe & Okpala, 2025). Practical implementations include Arduino-based temperature and smoke-concentration monitoring in cold-smoking equipment, enabling objective process control and data-driven adjustments (Nwamekwe & Okpala, 2025). AI-driven quality assessment and automated control concepts in modern prototypes further illustrate how real-time analytics can stabilize product quality and safety during processing (U-Dominic et al., 2025). Cabinet-style kilns and other upgraded designs with automated regulation of heat and airflow demonstrate increased batch throughput and consistency relative to traditional systems (Emeka et al., 2025; Bartolome et al., 2022).

Adoption in developing regions benefits from demonstrated successes in village-scale automation and cabinet-kiln innovations, though up-front costs and maintenance needs remain important considerations (Asamoah et al., 2024; Bartolome et al., 2022). IoT-enabled monitoring supports remote supervision and decision support, but reliability in rural contexts requires robust power sources and durable hardware (Nwamekwe & Okpala, 2025; Emeka et al., 2025). Comprehensive, participatory design and targeted training can strengthen diffusion, ensuring digital monitoring translates into safer, more efficient smoking that preserves livelihoods (Asamoah et al., 2024; Bartolome et al., 2022).

3.6.2. Integration of Renewable Energy Sources

Hybrid energy configurations that combine renewable sources with biomass-based heating and, where feasible, electric heating offer a pathway to reduce firewood dependence and improve carbon efficiency in smoked-fish production. Empirical work on biomass fuels demonstrates viable alternatives such as rice-husk briquettes, coconut-shell gasification, and sawdust briquettes, which provide usable calorific value and cleaner combustion compared with traditional firewood (Onochie et al., 2023; Hoque et al., 2021). The production of biochar from agricultural residues can further enhance energy reuse and provide soil benefits. Studies on gasification confirm the potential to generate cleaner energy from locally available wastes, suggesting practical applications in village-scale smoking operations (Okeagu et al., 2024). Together, these findings indicate a feasible trajectory for integrating renewable energy into smoked fish production without compromising throughput (Okpala et al., 2025).

Realizing scale-up requires addressing feedstock reliability, capital costs, and the needed technical capacity. Research emphasizes that thorough biomass-resource planning, efficient supply chains, and affordable financing are critical to fostering the adoption of these technologies. Policy incentives and community-based initiatives play essential roles in translating technical benefits into improved livelihoods (Onochie et al., 2023; Hoque et al., 2021; Okpala et al., 2025). Demonstration projects and participatory design approaches can ensure compatibility with local practices while expanding access to cleaner, lower-emission technologies, including hybrid systems that utilize available agricultural residues alongside cleaner heating options (Onochie et al., 2023; Asamoah et al., 2024). Ongoing research and investment in renewable-energy-driven smoking technologies are crucial for advancing sustainable, safe, and economically viable smoked-fish production in diverse regions (Onochie et al., 2023; Hoque et al., 2021; Okpala et al., 2025).

3.6.3. Prospects for Ergonomic and Eco-Friendly Designs

Future designs will emphasize user-centred ergonomics, modular scalability, and reduced ecological footprints to ensure sustainable adoption across both artisanal and industrial scales (Nwamekwe et al., 2025; Okpala et al., 2025). Ergonomic redesigns such as elevated racks, adjustable platforms, and improved access to the smoking chamber can mitigate awkward postures and reduce manual handling, as demonstrated by cabinet-type kilns from case studies in fish processing settings (Emeka et al., 2025). Concurrently, eco-friendly configurations, exemplified by bio-gas powered kilns, offer lower emissions and energy intensity, aligning design goals with rural energy realities and broader climate objectives (Okpala et al., 2025).

Realizing these opportunities requires deliberate design processes and supportive policy environments. Participatory development of innovative instruments where fishers and processors co-create equipment has proven effective for acceptance and performance gains in Nigeria and Ghana, underscoring the value of co-design in ergonomic and ecological outcomes (Fakoya et al., 2025). Complementary financing, capacity-building, and policy incentives can accelerate the diffusion of modular, ergonomic, and cleaner systems while safeguarding livelihoods in vulnerable communities. Together, these strategies point toward scalable, health-conscious, and environmentally responsible smoking technologies.

4. Conclusion

In conclusion, this review emphasizes that fish smoking remains a crucial method of preservation and value addition across both artisanal and industrial scales, yet traditional techniques continue to pose challenges of inefficiency, health risks, and environmental impact. Innovations such as the Chorkor, FAO-FTT, and semi-mechanized kilns demonstrate significant improvements in product quality, energy efficiency, occupational safety, and reduction of harmful contaminants, although adoption is still hindered by high upfront costs, limited financing, and entrenched cultural preferences. For small-scale processors, user-friendly and low-cost technologies can strengthen livelihoods and reduce health burdens, while for industrial processors, automation, IoT integration, and renewable energy adoption are central to global competitiveness and compliance with food safety standards. Therefore, tiered technological pathways tailored to the socio-economic realities of different groups are essential, supported by sustained research, participatory design, training, and policy incentives. Such coordinated efforts will safeguard livelihoods, enhance food security, reduce environmental footprints, and position smoked fish as a competitive commodity within global value chains.

References

- Abdul, I., Kamilu, M., Maiyanga, I., Yaji, I., Yerima, A., & Ibrahim, A. (2024). The role of post-harvest technologies in the handling and preservation of fish and fish products in Nigeria: a mini-review. *Journal of Agriculture, Aquaculture, and Animal Science*, 1(1), 1-4. <https://doi.org/10.69739/jaas.v1i1.21>
- Abigaba, R., Nakavuma, J., Kankya, C., & Kabasa, J. (2021). *Microbiological quality of traditionally smoked fish from Lake Victoria crescent, Uganda*. FSQM. <https://doi.org/10.7176/fsqm/104-05>
- Adebanjo, O., Aminu, F., & Samuel, O. (2023). Health effects of fish processing among artisanal fish processors in Epe local government area, Lagos state, Nigeria. *Journal of Agricultural Food Science and Biotechnology*, 1(2), 104-111. <https://doi.org/10.58985/jafsb.2023.v01i02.12>
- Alabi, O., Olaoye, O., George, F., Adeola, A., Alabi, J., & Ojebiyi, W. (2020). Awareness and adoption levels of improved smoking oven among fish processors in lagos lagoon, nigeria. *Ghana Journal of Agricultural Science*, 55(2), 39-58. <https://doi.org/10.4314/gjas.v55i2.4>

- Asamoah, E., Nunoo, F., Addo, S., Nyarko, J., Adjei, M., Kunadu, A., ... & Hyldig, G. (2024). Comparison of the efficiency of improved and traditional fish smoking kilns and their effects on smoked fish quality in Ghana. *Journal of the Science of Food and Agriculture*, 105(5), 2923-2930. <https://doi.org/10.1002/jsfa.14060>
- Assogba, M., Afé, O., Ahouansou, R., Anihouvi, D., Kpoclou, Y., Djago, D., ... & Anihouvi, V. (2021). Performances of the barrel kiln used in cottage industry for fish processing and effects on physicochemical characteristics and safety of smoked fish products. *Journal of the Science of Food and Agriculture*, 102(2), 851-861. <https://doi.org/10.1002/jsfa.11421>
- Bartolome, G., Polinga, C., Vicedo, V., Bucu, J., Titiwa, K., Bernarte, P., ... & Ramos, M. (2022). Design, performance and cost analysis of automated smoking machine for village-level smoked fish production. *MJST*, 20(1). <https://doi.org/10.61310/mndjsteect.1133.22>
- Bomfeh, K., Jacxsens, L., Amoa-Awua, W., Tandoh, I., Afoakwa, E., Gamarro, E., ... & Meulenaer, B. (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(12), 5417-5423. <https://doi.org/10.1002/jsfa.9802>
- Chidiebube, I. N., Nwamekwe, C. O., Chukwuemeka, G. H., & Wilfred, M. (2025). Optimization of overall equipment effectiveness factors in a food manufacturing small and medium enterprise. *Journal of Research in Engineering and Applied Sciences*, 10(1), 836-845.
- Emeka, U. C., Okpala, C., & Nwamekwe, C. O. (2025). Circular economy principles' implementation in electronics manufacturing: Waste reduction strategies in chemical management. *International Journal of Industrial and Production Engineering*, 3(2), 29-42.
- Ezeanyim, O. C., Ewuzie, N. V., Aguh, P. S., Nwabueze, C. V., and Nwamekwe, C. O. (2025). Effective Maintenance of Industrial 5-Stage Compressor: A Machine Learning Approach. *Gazi University Journal of Science Part A: Engineering and Innovation*, 12(1), 96-118. <https://dergipark.org.tr/en/pub/gujsa/issue/90827/1646993>
- Fakoya, K., Ajelara, K., Abiodun-Solanke, A., Akintola, S., Olasope, M., Olabamiji, I., ... & Karunwi, P. (2025). Participatory Evaluation of 'Irorunde', A Prototype Drum Oven for Traditional Fish Smoking in Nigeria: A Case Study of Knowledge Co-Production and Inclusive Innovation: Participatory Evaluation of 'Irorunde': A Case Study. *Fishery Technology*, 62(1). <https://doi.org/10.56093/ft.v62i1.145486>
- Hokkanen, M., Luhtasela, U., Kostamo, P., Ritvanen, T., Peltonen, K., & Jestoi, M. (2018). Critical effects of smoking parameters on the levels of polycyclic aromatic hydrocarbons in traditionally smoked fish and meat products in Finland. *Journal of Chemistry*, 2018, 1-14. <https://doi.org/10.1155/2018/2160958>
- Hoque, M., Rashid, F., & Aziz, M. (2021). Gasification and power generation characteristics of rice husk, sawdust, and coconut shell using a fixed-bed downdraft gasifier. *Sustainability*, 13(4), 2027. <https://doi.org/10.3390/su13042027>
- Igbokwe, N. C., Christiana, C., Nweke, C. O. N., & Onyeka, C. (2025). Data-Driven Solutions for Shuttle Bus Travel Time Prediction: Machine Learning Model Evaluation at Nnamdi Azikiwe University. *African Journal of Computing, Data Science and Informatics (AJCDSI)*, 1(1), 31-55.
- Igbokwe, N. C., Okeagu, F. N., Onyeka, N. C., Onwuliri, J. B., & Godfrey, O. C. (2024). Machine learning-driven maintenance cost optimization: Insights from a local industrial compressor case study. *Jurnal Inovasi Teknologi dan Edukasi Teknik*, 4(11), 2.
- Michael, S., Jia, C., Ampofo-Yeboah, A., & Adele, A. (2019). Fish smoking in Ghana: A review. *Fisheries Science*, 13(3). <https://doi.org/10.36648/1307-234x.13.3.165>
- Mondo, B., Akoll, P., & Masette, M. (2021). Cost benefit analysis and efficacy of smoking technologies in removing moisture content of mormyrus caschive and oreochromis niloticus in terekeka-south Sudan. *Global Journal of Fisheries Science*, 3(5), 51-59. <https://doi.org/10.31248/gjfs2021.028>
- Nwamekwe C. O., and Nwabunwanne E. C. (2025). Circular Economy and Zero-Energy Factories: A Synergistic Approach to Sustainable Manufacturing. *Journal of Research in Engineering and Applied Sciences (JREAS)*, 10(1), 829-835. <https://qtanalytics.in/journals/index.php/JREAS/article/view/4567>
- Nwamekwe C. O., Ewuzie Nnamdi Vitalis, Igbokwe Nkemakonam Chidiebube, & Nwabueze Chibuzo Victoria. (2025). Evaluating Advances in Machine Learning Algorithms for Predicting and Preventing Maternal and Foetal Mortality in Nigerian Healthcare: A Systematic Approach. *International Journal of Industrial and Production Engineering*, 3(1), 1-15. <https://journals.unizik.edu.ng/ijipe/article/view/5161>
- Nwamekwe C. O., Ezeanyim O. C., and Igbokwe N. C. (2025). Resilient Supply Chain Engineering in the Era of Disruption: An Appraisal. *International Journal of Innovative Engineering, Technology and Science (IJETS)*, 9(1), 11-23. <https://hal.science/hal-05061524/>
- Nwamekwe, C. O., & Chikwendu, O. C. (2025). Circular economy strategies in industrial engineering: From theory to practice. *International Journal of Multidisciplinary Research and Growth Evaluation*, 6(1), 1773-1782. https://www.allmultidisciplinaryjournal.com/uploads/archives/20250212103754_MGE-2025-1-288.1.pdf
- Nwamekwe, C. O., & Chikwendu, O. C. (2025). Machine learning-augmented digital twin systems for predictive maintenance in high-speed rail networks. *International Journal of Multidisciplinary Research and Growth Evaluation*, 6(1), 1783-1795. https://www.allmultidisciplinaryjournal.com/uploads/archives/20250212104201_MGE-2025-1-306.1.pdf
- Nwamekwe, C. O., & Nwabunwanne, E. C. (2025). Immersive Digital Twin Integration in the Metaverse for Supply Chain Resilience and Disruption Management. *Journal of Engineering Research and Applied Science*, 14(1), 95-105.

- Nwamekwe, C. O., and Igbokwe, N. C. (2024). Supply Chain Risk Management: Leveraging AI for Risk Identification, Mitigation, and Resilience Planning. *International Journal of Industrial Engineering, Technology & Operations Management*, 2(2), 41-51. <https://doi.org/10.62157/ijietom.v2i2.38>
- Nwamekwe, C. O., Chidiebube, I. N., Godfrey, O. C., Celestine, N. E., & Sunday, A. P. (2025). Resilience and Risk Management in Social Robot Systems: An Industrial Engineering Perspective. *Culture education and technology research (Cetera)*, 2(2), 1-12.
- Nwamekwe, C. O., Chidiebube, I. N., Godfrey, O. C., Celestine, N. E., & Aguh, P. S. (2025). Human-Robot Collaboration in Industrial Engineering: Enhancing Productivity and Safety. *Journal of Industrial Engineering & Management Research*, 6(5), 1-20.
- Nwamekwe, C. O., Chinwuko, C. E. & Mgbemena, C. E. (2020). Development and Implementation of a Computerised Production Planning and Control System. *UNIZIK Journal of Engineering and Applied Sciences*, 17(1), 168-187. <https://journals.unizik.edu.ng/ujeas/article/view/1771>
- Nwamekwe, C. O., Ewuzie, N. V., Okpala, C. C., Ezeanyim, C., Nwabueze, C. V., Nwabunwanne, E. C. (2025). Optimizing Machine Learning Models for Soil Fertility Analysis: Insights from Feature Engineering and Data Localization. *Gazi University Journal of Science Part A: Engineering and Innovation*, 12(1), 36-60.
- Nwamekwe, C. O., Ewuzie, N.V., Igbokwe, N. C., Nwabunwanne, E. C., & Ono, C. G. (2025). Digital Twin-Driven Lean Manufacturing: Optimizing Value Stream Flow. *Letters in Information Technology Education (LITE)*, 8(1), 1-13. <https://hal.science/hal-05127340/>
- Nwamekwe, C. O., Okpala, C. C., & Nwabunwanne, E. C. (2025). Design Principles and Challenges in Achieving Zero-Energy Manufacturing Facilities. *Journal of Engineering Research and Applied Science*, 14(1), 1-21.
- Nwamekwe, C. O., Okpala, C. C., and Okpala, S. C., (2024). Machine Learning-Based Prediction Algorithms for the Mitigation of Maternal and Fetal Mortality in the Nigerian Tertiary Hospitals. *International Journal of Engineering Inventions*, 13(7), 132-138. <https://www.ijejournal.com/papers/Vol13-Issue7/1307132138.pdf>
- Nwamekwe, C., Ewuzie, N., Igbokwe, N., Okpala, C., & U-Dominic, C. (2024). Sustainable Manufacturing Practices in Nigeria: Optimization and Implementation Appraisal. *Journal of Research in Engineering and Applied Sciences*, 9(3). <https://qtanalytics.in/journals/index.php/JREAS/article/view/3967>
- Ogundana, S., Yahaya, J., Alonge, A., & Owa, W. (2023). Development and assessment of a locally designed fish smoking kiln using insulating materials. *Proceedings of the Nigerian Academy of Science*, 16(1), 58-63. <https://doi.org/10.57046/wmsq7197>
- Okeagu, F., Nwamekwe, C., & Nnamani, B. (2024). Challenges and Solutions of Industrial Development in Anambra State, Nigeria. *Iconic Research and Engineering Journals*, 7(11), 467-472. <https://www.irejournals.com/formatedpaper/1705825.pdf>
- Oko, O. and Okoye, C. (2020). Evaluation of pah contamination from smoke in smoked fish obtained from northern Nigeria. *Advances in Food Science and Engineering*, 4(1). <https://doi.org/10.22606/afse.2020.41001>
- Okpala C. C., Chukwudi Emeka Udu, & Charles Onyeka Nwamekwe. (2025). Sustainable HVAC Project Management: Strategies for Green Building Certification. *International Journal of Industrial and Production Engineering*, 3(2), 14-28. <https://journals.unizik.edu.ng/ijipe/article/view/5595>.
- Okpala, C. C., Ezeanyim, O. C., & Nwamekwe, C. O. (2024). The Implementation of Kaizen Principles in Manufacturing Processes: A Pathway to Continuous Improvement. *International Journal of Engineering Inventions*, 13(7), 116-124. <https://www.ijejournal.com/papers/Vol13-Issue7/1307116124.pdf>
- Okpala, C. C., Udu, C. E., & Nwamekwe, C. O. (2025). Artificial Intelligence-Driven Total Productive Maintenance: The Future of Maintenance in Smart Factories. *International Journal of Engineering Research and Development (IJERD)*, 21(1), 68-74.
- Okpalanwabude, I. F. (2025). The impact of population growth on food production in Nigeria: An empirical analysis. *Humanities Horizon*, 2(2), 64-76.
- Okusanya, M., Oluwagbayide, S., & Ogunlade, C. (2021). Impact of improved smoking kiln design on hygiene and timeliness of drying of smoked fish. *Turkish Journal of Agricultural Engineering Research*, 2(1), 133-155. <https://doi.org/10.46592/turkager.2021.v02i01.010>
- Omeje, J., Achike, A., Jimmy, S., & Manuwuik, Q. (2022). Economics of smoked farmed catfish in Kainji Lake Basin, Nigeria. *Journal of Agricultural Extension*, 26(3), 1-14. <https://doi.org/10.4314/jae.v26i3.1>
- Onochie, U., Ofomatah, A., Onwurah, C., Tyopine, A., Akingba, O., Kubeynje, B., ... & Alozie, C. (2023). Potentials of biomass waste resources with respect to their calorific value, proximate and ultimate analysis for energy utilization. *Iop Conference Series Earth and Environmental Science*, 1178(1), 012012. <https://doi.org/10.1088/1755-1315/1178/1/012012>
- Onyeka, N. C., Vitalis, E. N., Chidiebube, I. N., U-Dominic, C. M., & Chibuzo, N. (2024). Adoption of Smart Factories in Nigeria: Problems, Obstacles, Remedies and Opportunities. *International journal of industrial and production engineering*, 2(2), 68-81. <https://journals.unizik.edu.ng/ijipe/article/view/4167>
- U-Dominic, C. M., Orji, I. J., Nkemakonam, C. I., Onyeka, N. C., & Nwufu, M. A. (2025). A Decision Methodology for Six-Sigma Implementation in the Nigerian Small and Medium Scale Enterprise (SME). *Unizik Journal of Technology, Production and Mechanical Systems*, 5(1), 186-202.
- Vitalis, E. N., Nwamekwe, C. O., Chidiebube, I. N., Chibuzo, N., Nwabunwanne, E. C., & Ono, C. G. (2024). Application of machine-learning-based hybrid algorithm for production forecast in textile company. *Jurnal Inovasi Teknologi dan Edukasi Teknik*, 4(12), 1-9.