INTERNATIONAL JOURNAL OF MULTIDISCIPLINARY FUTURISTIC DEVELOPMENT

Circular Economy in Fisheries: Transforming Aquatic Waste into Sustainable Resources for Agricultural and Industrial Use

Olasumbo Olagoke-Komolafe [1*], Joshua Oyeboade [2]
[1] Sweet Sensation Confectionery Limited, Lagos, Nigeria
[2] Bio Logical LLC, Boulder City, NV, USA

* Corresponding Author: **Olasumbo Olagoke-Komolafe**

Article Info

P-ISSN: 3051-3618
E-ISSN: 3051-3626
Volume: 06
Issue: 02
July - December 2025
Received: 12-06-2025
Accepted: 13-08-2025
Published: 01-09-2025
Page No: 45-58

Abstract
Amid increasing environmental concerns and inefficiencies in marine resource management, this study investigates how regenerative principles can be used to recover value from biological residues in aquatic production systems. The main goal is to explore strategies that transform discarded materials from harvesting and processing into useful inputs for agriculture, industry, and energy. By reviewing scholarly literature, global case studies, and regulatory analyses from 2020 to 2025, the research critically evaluates technological innovations, policy changes, and socio-economic impacts of resource reuse.
The findings highlight the significant potential of underused biomaterials—such as viscera, shells, scales, and wastewater—to be turned into fertilizers, functional proteins, collagen-based products, and bioplastics. Methods like fermentation, anaerobic digestion, enzymatic hydrolysis, and thermal processing have become key drivers of this change. Paired with the growth of digital technologies and smart monitoring systems, these processes improve traceability, accuracy, and efficiency across supply chains. Importantly, the environmental advantages include reduced pollution, greenhouse gas reduction, and preservation of natural ecosystems.
Despite these advances, widespread adoption remains limited by infrastructural deficiencies, regulatory inconsistencies, limited technical expertise, and market hesitancy. The study highlights specific challenges in policy enforcement, financial access, and consumer confidence, especially in low-resource settings where traditional practices and linear models still prevail.
It is concluded that a multi-level transformation is necessary—integrating technological readiness, institutional reform, and stakeholder engagement. The recommendations include strengthening policy coherence and incentives, decentralizing processing, expanding educational outreach, and fostering transparent communication to increase acceptance of recycled bio-based products. The insights presented here contribute significantly to the global sustainability dialogue by framing a regenerative model as both essential and achievable for resource-intensive sectors.

DOI: https://doi.org/10.54660/IJMFD.2025.6.2.45-58

Keywords: Bioresource Recovery, Regenerative Systems, Marine Residues, Valorisation Pathways, Sustainable Innovation, Environmental Resilience.

1. Introduction

The concept of a circular economy has emerged as a transformative approach addressing ecological harm and resource waste caused by traditional linear production systems. It shifts from the extract-produce-dispose model to one emphasizing regenerative design, closed-loop resource circulation, and sustainability across entire value chains. In fisheries—a sector vital to ecological health, food security, and rural communities—this framework proves especially effective. It not only aims to reduce waste but also seeks to convert aquatic waste into valuable bioresources for reuse in agricultural and industrial applications (Campanati, Willer& Schubert, 2022).

Worldwide, the fisheries and aquaculture sectors generate large amounts of residual materials such as fish heads, viscera, scales, shells, and discarded bycatch. When left unmanaged or improperly disposed of, these by-products contribute to environmental degradation. However, if directed through strategic valorization processes, they can become rich sources of valuable biomolecules, including proteins, lipids, chitin, collagen, and other bioactive substances (Caruso *et al.*, 2020). Using these resources not only reduces ecological pressures but also creates new economic opportunities, supporting both environmental and socio-economic goals. In this context, circular practices go beyond traditional waste disposal—they are essential tools for resource regeneration and cross-sectoral industrial collaboration (Triunfo *et al.*, 2022).

Introducing circular economy principles into the fisheries sector reflects a wider shift toward a bioeconomy, where biological materials are managed sustainably and continually reintroduced into production cycles. In this regenerative model, aquatic waste—traditionally seen as a disposal problem—is redefined as a valuable resource. According to Jacob *et al.* (2021), applying circular thinking in fisheries can improve the sustainability of food systems, reduce ecological stress on marine environments, and support the growth of a more diverse, low-emission economy. Practical examples include turning fish offal into nutrient-rich fertilizers for agriculture, extracting collagen for medical and cosmetic uses, and repurposing shell waste into bioplastics or water purification materials.

However, despite the growing acknowledgment of the benefits of a circular economy, its practical implementation in the fisheries sector remains inconsistent. Challenges include fragmented regulatory systems, technological gaps, and limited stakeholder capacity—especially in low- and middle-income countries where waste valorization infrastructure is minimal (Pizzone, 2023). Effective implementation of circularity requires not only technological innovation but also coordinated governance, market development, and cultural change. So far, much of the existing research emphasizes the technological potential of waste valorization without adequately addressing the social and institutional factors that influence adoption.

In recent years, a confluence of environmental priorities, shifting consumer attitudes, and evolving policy agendas has set the stage for a renewed approach to managing marine resources. Notably, initiatives like the European Union's Green Deal and Blue Economy policies have positioned circularity at the heart of strategies aimed at achieving sustainable use of ocean ecosystems. Concurrently, there is growing consumer enthusiasm for products derived from regenerative or repurposed sources, especially in emerging markets such as nutraceuticals, biocosmetics, and organic fertilisers (Campanati *et al.*, 2022). Together, these developments reflect a fundamental transformation in how discarded materials are perceived—not as waste, but as valuable inputs. As such, the justification for adopting circular models in the fisheries sector extends beyond ecological necessity, encompassing economic viability and cultural relevance.

Importantly, the role of technological advancement cannot be overlooked. Novel bioprocessing techniques, including enzymatic hydrolysis, anaerobic digestion, and microbial fermentation, have revolutionised the possibilities for fish waste valorisation. These methods allow for the separation and purification of valuable components in an energy-efficient and environmentally friendly manner. As demonstrated by Kurniawan *et al.* (2025), digital technologies such as AI and IoT are also playing an increasingly prominent role in monitoring waste streams, forecasting outputs, and optimising recovery processes. Such integration of smart systems into circular frameworks adds precision and scalability to what has traditionally been a labour-intensive process.

Nevertheless, while the technological toolkit continues to expand, its deployment must be context-sensitive. Regions differ markedly in terms of infrastructure, governance, and cultural acceptance. Thus, the circular transformation of fisheries cannot rely on a one-size-fits-all approach. Instead, it requires locally adapted solutions that consider ecological constraints, value chain structures, and the knowledge systems of coastal communities (Pizzone, 2023). Capacity-building, inclusive policymaking, and access to financing are therefore critical enabling conditions for meaningful progress.

The academic and policy imperative now lies in moving from conceptual advocacy to empirical substantiation. It is no longer sufficient to idealise the circular economy as a panacea for fisheries sustainability. Rather, what is required is a comprehensive and critical examination of how circular principles are being—or could be—operationalised within the specific material realities of aquatic resource systems. This includes an exploration of the barriers, trade-offs, and co-benefits associated with circular models, as well as the roles of various actors across the value chain.

Against this backdrop, this review aims to provide a comprehensive examination of the circular economy within the fisheries sector, with a specific focus on the valorization of aquatic waste for agricultural and industrial applications. The objective is to synthesise current knowledge on waste types, technological enablers, socioeconomic implications, and policy frameworks, thereby offering a coherent understanding of the state-of-play and identifying critical knowledge gaps. The scope of the study spans the full aquatic waste lifecycle—from generation through processing to reintegration—while drawing attention to cross-sectoral synergies, such as agriculture, bioplastics, and renewable energy. This sets the foundation for a deeper exploration in subsequent sections of the review.

2. Conceptual Foundation for Circular Approaches to Aquatic Waste Utilisation in Fisheries

The pursuit of sustainability in global fisheries has generated growing interest in the application of circular economy (CE) principles as a transformative pathway for the valorisation of aquatic waste. The conceptual grounding for this transformation rests on the idea that waste is not a terminal point but a secondary resource that, if appropriately managed, can re-enter the economic cycle as a value-added input. Central to this framework is a recognition that aquatic by-products—such as fish heads, shells, viscera, and scales—are nutrient-rich materials capable of being repurposed into bioplastics, fertilisers, pharmaceuticals, and functional food ingredients. Within African contexts, particularly in Nigeria, this reconceptualisation of waste aligns not only with ecological goals but also with urgent socio-economic imperatives, including food security, youth employment, and rural revitalisation (Elegbede *et al.*, 2025).

The CE framework in fisheries departs from linear extractive models by foregrounding closed-loop systems that prioritise regeneration, reuse, and reduced environmental footprint. In Africa's coastal and riverine economies, such as Nigeria, Ghana, and Kenya, where fisheries are integral to livelihoods, yet often beset by underutilisation of biomass and lack of processing infrastructure, CE offers both a corrective and an opportunity. Ginikanwa, Kanu, and Fadayomi (2024) highlight that through innovations in blue economy technologies—such as localised fishmeal production and anaerobic digestion of aquatic residues—communities can generate wealth from previously discarded resources, thus enhancing food system resilience.

The conceptual orientation of CE in fisheries is multidimensional. It encompasses ecological regeneration, technological innovation, and socio-institutional transformation. As noted by Ogwu *et al.* (2025), one of the pillars of CE in the bioeconomy of the Global South is the integration of indigenous practices with modern biotechnological systems. For example, fish scraps in artisanal processing communities, once discarded into local waterways, are now being redirected into compost production for vegetable farming. This not only reduces organic load in aquatic systems but also closes the nutrient loop between marine and terrestrial ecosystems, reinforcing the interconnectedness of food systems under a circular logic.

However, operationalising CE in fisheries necessitates not merely a shift in technological practices but also a paradigmatic shift in policy and institutional structures. Regulatory harmonisation across waste management, environmental protection, and fisheries governance is essential. Musazura and Odindo (2025) emphasise the importance of adaptive governance frameworks in South Africa's transition to a circular sanitation bioeconomy. A similar requirement exists in the fisheries sector, where fragmented regulations often hinder resource circulation and disincentivise innovation. Therefore, embedding CE into national fisheries development strategies can provide the institutional backbone required to support systematic waste valorisation.

Scientific progress continues to reinforce the conceptual foundation of circular fisheries. A prime example is the extraction of chitin and chitosan from shrimp shells, which has emerged as a key focus within the bioeconomy due to its wide-ranging applications, including drug delivery systems and biodegradable packaging (Triunfo *et al.*, 2022). The importance of these innovations extends beyond their market potential; they offer a sustainable alternative to petrochemical-based materials, thereby decreasing reliance on finite resources. This intersection of biotechnology and materials science is crucial for advancing circular economy models from isolated pilot initiatives to scalable, system-wide solutions.

In the Nigerian context, Folorunso (2025) illustrates that the valorisation of aquatic waste is not limited to food-based applications. Through the conversion of fish offal into activated carbon and bio-adsorbents for water treatment, new industrial linkages are being formed between the fisheries and environmental sectors. These cross-sectoral integrations exemplify the systemic thinking required to fully implement circular models. Furthermore, they speak to the economic diversification potential that lies within aquatic biomass, particularly in regions where industrialisation remains nascent.

Despite the conceptual promise, implementation challenges persist. Social acceptance of waste-derived products, gaps in cold chain logistics, and knowledge limitations among fisherfolk and processors remain formidable barriers. Nonetheless, the conceptual framework of CE in fisheries encourages a co-evolutionary process wherein institutional learning, community engagement, and technological uptake occur simultaneously. To this end, capacity-building programmes that connect scientific institutions with coastal communities are essential for translating theoretical constructs into everyday practice.

It is equally important to recognise that Africa's contribution to the CE discourse must not be peripheral. As Elegbede *et al.* (2025) assert, frameworks must be decolonised and tailored to the specificities of African economies, cultures, and ecologies. The valorisation of aquatic waste should thus be viewed through a contextual lens that acknowledges the informal economies, gendered labour divisions, and localised knowledge systems that shape fisheries in the region.

2.1. Understanding Aquatic Waste: Types and Sources

Previously considered an unavoidable and economically insignificant by-product of fisheries and aquaculture, aquatic waste is now being re-envisioned as a valuable resource within the circular economy paradigm. This shift in perception necessitates a nuanced understanding of the various types, sources, and biochemical potential of such waste. Across both small-scale and industrial operations, aquatic waste encompasses a broad range of materials, including fish offal, heads, skins, bones, shells, processing effluents, and non-target species. When systematically collected and channelled through effective valorisation strategies, these materials present significant opportunities for resource recovery, enhanced food system sustainability, and ecological rehabilitation (Triunfo *et al.*, 2022).

The typology of aquatic waste is broadly classified into post-harvest processing waste, harvest-stage discards, and system-level effluents. Post-harvest waste arises primarily from fish cleaning and filleting activities, comprising over 50% of the total fish biomass in many value chains. This includes bones, viscera, skin, and heads, all of which are rich in proteins, oils, and micronutrients suitable for transformation into fishmeal, fertilisers, bioactive peptides, and collagen-based biomedical products. On the other hand, harvest-stage discards involve non-target species and undersized catch returned to the sea, often due to regulatory quotas or market preferences. These materials, while often discarded at sea, represent a biomass segment with untapped potential for feed, compost, or energy production (Karani *et al.*, 2022).

In African coastal nations, the character and volume of aquatic waste differ due to the prevalence of small-scale and subsistence fishing practices. In Nigeria, for instance, fisheries in the Niger Delta and Atlantic coastline are dominated by artisanal operators with limited access to cold storage, efficient processing tools, or waste recovery technologies. As Eli and Lelei (2025) note in their assessment of Bayelsa State, much of the waste generated is lost through spoilage or haphazard disposal into water bodies, exacerbating pollution and reducing the overall productivity of aquatic ecosystems. This mismanagement of biomass not only hinders resource recovery but also threatens food security, as vital proteins are eliminated from the value chain.

Furthermore, the characterisation of aquatic waste must also include aquatic processing residues such as blood water and cleaning effluents, which contribute significantly to organic and nutrient pollution when released untreated. These system-level wastes are increasingly being targeted through eco-innovations, such as integrated aquaculture-agriculture systems that reuse nutrient-rich wastewater for crop production. As shown by Ginikanwa, Kanu, and Fadayomi (2024), there is growing interest in West Africa in leveraging blue economy initiatives that valorise aquatic waste as part of broader food safety and circular wealth-generation strategies.

Regionally, specific sources of aquatic waste in Nigeria and the Gulf of Guinea also reflect the structure of fisheries supply chains and urban-rural interfaces. Urban fish markets, such as those in Lagos, Port Harcourt, and Warri, are focal points for the generation of large-scale post-market waste. Heads, scales, and internal organs are often discarded in bulk due to a lack of commercial reuse strategies or infrastructure. At the same time, inland and estuarine fisheries contribute significantly to low-value biomass through catfish farming residues, which are often mismanaged in peri-urban settlements. Jimmy *et al.* (2025) observe that in AkwaIbom State, blue resources such as marine snails, crustaceans, and bonga fish generate a high proportion of underutilised biomass that could otherwise serve industrial purposes.

Across the continent, similar trends have emerged. Many African countries possess substantial aquatic biomass potential but lack the formal institutions and logistics to harness these resources systematically. This condition is a central focus of emerging blue economy strategies, which increasingly prioritise sustainable fisheries as leverage points for circular transitions. According to Karani *et al.* (2022), national and regional development strategies are beginning to frame aquatic waste as a development asset rather than a liability, particularly through policy innovations and transboundary collaboration on marine waste governance.

Aquatic waste holds significant potential as a source of bio-based compounds due to its rich chemical and material composition. For instance, fish bones and scales contain high levels of calcium and hydroxyapatite, both of which are valuable in pharmaceutical formulations and water purification technologies. Similarly, shellfish residues—particularly from shrimp and crab—are abundant in chitin and chitosan, which are widely utilised in agriculture, medical applications, textiles, and the production of biodegradable packaging (Triunfo *et al.*, 2022). In tropical regions like Nigeria, the warm climate accelerates the decomposition of organic matter, making it imperative to implement timely and technologically advanced valorisation processes to mitigate environmental harm and associated public health concerns.

The diversity of aquatic waste types, their origins, and regional contexts, particularly in Nigeria and broader African nations, presents a compelling case for the localisation of circular economy strategies. While global frameworks offer valuable guidance, the realities of artisanal fisheries, infrastructural deficiencies, and socio-cultural determinants in Africa require tailored approaches. As highlighted by Ginikanwa, Kanu, and Fadayomi (2024), fostering waste-to-wealth transitions in aquatic systems demands not only technological inputs but also inclusive knowledge systems that draw from traditional practices, community participation, and adaptive policy support.

2.2. Post-Harvest Waste

Post-harvest waste represents a significant yet undervalued stream of biomass within global fisheries systems. It encompasses all organic materials generated after harvesting aquatic organisms, particularly during handling, processing, storage, and distribution. Common examples include fish viscera, heads, bones, scales, skins, crustacean shells, and processing effluents—waste products which, under traditional linear economic models, are often discarded with little or no attempt at recovery. In the emerging context of circular economy thinking, however, these wastes are increasingly being recognised as valuable feedstock for biotechnological conversion and bioeconomic innovation (Ariyo *et al.*, 2025).

In Africa, and notably in Nigeria, the scale and impact of post-harvest loss in the fisheries sector are both economically and environmentally profound. Conservative estimates suggest that up to 30–40% of fish caught in small-scale artisanal systems are lost post-harvest due to poor infrastructure, delayed market access, and rudimentary processing methods. This high volume of organic waste contributes significantly to environmental degradation in coastal and inland fishing communities, while simultaneously depriving value chains of potential inputs for value-added production. As Agbugui, Inobeme, and Okhamafe (2025) argue, the deficit of large-scale post-harvest infrastructure in Nigeria not only contributes to significant losses but also limits the transformation of fishery by-products into usable industrial materials.

Central to the reconceptualisation of post-harvest aquatic waste within a circular economy framework is its biochemical potential. Fish waste is a rich source of high-protein materials and essential micronutrients. For instance, fish heads and bones contain calcium and phosphorus, while skins and scales are dense in collagen, a bioactive compound widely used in cosmetics, nutraceuticals, and pharmaceuticals. The enzymatic hydrolysis of fish viscera produces fish protein hydrolysates with potential applications in animal feed and organic fertiliser production. These processes align directly with CE goals of regeneration, resource recirculation, and bio-based substitution of synthetic inputs (Oranusi, Mameh&Oyegbade, 2024).

From a Nigerian perspective, integrating post-harvest waste valorisation into blue economy development is also aligned with broader national sustainability objectives. Jacob and Umoh (2025) observe that the convergence of blue, green, and grey economic models presents unique opportunities for Nigeria’s coastal regions, especially in sectors where waste outputs can be reabsorbed into production cycles. For instance, fish processing clusters in states such as Rivers, AkwaIbom, and Lagos are fertile ground for deploying decentralised waste-to-value facilities that transform shell waste into chitosan, a biopolymer with antimicrobial and biodegradable properties. This dual functionality offers benefits for both marine conservation and industrial innovation.

Moreover, the informal nature of post-harvest activity in Africa—where women constitute a majority of fish processors and traders—highlights the importance of inclusive circular economy strategies. Transforming fish by-products into high-value commodities could provide significant livelihood enhancement for women, youth, and rural populations. However, the adoption of such models is contingent upon access to training, finance, and regulatory

support. As noted by Ariyo *et al.* (2025), multidisciplinary approaches that combine indigenous knowledge with modern bioprocessing technologies are essential for overcoming these socio-technical barriers and achieving systemic impact.
Technology is pivotal in transitioning from waste disposal to waste valorisation. Innovations such as cold chain logistics, solar drying, vacuum packaging, and mobile processing units significantly reduce spoilage while increasing the quality and recoverability of by-products. In particular, the application of nanotechnology, such as the development of nanochitosan from crustacean waste, is opening new frontiers in agricultural input production and water treatment. Oranusi, Mameh, and Oyegbade (2024) emphasise that these emerging technologies, when contextualised for low-resource settings, could become game changers in regions where waste is abundant but underutilised.

2.3. Pre-Harvest and Bycatch Waste

Pre-harvest and bycatch waste constitutes a significant yet often overlooked aspect of aquatic resource loss, particularly in the context of global and regional fisheries management. These forms of waste refer to materials unintentionally captured or lost before formal harvest, including undersized fish, non-target species, and collateral ecosystem disruptions that yield no direct economic return. In contrast to post-harvest waste, which arises after fish have entered the formal value chain, pre-harvest and bycatch losses reflect inefficiencies in harvesting practices themselves—inefficiencies that have profound implications for sustainability, food security, and ecosystem health. Within a circular economy (CE) framework, addressing such losses involves not only recovery but prevention, valorisation, and redirection of bycatch and pre-harvest discards into productive loops (Cooke, Piczak&Nyboer, 2023).
In Africa, especially within artisanal and semi-industrial fisheries in regions like Nigeria, Ghana, and Senegal, bycatch waste represents both an ecological burden and a latent economic opportunity. Trawl fishing in West African waters, for example, has been documented to yield bycatch rates that exceed 50%, comprising juvenile fish, invertebrates, and non-commercial species that are often discarded at sea. These high bycatch volumes are compounded by weak enforcement of fishing regulations, limited access to selective gear technology, and the absence of comprehensive waste-reduction policies. Jacob and Umoh (2025) contend that in Nigeria, the unregulated discharge of bycatch into coastal ecosystems contributes significantly to resource depletion, local food scarcity, and marine biodiversity loss, particularly among benthic and pelagic species critical to ecosystem balance.
Within the circular economy paradigm, the sustainable management of pre-harvest and bycatch waste involves reframing these discards as resources that, if captured and redirected appropriately, can contribute to value-added chains. One emerging avenue is the development of secondary products—such as fish silage, low-grade fishmeal, and organic fertilisers—from non-commercial species and off-target biomass. These products have substantial utility in both agriculture and animal husbandry, where they can substitute synthetic inputs and reduce dependency on imported feedstocks. Additionally, bycatch-derived products have niche applications in cosmetics, pet food, and bioplastic manufacturing when processed with the appropriate technologies (Karani *et al.*, 2022).
Furthermore, indigenous knowledge systems in many African fishing communities offer insight into historical practices for bycatch utilisation, such as drying and smoking small fish for local consumption. Revitalising and commercialising such practices under modern quality control protocols can enhance local economies and contribute to food system resilience. However, significant gaps remain in infrastructure, technology, and market integration. A major constraint to bycatch valorisation is the lack of cold storage and transportation networks in coastal areas, which accelerates spoilage and limits the feasibility of downstream processing.
From a policy perspective, tackling pre-harvest and bycatch waste in African fisheries demands more than regulatory adjustments—it calls for institutional transformation. Cooke *et al.* (2023) point out that current global fisheries governance structures tend to prioritise large-scale industrial operations, often marginalising smallholder fishers and contributing to both social inequity and environmental degradation. To effectively implement circular economy principles, governance must become more inclusive, ensuring that small-scale fishers are empowered, gear innovation is incentivised, and discard reporting and monitoring are made mandatory. Moreover, embedding circular strategies into national fisheries policies and broader regional blue economy frameworks is essential to deliver a coordinated and systemic approach to reducing resource inefficiencies.
In freshwater systems, particularly in inland lakes and rivers of East and Central Africa, pre-harvest loss is further complicated by destructive fishing methods such as the use of fine-mesh nets and illegal gear, which increase the proportion of juvenile and non-target species captured. Cooke, Piczak, and Nyboer (2023) highlight the pressing need for technological interventions, including selective harvesting equipment and spatial fishing closures, to reduce inadvertent biomass capture. These tools are essential in transitioning from extractive to regenerative fisheries and realising the closed-loop ethos of CE in aquatic resource systems.

2.4. Circular Economy Principles in the Fisheries Context

The application of circular economy (CE) principles within the fisheries sector signals a transformative shift from linear extractive systems to regenerative, restorative, and resource-efficient paradigms. In essence, circularity in fisheries promotes the design of closed-loop systems in which aquatic biomass, waste streams, and by-products are retained, repurposed, and reintegrated into economic and ecological cycles. This approach fosters long-term sustainability by prioritising regeneration over depletion, reuse over disposal, and value maximisation over extraction. Particularly in the African context, including Nigeria, the operationalisation of CE principles within fisheries has the potential to address systemic inefficiencies while promoting inclusive development and ecological resilience (Manyara, Raubenheimer&Sadan, 2023).
At the core of CE is the principle of designing out waste and pollution. In fisheries, this implies the strategic utilisation of both targeted and non-targeted aquatic biomass, including bycatch, fish processing residues, and organic effluents. These materials, traditionally discarded or underutilised, are now being viewed as vital raw materials for the production of fertilisers, bioplastics, fishmeal, pharmaceuticals, and nutraceuticals. Circularity further entails extending the

lifecycle of fisheries products through improved preservation, traceability, and value addition. Hlangwani, Mpye, and Matsuro (2023) emphasise that technological innovation—particularly in bio-based processing, cold chain logistics, and nanomaterials—plays a pivotal role in advancing these principles, especially within resource-constrained environments across sub-Saharan Africa.

Another foundational element of CE in fisheries is systems thinking, which encourages an integrated view of aquatic ecosystems, economic sectors, and community practices. This perspective aligns particularly well with African fisheries, where subsistence, artisanal, and industrial operations coexist within complex socio-ecological landscapes. Integrating CE principles across these layers requires harmonising local knowledge systems with scientific innovation, while aligning national strategies with regional and global frameworks. In Nigeria, emerging circular practices are increasingly visible in initiatives such as Fishing Net Gains and waste-to-wealth programs that promote reuse of gear, valorisation of offal, and community-led resource recovery (Manyara, Raubenheimer&Sadan, 2023).

Resource efficiency is also central to CE and directly addresses the inefficiencies that characterise many fisheries in the Global South. Overfishing, post-harvest losses, and regulatory gaps lead to the dissipation of value at multiple stages of the aquatic value chain. CE seeks to redress this by fostering cascading use models where each output serves as an input for another process, thereby creating synergistic loops between fisheries, agriculture, energy, and manufacturing sectors. Hetemäki,Tegegne&Ochieng(2023) underscore that in countries like Nigeria, integrated bioeconomy planning can enable such cross-sectoral flows, provided that enabling policies and investment frameworks are in place.

From a governance standpoint, CE in fisheries necessitates adaptive policy frameworks that incentivise innovation while ensuring equitable access to resources and markets. Karani *et al.* (2022) argue that Africa's blue economy strategies are beginning to reflect circular imperatives by embedding waste minimisation, marine biodiversity conservation, and industrial symbiosis into national planning. However, practical implementation remains fragmented, hindered by infrastructural deficits, a lack of monitoring systems, and limited financing. Public-private partnerships, capacity-building programs, and community engagement are critical levers for overcoming these barriers and localising circular principles in diverse fisheries settings.

2.5. Policy and Regulatory Landscape

A coherent and enabling policy and regulatory framework forms the bedrock for embedding circular economy (CE) principles within fisheries systems, particularly in regions where resource inefficiencies and environmental degradation intersect with socio-economic fragility. Across Africa, and notably in Nigeria, the regulatory ecosystem governing fisheries and circular economy development is at a transitional juncture—simultaneously aspirational and fragmented. Aligning fisheries policies with CE frameworks entails the incorporation of principles such as waste minimisation, by-product valorisation, regenerative production, and inter-sectoral integration. These elements must be legislatively codified, institutionally enforced, and economically incentivised (Jacob &Umoh, 2025).

In Nigeria, policy discourse surrounding the blue economy and circularity has gained prominence in recent years, catalysed by the growing urgency to diversify from fossil fuel dependence and respond to marine ecosystem degradation. The Federal Ministry of Agriculture and Rural Development, alongside state-level fisheries departments, has articulated strategies that acknowledge resource circularity, but practical enforcement remains weak. Ekpemuaka and Odunlade (2025) observe that although Lagos State has emerged as a leader in blue economy initiatives—particularly through policies supporting artisanal fishers and aquatic waste reuse—there is a persistent gap between high-level strategy and operational frameworks that support innovation, market entry, and value-chain coordination.

One of the key limitations in the regulatory architecture is the lack of explicit legal recognition of aquatic waste as a resource class within national waste management and fisheries legislation. This omission hampers the development of valorisation infrastructure, inhibits investment, and perpetuates informal disposal practices. In their analysis of CE governance in the Global South, Ogwu *et al.* (2025) stress the need for an integrated regulatory framework that unites marine resource policy, environmental law, public health, and industrial strategy under a unified CE agenda. Such alignment is essential for transforming fisheries discards into raw materials for other sectors, such as agriculture, bioenergy, and pharmaceuticals.

Regionally, the African Union's 2063 Agenda and the African Blue Economy Strategy provide high-level policy scaffolding, encouraging member states to adopt sustainable aquatic resource management within a CE framework. However, national implementations are often uneven. Karani *et al.* (2022) highlight that while Nigeria, South Africa, and Kenya have begun integrating CE concepts into marine governance and coastal development planning, enforcement mechanisms remain underdeveloped. Moreover, the lack of harmonisation between ministries and agencies dealing with fisheries, trade, environment, and technology results in policy silos that obstruct cross-sectoral collaboration and funding.

The opportunity, therefore, lies in crafting a governance model that fuses local realities with global CE aspirations. This includes the institutionalisation of standards for fish waste valorisation, tax incentives for CE-compliant enterprises, certification schemes for sustainable fish products, and inclusive platforms for stakeholder participation. Importantly, given the gendered nature of post-harvest fisheries work in Nigeria, regulatory reforms must be gender-responsive, ensuring that women processors and traders have access to resources, credit, and training within the CE transition.

2.6. Cross-Sector Integration: Agriculture and Industry

The circular economy model necessitates robust cross-sectoral integration, particularly between fisheries, agriculture, and industry, to maximise resource efficiency, foster innovation, and generate shared socioeconomic benefits. In this context, aquatic waste—often perceived as terminal loss—represents a transformative input into parallel systems. By leveraging intersectoral synergies, countries can transform fishery by-products into valuable agricultural inputs and industrial raw materials, creating regenerative loops that align with sustainability goals and national development strategies.

In Nigeria and across Africa, cross-sector integration is increasingly recognised as a strategic enabler of circular bioeconomies. One of the most promising examples is the utilisation of fish waste in organic agriculture. Fish entrails, bones, and scales are rich in nitrogen, phosphorus, and trace minerals essential for plant growth. As Ogunlade *et al.* (2025) demonstrate, traditional and emerging bio-processing methods—including fermentation, drying, and hydrolysis—allow for the production of fish-based compost, biofertilisers, and growth enhancers. These organic alternatives offer a dual advantage: reducing dependency on imported chemical fertilisers and enhancing soil microbiota health, thereby contributing to more resilient food systems.

Industrially, fish processing residues are being explored for biotechnological applications, such as collagen extraction, chitosan production, and biodegradable packaging materials. In West African contexts, this growing interest in the industrial valorisation of aquatic biomass is supported by the proliferation of small and medium-scale enterprises (SMEs) that bridge fisheries and manufacturing. Nwakoby and Bielu (2025) highlight that fiscal mechanisms—such as incentives under Nigeria's blue economy tax initiatives—could further catalyse private-sector involvement in these sectors, provided that regulatory coherence and infrastructure investment are prioritised.

Cross-sector collaboration also has implications for supply chain resilience and regional trade. The repurposing of fish waste into animal feed, pet food, and aquaculture feedstock not only supports circularity within the food system but also reduces pressure on land-based protein sources. Ralph, Peter, and Festus (2025) argue that such integration aligns with Sustainable Development Goals (SDGs), particularly those linked to responsible consumption and production (SDG 12), zero hunger (SDG 2), and economic growth (SDG 8). Moreover, by fostering agri-food trade linkages, cross-sectoral integration expands market access and value retention within domestic economies, mitigating reliance on external inputs.

Despite these advantages, operationalising cross-sector integration remains fraught with institutional and infrastructural challenges. The absence of logistical frameworks for waste aggregation, poor access to processing technologies, and knowledge asymmetries between actors impede effective implementation. In Nigeria, Ekpemuaka and Odunlade (2025) note that although policy frameworks increasingly acknowledge blue economy innovation, tangible mechanisms to foster collaboration between fishers, farmers, and industrial processors are underdeveloped. Bridging these gaps requires multi-stakeholder platforms, capacity building, and digital infrastructure that enable data-sharing and coordinated action.

2.7. Technologies and Innovations Enabling Waste Valorization

Technological innovation plays a foundational role in unlocking the economic and ecological potential of aquatic waste within a circular economy framework. As fisheries increasingly shift from linear extraction models to regenerative systems, valorisation technologies enable the transformation of fish processing residues, shell waste, and aquatic biomass into high-value products. In African nations such as Nigeria, this transformation is both an environmental imperative and an economic opportunity, offering scalable solutions to waste management challenges while catalysing local industries.

Several emerging technologies underpin aquatic waste valorisation. Among the most impactful are biochemical conversion methods such as enzymatic hydrolysis, fermentation, and anaerobic digestion. These processes facilitate the extraction of functional proteins, fish oils, collagen, chitin, and chitosan from post-harvest waste. Ginikanwa, Kanu, and Fadayomi (2024) describe how fish entrails, scales, and heads—traditionally discarded—can be processed into biofertilisers, animal feed, and pharmaceutical precursors. This innovation not only reduces organic marine pollution but also fosters new value chains that intersect agriculture, health, and manufacturing sectors.

Thermochemical technologies, including pyrolysis and gasification, are also gaining traction, particularly for large-scale operations. These technologies convert organic fish waste into syngas, bio-oils, and char, which can be used for energy generation or as soil amendments. In the Nigerian context, Uzoagba *et al.* (2024) highlight the growing application of biomass valorisation for rural electrification, emphasising the use of fishery by-products as alternative feedstocks. This intersection of energy and aquaculture illustrates the multiplicity of benefits that innovative valorisation strategies can generate, from carbon reduction to enhanced rural livelihoods.

In addition to biochemical and thermochemical pathways, digital technologies are being deployed to optimise waste collection, monitoring, and traceability. Smart sensors and blockchain platforms now enable real-time tracking of aquatic waste from source to transformation facility, enhancing supply chain transparency and enabling data-driven policy decisions. Folorunso (2025) underscores the role of digital analytics in improving waste stream forecasting, resource recovery efficiency, and operational scalability across processing hubs in Nigeria. These technologies also facilitate collaboration between informal actors and formal institutions, a key requirement for systemic circularity.

However, despite the technological potential, challenges remain. Infrastructure gaps, limited technical expertise, and inconsistent access to finance hinder widespread deployment, particularly in rural and artisanal fisheries. Overcoming these barriers will require supportive policies, public-private partnerships, and capacity-building initiatives. In this regard, the integration of local knowledge with high-tech solutions can create hybrid models tailored to regional contexts, ensuring technological relevance and social acceptance

2.8. Bioconversion Technologies

Bioconversion technologies represent a cornerstone of sustainable waste management within the circular economy paradigm, especially in transforming aquatic waste into bio-based products. These biological methods utilise microbial activity or enzymatic pathways to convert organic substrates—such as fish offal, shells, viscera, and bloodwater—into value-added commodities including biofertilisers, biogas, animal feed, and functional proteins. In Africa, and particularly in Nigeria, bioconversion presents a promising and contextually relevant approach to valorising fisheries waste in low-resource environments.

One of the most widely adopted techniques is anaerobic digestion, wherein microbial consortia break down organic fish waste under oxygen-deprived conditions to produce methane-rich biogas and nutrient-dense digestate. As highlighted by Adeleke *et al.* (2025), this process is being applied to fish shell and scale biomass, not only to mitigate waste accumulation but to generate renewable energy and soil amendment inputs. Anaerobic digestion systems are scalable, relatively low-tech, and suitable for decentralised deployment—making them ideal for artisanal fisheries and small processing hubs along Nigeria's coastal and riverine zones.

In parallel, fermentation-based methods, including both solid-state fermentation (SSF) and submerged fermentation (SmF), are increasingly employed for the recovery of bioactive compounds from aquatic residues. These methods enable the production of fish protein hydrolysates, enzymes, and organic acids, which have applications in food, agriculture, and pharmaceutical sectors. Egbune, Ezedom, and Odeghe (2025) emphasise the growing relevance of SSF in the African context due to its lower water and energy requirements. In Nigeria, small-scale processors are beginning to adopt fermentation pits and mobile fermenters to convert fish waste into animal feed and organic soil conditioners.

Furthermore, microbial biotechnology is facilitating the selective conversion of complex biomolecules such as chitin, collagen, and lipids using engineered microbial strains. This approach enhances efficiency and specificity, leading to the production of niche bio-products such as biodegradable polymers and nutraceuticals. According to Ameh *et al.* (2025), such high-value applications are increasingly being explored in sub-Saharan Africa through collaborative research between universities and bio-entrepreneurs. These innovations reflect a shift away from bulk conversion toward precision valorization, with implications for higher profitability and industrial linkage.

Despite these advancements, barriers persist. The limited availability of fermentation infrastructure, skilled personnel, and microbial starter cultures constrains widespread adoption. Additionally, the lack of cold chain systems to preserve perishable fish waste poses a threat to feedstock quality. Addressing these constraints will require public-sector investment, donor-supported incubation centres, and knowledge exchange platforms that link traditional knowledge with scientific innovation.

2.9. Extraction and Processing Techniques

Advanced extraction and processing technologies are central to the efficient valorisation of aquatic waste, particularly in regions such as Nigeria and other African coastal nations where fish production generates significant volumes of underutilised biomass. These techniques, grounded in chemical, enzymatic, and mechanical innovations, facilitate the recovery of high-value compounds such as collagen, gelatin, omega-3 fatty acids, chitin, and hydrolysates from what would otherwise be discarded materials. Within the circular economy framework, such processes serve not only to mitigate environmental burdens but also to generate new economic streams across agriculture, health, and materials industries.

In practice, extraction techniques vary in complexity and yield depending on the desired end-product. Conventional methods such as boiling and acid/base hydrolysis remain prevalent in artisanal contexts due to their simplicity and low cost. However, there is increasing adoption of enzymatic hydrolysis using microbial or plant-derived enzymes, which provide higher specificity and minimise thermal degradation of sensitive bioactives. Elegbede *et al.* (2025) report that these approaches are increasingly utilized in halal-certified processing centres across Nigeria, where sustainability and ethical compliance intersect with efficiency.

Processing innovations also extend to drying, grinding, and milling technologies that stabilise aquatic biomass for further industrial application. These techniques are essential for transforming perishable fish skins, bones, and shells into powdered or pelletised intermediates for the feed, cosmetic, and pharmaceutical sectors. According to Folorunso (2025), resource recovery frameworks in West Africa increasingly depend on the integration of such mechanical systems, particularly in urban fish processing clusters with access to electricity and cold storage.

At an industrial scale, emerging technologies such as membrane filtration, supercritical fluid extraction, and microwave-assisted processing are gaining traction in pilot projects and research institutions. These methods offer higher purity, reduced solvent usage, and faster throughput. As noted by Okiemute *et al.* (2025), despite infrastructural limitations, Nigerian bioresource hubs are gradually exploring modular units that incorporate these technologies for niche product development, including marine-based nutraceuticals and bioplastics.

2.10. Digital and Smart Technologies in Waste Monitoring

Digital and smart technologies are rapidly redefining waste monitoring systems in fisheries, providing transformative tools for tracking, analysing, and optimising resource use across the aquatic value chain. As part of the broader shift toward a circular economy, the integration of Internet of Things (IoT), artificial intelligence (AI), blockchain, and geospatial analytics offers a real-time approach to the management and valorisation of aquatic waste. These technologies not only enhance operational efficiency but also foster transparency and traceability, which are vital for regulatory compliance and market access in sustainability-conscious industries.

In Nigeria, where artisanal and semi-industrial fisheries dominate the coastal landscape, digital technologies are being piloted to address inefficiencies in waste management and supply chain coordination. Ekpemuaka and Odunlade (2025) highlight emerging policy frameworks that encourage the deployment of marine sensors, digital waste logs, and automated data collection tools, particularly in Lagos State's blue economy initiatives. These technologies enable the geolocation of waste hotspots, prediction of biomass yield, and prompt decision-making on waste diversion strategies.

Advanced digital solutions are also being adopted in aquaculture supply chains to monitor feed use, water quality, and biomass outputs, thereby identifying waste generation patterns at upstream production stages. Adebayo *et al.* (2025) report that smart cages equipped with IoT sensors are now able to monitor organic waste discharges in real time, providing feedback loops that inform feed formulation and system design. These innovations align with circularity principles by reducing input waste while enabling the repurposing of sludge and fish residues into biogas or fertiliser.

Despite this progress, infrastructural gaps and digital illiteracy among smallholder fishers remain significant barriers to scale. Anukwonke *et al.* (2025) observe that localised digital solutions tailored to Nigeria's urban and peri-urban contexts—such as mobile apps for fish waste collection and mapping—are proving effective in bridging these challenges. Moreover, partnerships between tech startups and fisheries cooperatives are key to embedding these technologies into community-led waste valorisation practices.

2.11. Socioeconomic and Environmental Impacts

The application of circular economy (CE) principles to fisheries waste management holds significant socio-economic and environmental relevance, especially for resource-dependent nations like Nigeria. As Bunting (2024) emphasises, sustainable aquaculture practices must promote resilience across social, economic, and ecological domains. In this context, adopting circular strategies not only mitigates environmental degradation but also enhances livelihood opportunities, strengthens food systems, and fosters long-term sustainability within communities reliant on aquatic resources.From a socioeconomic standpoint, the valorisation of aquatic waste through recovery, processing, and reuse not only reduces dependency on linear resource extraction but also generates employment, supports local industries, and fosters inclusive economic growth. Jacob and Umoh (2025) emphasise that integrating blue, green, and grey economic strategies in Nigeria has catalysed localised entrepreneurship in waste repurposing, especially among coastal communities where artisanal fishing predominates.

The transformation of fish offal, shells, and wastewater into usable products such as fertilisers, biofuels, and feed supplements has triggered new markets in rural and peri-urban areas. These developments provide alternative income streams for women and youth, historically marginalised in formal aquaculture economies. In addition, Ginikanwa, Kanu, and Fadayomi (2024) note that CE-based enterprises in Nigeria's blue economy have supported food system resilience by enhancing biosecurity, reducing import dependency, and linking smallholders to broader agricultural value chains.

Environmentally, circular practices in fisheries reduce pollution loads, mitigate marine ecosystem degradation, and promote regenerative ecological cycles. Organic waste that would otherwise contribute to eutrophication or greenhouse gas emissions is redirected toward carbon-neutral applications, such as composting and anaerobic digestion. Ogwu *et al.* (2025) report that startups and cooperatives in the Global South are advancing CE-aligned bioeconomy models that integrate environmental stewardship with economic functionality—models that are particularly critical in biodiversity-rich but infrastructure-limited regions like the Niger Delta.

2.12. Economic Viability of Aquatic Waste Valorization

The economic viability of aquatic waste valorization has increasingly become a cornerstone of global circular economy agendas, particularly within the fisheries and aquaculture sectors. By transforming low-value discards such as heads, viscera, scales, and shells into high-value derivatives—including collagen, fish oil, enzymes, and bioplastics—valorization supports both resource efficiency and profitability. Rigueto, de Oliveira, and Gomes (2023) underscore that economic returns from fish waste valorization often exceed the value of primary fish products, particularly when integrated into cascading use models. These models not only optimise material flow but also open access to high-margin markets in pharmaceuticals, nutraceuticals, and agriculture.

Capital expenditures associated with valorization technologies have historically posed barriers to small and medium enterprises (SMEs). However, recent innovations in low-cost bioprocessing systems and modular extraction units have reduced entry thresholds, especially in emerging economies. Coppola *et al.* (2021) note that enzymatic hydrolysis and fermentation technologies are now deployable at a small scale while still maintaining economic feasibility. When adopted alongside decentralised cold chains and cooperative-led processing clusters, these solutions significantly enhance return on investment and shorten the payback period for waste-based enterprises.

Furthermore, the systemic economic benefits of aquatic waste valorization extend beyond direct profits. By reducing environmental remediation costs, lowering disposal fees, and generating employment across processing, logistics, and research, valorization contributes to macroeconomic resilience and rural development. Masi *et al.* (2024) demonstrate through a content analysis of circular aquaculture literature that integrating waste recovery into supply chains enhances overall sectoral competitiveness. It does so by meeting sustainability certifications, reducing carbon footprints, and diversifying product portfolios—factors increasingly valued by international markets and regulatory bodies.

2.13. Environmental Benefits and Sustainability Metrics

The valorization of aquatic waste within circular fisheries systems yields substantial environmental dividends, especially in regions facing ecosystem degradation due to overfishing, pollution, and unsustainable resource management. Transitioning from a linear extractive model to a circular economy paradigm curtails the environmental burden of fisheries by converting organic waste into productive inputs, thus minimizing emissions, nutrient loading, and marine litter. Kurniawan *et al.* (2025) demonstrate that bio-based conversion of fish processing residues into biogas, biofertilisers, and feedstock reduces dependence on fossil-derived products and mitigates the release of harmful effluents into aquatic systems.

Crucially, the use of sustainability metrics—such as Life Cycle Assessment (LCA), carbon footprinting, and material flow analysis—has enabled practitioners to quantify these environmental gains. Das *et al.* (2023) emphasise the relevance of wastewater reuse metrics in aquaculture, which assess water savings, organic load reductions, and greenhouse gas mitigation potential. These tools provide scientific evidence to support policy decisions and guide investment into sustainable infrastructure.

Moreover, the circular transformation of aquatic waste aligns with broader global sustainability targets, including SDGs 12 (Responsible Consumption and Production) and 14 (Life Below Water). Masi *et al.* (2024) note that aquaculture enterprises that integrate sustainability indicators into their waste management practices not only reduce environmental impacts but also gain competitive advantages through eco-certifications and access to green finance. Therefore, embedding robust sustainability metrics into circular economy models is essential for long-term ecological viability and international accountability in the fisheries sector.

2.14. Challenges and Barriers to Circular Adoption

Despite the evident potential of circular economy (CE) principles to transform fisheries and aquatic waste management, their broader adoption continues to face multifaceted challenges. Chief among these are entrenched regulatory, technological, financial, and socio-cultural barriers. On the policy front, a persistent adherence to linear economic models significantly impedes progress. As Sharma *et al.* (2021) argue, the transition from linear to circular frameworks is often obstructed by rigid institutional structures and outdated regulatory mechanisms that fail to support regenerative practices. This inertia not only discourages innovation but also limits stakeholder engagement, particularly in sectors like fisheries where value chains are often fragmented and dominated by conventional extraction and disposal paradigms.Many policy frameworks in the fisheries sector are oriented toward maximising extraction and throughput, often overlooking the regenerative and resource-circulating logic that defines CE. Cozzolino (2025) notes that in numerous jurisdictions, especially in developing economies, there is a lack of harmonisation between environmental, fisheries, and industrial policies. Fragmented governance, outdated legislative instruments, and institutional silos collectively inhibit the creation of cross-sectoral synergies necessary for scaling circular models.

Technological and economic limitations further complicate adoption. Small and medium-sized enterprises (SMEs), which constitute the backbone of the seafood processing and aquaculture sectors in many regions, frequently face prohibitive costs when attempting to access cutting-edge valorization technologies such as enzymatic hydrolysis, anaerobic digestion, or membrane filtration. Even when such technologies are available, the infrastructure required to implement them—such as energy supply, cold storage, and skilled technical personnel—is often lacking. DíazEnríquez (2022) highlights that the cost-benefit profile of these technologies may appear unfavourable in the short term, particularly in low-margin fisheries industries where immediate financial returns take precedence over long-term sustainability gains. This economic calculus discourages private investment and impedes innovation uptake.

Cultural perceptions and social norms also pose non-trivial challenges. In many communities, fish waste is viewed not as a recoverable resource but as a nuisance or pollutant. This perception undermines public acceptance and reduces the likelihood of grassroots engagement with circular initiatives. Mozumder *et al.* (2022) argue that such views stem from deep-seated cultural beliefs and a lack of awareness regarding the economic and environmental value of waste transformation. Bridging this knowledge gap will require targeted awareness campaigns, participatory education programs, and the inclusion of local knowledge systems to foster ownership and legitimacy. Ultimately, a successful transition to circularity in the fisheries sector will depend on integrated strategies that combine policy reform, financial innovation, technological adaptation, and socio-cultural engagement.

3. Technical and Infrastructure Barriers

The transition toward circular economy (CE) practices in fisheries and aquatic waste valorization faces significant technical and infrastructure-related impediments, particularly in developing and transition economies. Among the most pressing challenges is the lack of fit-for-purpose processing facilities capable of handling diverse waste streams generated by aquaculture and seafood industries. Cozzolino (2025) underscores that the absence of decentralised infrastructure hampers the logistical feasibility of valorisation, especially for remote or small-scale fisheries. The centralisation of waste processing hubs increases transport costs, shortens the usable life of organic waste, and discourages participation from informal actors.

Moreover, limited access to advanced technologies—such as enzymatic hydrolysis, anaerobic digesters, and supercritical fluid extractors—remains a critical barrier. Many SMEs are unable to invest in or maintain these high-cost systems, leaving a technological divide between industrial processors and local operators. Santos, Freitas, and Sobral (2025) argue that although innovations in microalgal biotechnology and biorefinery platforms offer sustainable valorisation routes, their deployment is often impeded by infrastructural deficits, a lack of trained personnel, and inconsistent electricity or water supply.

Infrastructure gaps are compounded by systemic regulatory weaknesses. As noted by Cudecka-Purina (2025), the absence of institutional frameworks that mandate or incentivise shared infrastructure models, such as industrial symbiosis or resource pooling, perpetuates fragmentation. Without coordinated investment in waste collection, cold chains, and modular processing units, the technical foundation necessary to support circular fisheries remains underdeveloped and exclusionary to small stakeholders.

4. Fragmented Value Chains

Fragmentation within fisheries and aquaculture value chains presents a substantial barrier to the effective implementation of circular economy (CE) practices. Discontinuities between production, processing, distribution, and waste recovery limit the flow of materials, information, and collaboration necessary for efficient waste valorisation. Sultan, Routroy, and Thakur (2023) highlight that poorly coordinated supply chain actors often operate in isolation, resulting in unutilised fish waste, duplication of processes, and inefficiencies that undermine circular resource loops.

One critical dimension of this fragmentation is the limited vertical integration across the sector. In many regions, small-scale fishers, processors, and waste handlers lack shared infrastructure and digital platforms to facilitate transparency and traceability. As a result, waste generated in upstream segments rarely finds its way into valorisation processes downstream. Cozzolino (2025) observes that even where CE knowledge exists, the absence of collaborative mechanisms and supply chain interoperability inhibits the scaling of sustainable innovations.

Moreover, Montocchio, March, and Brokensha (2025) note that policy fragmentation exacerbates the problem by failing to synchronize incentives and regulatory frameworks across the fisheries value chain. Without systemic alignment and stakeholder co-governance, the circular transformation remains partial and sectorally confined. Addressing this challenge necessitates the creation of integrative networks, supply chain mapping tools, and public-private partnerships that foster end-to-end coordination for value retention and waste minimisation.

5. Knowledge and Skill Gaps

The effective adoption of circular economy (CE) frameworks in the fisheries sector is significantly constrained by widespread knowledge and skill deficits. These gaps span across all nodes of the value chain—from artisanal fishers to waste processors and local policymakers—compromising the sector's ability to operationalise waste valorisation technologies and practices. Cozzolino (2025) highlights that even among aquaculture enterprises with sustainability ambitions, a lack of technical literacy in CE methodologies and performance metrics leads to inefficiencies and suboptimal implementation.

In many developing contexts, the absence of formal education and training programs dedicated to circularity principles further exacerbates these gaps. Montocchio, March, and Brokensha (2025) argue that the development of institutional capacity remains uneven, with few integrated curricula or certification schemes tailored to fisheries-specific CE competencies. Consequently, key stakeholders are often ill-equipped to engage with modern tools such as life cycle assessment, material flow analysis, or digital waste tracking systems.

Moreover, socio-cultural attitudes surrounding fish waste as valueless perpetuate behavioural resistance. Mozumder *et al.* (2022) note that in several fishing communities, the lack of demonstrable success stories or role models in circular practice stymies motivation for skills acquisition. Addressing these knowledge gaps requires the mainstreaming of CE education, localised training modules, and cross-sectoral capacity building that extends beyond technical knowledge to include social innovation and behavioural transformation.

6. Market and Consumer Acceptance

Market and consumer acceptance remain a critical bottleneck in the adoption of circular economy (CE) models within fisheries and aquatic waste valorization. Although the technical capacity to convert fish waste into high-value products—such as collagen, biofertilisers, and nutraceuticals—is growing, consumer perceptions of safety, hygiene, and ethical quality often hinder demand. Rigueto, de Oliveira, and Gomes (2023) argue that stigma associated with waste-derived products, particularly in food and cosmetics sectors, undermines the scalability of these innovations despite their proven functionality.

Saviolidis *et al.* (2025) emphasize that even in high-income economies with advanced bioeconomy infrastructure, a lack of awareness and standardised labelling erodes consumer confidence. This hesitation is further exacerbated by weak market incentives and minimal marketing campaigns to educate consumers on the environmental benefits and safety profiles of such products. Consequently, producers are disincentivised from investing in circular models due to limited market uptake.

Furthermore, Cozzolino (2025) identifies insufficient trust in certification schemes and regulatory ambiguity as compounding factors. Without reliable assurance frameworks that validate product integrity and sustainability claims, consumer scepticism persists. To overcome these barriers, transparent traceability systems, targeted consumer education, and inclusive market strategies that embed social narratives around circularity are essential. Only then can CE models in fisheries gain legitimacy and competitive traction in mainstream markets.

7. Case Studies and Best Practices

Successful adoption of circular economy (CE) principles in fisheries and aquaculture is best illustrated through concrete case studies that showcase scalable, replicable, and contextually tailored innovations. One such example comes from Bangladesh, where a community-driven initiative has pioneered the transformation of fishery waste into organic fertilisers and animal feed. This initiative demonstrates the importance of grassroots engagement and low-cost technologies in facilitating CE transitions, even in resource-constrained settings. According to Mozumder *et al.* (2022), stakeholder collaboration, government facilitation, and culturally aligned messaging were key to its sustained impact.

In India, a national model has emerged that bridges public policy with industrial innovation. The country's investment in decentralised biorefineries—designed to convert fish processing waste into bioenergy, pharmaceuticals, and biodegradable materials—has significantly enhanced both environmental performance and rural employment. Hussain and Yasmin (2025) highlight that economic incentives, skill development programmes, and inter-ministerial coordination underpinned the programme's success, demonstrating how targeted governance can unlock circular value chains.

From a European perspective, the Italian aquaculture sector has demonstrated best-in-class practices by embedding CE performance metrics into core operational strategies. Cozzolino (2025) documents how Italian firms have adopted life cycle assessments (LCAs), resource recovery indicators, and eco-labelling to evaluate their circular maturity. These tools not only inform environmental compliance but also enhance market competitiveness and consumer trust.

8. Future Directions and Research Priorities

Advancing circular economy (CE) principles in fisheries and aquatic waste valorization requires a future-oriented research agenda that bridges knowledge gaps, scales innovations, and enhances system integration. One pressing area is the standardization of environmental performance metrics. While life cycle assessment (LCA) tools are increasingly applied in industrial settings, their adaptation to artisanal and small-scale fisheries remains limited. Cozzolino (2025) emphasizes the need for methodological frameworks that align with the operational realities of diverse stakeholders, enabling robust and comparative sustainability assessments.

Another vital research priority lies in unlocking the bioeconomic potential of alternative protein sources. Emerging studies show promise in transforming agri-food by-products into fish feed through closed-loop systems. Prabakusuma *et al.* (2023) highlight that integrating circular feed technologies, such as insect-based meal or algal biomass derived from food industry residues, could drastically reduce environmental footprints while enhancing food system resilience. However, research on regulatory frameworks, nutritional equivalency, and farmer acceptability remains nascent and warrants further empirical inquiry.

Social innovation is equally critical to the success of circular transitions. Existing literature reveals a deficit in participatory governance models and localized circular practices. Mozumder *et al.* (2022) advocate for community-led research that explores behavioural economics, local knowledge integration, and co-production of value across supply chains. Future research must thus move beyond technical feasibility to encompass social acceptability, market dynamics, and equity-driven outcomes that ensure inclusivity and scalability of circular economy models in aquatic systems.

9. Conclusion

This study effectively achieved its central aim by critically examining how resource recovery from aquatic biomass can be advanced through circular strategies, with attention to environmental, technological, and socioeconomic dimensions. The objectives—ranging from understanding waste types and valorization methods to evaluating policy landscapes and identifying implementation challenges—were comprehensively addressed. Each section of the review contributed to unpacking the intricacies of waste generation in aquatic systems and highlighted the innovations and governance structures shaping its circular transformation.

Findings demonstrated that converting by-products such as fish offal, shells, scales, and wastewater into valuable inputs like biofertilisers, animal feed, enzymes, and packaging materials is not only technologically viable but increasingly economically attractive. Technologies including bioconversion, thermal and enzymatic extraction, and smart monitoring tools are being adopted globally, with success stories emerging from Asia, Europe, and parts of Africa. The environmental benefits—ranging from reduced marine pollution to climate mitigation—were clear, as were the positive ripple effects on employment, rural development, and local enterprise formation.

Nevertheless, the review also revealed persistent systemic barriers. Fragmented value chains, limited technical capacity, infrastructure gaps, regulatory misalignment, and low consumer awareness all contribute to the slow pace of circular transitions. Particularly in developing economies, financial constraints and knowledge deficits hinder smallholder engagement and scalability of innovations.

Recommendations include the development of integrated policy frameworks that promote cross-sectoral collaboration and incentivise sustainable waste utilisation. Investment in modular, low-cost processing technologies should be coupled with training programs and institutional support to build capacity. Social acceptance can be improved through transparent labelling systems, consumer education, and inclusion of local narratives in circular transitions.

Ultimately, this review reinforces the importance of systems thinking and coordinated governance in driving sustainable innovation. The pathway forward lies in embedding regenerative practices into every level of aquatic resource management—from harvest to post-consumption—ensuring both environmental integrity and economic resilience.

10. References

1. Adebayo IT, Ajibola S, Ahmad A, Cartujo P, Muritala I, Elegbede IO, Cabral P, Martos V. Understanding the application of digital technologies in aquaculture supply chains through a systematic literature review. Aquac Int. 2025;33(6):397. doi:10.1007/s10499-025-02069-7
2. Adeleke AO, Babatunde KA, Kasavan S, Omar RC, Dele-Afolabi TT. Shell-based agricultural wastes biomass valorization for biofuel production: a bibliometric analysis into the circular bioeconomy. Environ Sci Pollut Res. 2025;32(3):1095-1119. doi:10.1007/s11356-024-35766-6
3. Agbugui MO, Inobeme A, Okhamafe EP, Abhulimen FE, Abe G, Odozie JC, Ogbiti JT. Aquaculture production and management practices of farmed fish in Nigeria. In: Prospects of fungal biotechnologies for livestock volume 1: fungal bioengineering in livestock health management. Cham: Springer Nature Switzerland; 2025. p. 167-89. doi:10.1007/978-3-031-90994-8_7
4. Ameh VI, Onu MA, Ayeleru OO, Nomngongo PN, Ramatsa IM. Challenges and opportunities in biotechnological waste valorization. In: Biotechnological applications in industrial waste valorization. Singapore: Springer Nature Singapore; 2025. p. 481-503. doi:10.1007/978-981-96-2302-0_14
5. Anukwonke C, Igwe P, Maduka N, Obidiegwu MC. Innovative technologies and circular economy strategies for sustainable waste management in Nigerian urban centers. FESCON Conf Proc. 2025;5(1):294-306. Available from: https://ajer.org.ng/index.php/fescon-proceedings/article/view/170
6. Ariyo DO, Ahmed T, Olowolaju ED, Onyegbula AF, Solana OI, Adediran BI, Atanda SA. Post-harvest management in Africa: a review of innovative technologies and multidisciplinary approaches for reducing food losses. JASIC. 2025. Available from: https://jasic.kiu.ac.ug/assets/articles/1751619481_post-harvest-management-in-africa-a-review-of-innovative-technologies-and-multidisciplinary-approaches-for-reducing-food-losses.pdf
7. Arthur RI, Skerritt DJ, Schuhbauer A, Ebrahim N, Friend RM, Sumaila UR. Small-scale fisheries and local food systems: transformations, threats and opportunities. Fish Fish. 2022;23(1):109-24. doi:10.1111/faf.12602
8. Bunting SW. Principles of sustainable aquaculture: promoting social, economic, and environmental resilience. London: Routledge; 2024. doi:10.4324/9781003342823
9. Campanati C, Willer D, Schubert J, Aldridge DC. Sustainable intensification of aquaculture through nutrient recycling and circular economies: more fish, less waste, blue growth. Rev Fish Sci Aquac. 2022;30(2):143-69. doi:10.1080/23308249.2021.1897520
10. Caruso G, Floris R, Serangeli C, Di Paola L. Fishery wastes as a yet undiscovered treasure from the sea: biomolecular sources, extraction methods, and valorization. Mar Drugs. 2020;18(12):622. doi:10.3390/md18120622
11. Cooke SJ, Piczak ML, Nyboer EA, Michalski F, Bennett A, Koning AA, Hughes KA, Chen Y, Wu J, Cowx IG, Koehnken L. Managing exploitation of freshwater species and aggregates to protect and restore freshwater biodiversity. Environ Rev. 2023;32(3):414-37. doi:10.1139/er-2022-0118
12. Coppola D, Lauritano C, Palma Esposito F, Riccio G, Rizzo C, de Pascale D. Fish waste: from problem to valuable resource. Mar Drugs. 2021;19(2):116. doi:10.3390/md19020116
13. Cozzolino M. Guiding aquaculture companies towards the transition to a circular economy (CE): opportunities, practices, and methods for measuring environmental performances. [dissertation]. Naples: Università degli Studi di Napoli Federico II; 2025. Available from: https://tesidottorato.depositolegale.it/handle/20.500.14242/209468
14. Cudecka-Purina N. Legal barriers and policy gaps in

industrial symbiosis: a pathway to regulatory innovation. In: ENVIRONMENT. TECHNOLOGY. RESOURCES. Proceedings of the International Scientific and Practical Conference. 2025;1:149-56. doi:10.17770/etr2025vol1.8663
15. Das SK, Mondal B, Sarkar UK, Das BK, Borah S. Understanding and approaches towards circular bio-economy of wastewater reuse in fisheries and aquaculture in India: an overview. Rev Aquac. 2023;15(3):1100-14. doi:10.1111/raq.12758
16. Díaz Enríquez M. Barriers to the implementation of the circular economy in the fish processing industry. [dissertation]. Valladolid: University of Valladolid; 2022. Available from: https://uvadoc.uva.es/handle/10324/53595
17. Egbune E, Ezedom T, Odeghe O, Egbune O, Eraga L, Avwioroko O, Anigboro A, Tonukari N. Sustainable bioprocessing: solid-state fermentation and agricultural waste. Afr Res Rep. 2025;1(2):40-54. Available from: https://reports.afjur.com/index.php/ARR/article/download/3/2
18. Ekpemuaka E, Odunlade OR, Maiyaki SF. Resilience in Africa's transition to a sustainable digital and blue economy: policy and regulatory framework in Nigeria. In: Securing sustainable futures through blue and green economies. Hershey: IGI Global Scientific Publishing; 2025. p. 149-72.
19. Elegbede IO, Salisu MA, Saba AO, Akanmu RT, Badmos L, Olaleye-Haroun S, Adewale R. Halal harvesting: exploring aquatic seafood and by-products as ethical and sustainable alternatives for fisheries. In: Green and blue economy frameworks for halal industry sustainability. Singapore: Springer Nature Singapore; 2025. p. 369-99. doi:10.1007/978-981-96-1729-6_19
20. Eli AA, Lelei KE. Small-scale fishers in sustainable fisheries management: the Bayelsa State experience. ResearchGate. 2025. Available from: https://www.researchgate.net/publication/393701675
21. Folorunso OC. Progress in resource recovery from solid wastes for water treatment. ResearchGate. 2025. Available from: https://www.researchgate.net/publication/389432651
22. Ginikanwa EG, Kanu AE, Fadayomi M, Sadiq FU, Daniel AI, Klein A. Food safety and waste-to-wealth through blue economy. In: Marine bioprospecting for sustainable blue-bioeconomy. Cham: Springer Nature Switzerland; 2024. p. 41-55. doi:10.1007/978-3-031-68911-6_3
23. Hetemäki L, Tegegne YT, Ochieng RM. Outlook for sustainable forest bioeconomy in Gabon, Kenya, Nigeria, South Africa, and Tanzania. 2023.
24. Hlangwani E, Mpye KL, Matsuro L, Dlamini B. The use of technological innovation in bio-based industries to foster growth in the bioeconomy: a South African perspective. Sustainability: Sci Pract Policy. 2023;19(1):2200300. doi:10.1080/15487733.2023.2200300
25. Hussain IA, Yasmin R. Transforming fish waste for economic and environmental gains. Scientia Rev. 2025;1(1):1-11. Available from: http://scientiafoundation.in/wp-content/uploads/2025/07/SR01001.pdf
26. Jacob A, Umoh O. Exploring the intersections of blue, green, and grey economies in Nigeria: opportunities, challenges, and strategic pathways for sustainable development. J Sustain Econ. 2025;3(1):1-26. doi:10.32734/jse.v3i1.19060
27. Jacob C, Noirot C, Anglada C, Binet T. The benefits of integrating socioeconomic dimensions of circular economy practices in the seafood sector. Curr Opin Environ Sci Health. 2021;22:100255. doi:10.1016/j.coesh.2021.100255
28. Jimmy UJ, Osogi MA, Inwang SE, Udofia UO, Akpan JW, Mosab IT, Pantsi C. Blue resources under-exploitation and development impediment along Atlantic coastline: example from Akwa Ibom State, Nigeria. Saudi J Humanit Soc Sci. 2025;10(4):131-44. Available from: https://saudijournals.com/media/articles/SJHSS_104_131-144.pdf
29. Karani P, Failler P, Gilau AM, Ndende M, Diop ST. Africa's blue economy strategies are integrated in planning to achieve sustainable development at national and regional economic communities (RECs). J Sustain Res. 2022:e220011. Available from: https://hal.science/hal-05114338
30. Kurniawan SB, Ahmad A, Imron MF, Abdullah SRS, Othman AR, Hasan HA. Achieving a biocircular economy in the aquaculture sector through waste valorization. Toxics. 2025;13(2):131. doi:10.3390/toxics13020131
31. Manyara P, Raubenheimer K, Sadan Z. Legal and policy frameworks to address marine litter through improved livelihoods. In: The African marine litter outlook. 2023. p. 137.
32. Masi M, Adinolfi F, Vecchio Y, Agnusdei GP, Coluccia B. Toward the circular economy in the aquaculture sector: bibliometric, network, and content analyses. Sustainability. 2024;16(13):5405. doi:10.3390/su16135405
33. Montocchio C, March A, Brokensha R, Andriamahefazafy M, Schuman C, Failler P, Yuan H. A circular economy roadmap for African and Indian Ocean developing island states. Circ Econ. 2025:100143. doi:10.1016/j.cec.2025.100143
34. Mozumder MMH, Uddin MM, Schneider P, Raiyan MHI, Trisha MGA, Tahsin TH, Newase S. Sustainable utilization of fishery waste in Bangladesh—a qualitative study for a circular bioeconomy initiative. Fishes. 2022;7(2):84. doi:10.3390/fishes7020084
35. Musazura W, Odindo AO, Ojwach SO. Transformative approaches in transitioning to a circular sanitation bioeconomy in South Africa: a scoping review. Bus Strategy Environ. 2025. doi:10.1002/bse.70079
36. Nwakoby GC, Bielu K, Ezewudo V. Taxation of the blue economy in Nigeria and a quest for economic renaissance. Nnamdi Azikiwe Univ J Priv Prop Law. 2025;2(1):63-75. Available from: https://journals.unizik.edu.ng/naujppl/article/download/5914/4911
37. Ogunlade CA, Olaniyan AR, Babalola RT, Oyefeso BO, Jaiyeoba KF. Processing techniques for bio-based products in the Global South. In: Sustainable bioeconomy development in the Global South: volume II bioeconomy techniques. Singapore: Springer Nature Singapore; 2025. p. 39-65. doi:10.1007/978-981-96-0305-3_2
38. Ogwu MC, Kosoe EA, Iyiola AO, Fawole WO. Circular

economy approaches in bioeconomy in the Global South. In: Sustainable bioeconomy development in the Global South: volume II bioeconomy techniques. Singapore: Springer Nature Singapore; 2025. p. 131-57. doi:10.1007/978-981-96-0305-3_5

39. Okiemute MF, Mathew JT, Bini EM, Adetunji CO, Kolawole M, Tanko MS, Abdullahi A, Ebhote E, Inobeme CP, Haruna I, Hussaini J. Regulations, policy framework, and acts related to the application of marine biomass/recycling in different countries. In: Biomass valorization: a sustainable approach towards carbon neutrality and circular economy. Singapore: Springer Nature Singapore; 2025. p. 331-45. doi:10.1007/978-981-97-8557-5_15
40. Oranusi SU, Mameh EO, Oyegbade SA, Balogun DO, Atokolo A, Aririguzoh VGO, Oyesile OS. Economic and social implications of nanochitosan. In: Nanochitosan-based enhancement of fisheries and aquaculture: aligning with sustainable development goal 14–life below water. Cham: Springer Nature Switzerland; 2024. p. 281-300. doi:10.1007/978-3-031-52261-1_12
41. Pizzone DM. A holistic approach for the full valorization of fish waste within the circular economy. [dissertation]. Naples: Università degli Studi di Napoli Federico II; 2023. Available from: https://tesidottorato.depositolegale.it/handle/20.500.14242/117863
42. Prabakusuma AS, Wardono B, Fahlevi M, Zulham A, Sunarno MTD, Syukur M, Aljuaid M, Saniuk S, Apriliani T, Pramoda R. A bibliometric approach to understanding the recent development of self-sufficient fish feed production utilizing agri-food wastes and by-products towards sustainable aquaculture. Heliyon. 2023;9(7). doi:10.1016/j.heliyon.2023.e17721
43. Ralph AN, Peter Q, Festus TE, Emmanuel AN, Butu MM, Ellen HN. Interlinkages between agri-food trade and the SDGs at the global, regional, and local level. J Int Dev. 2025;37(4):951-77. doi:10.1002/jid.3994
44. Rigueto CVT, de Oliveira R, Gomes KS, Alessandretti I, Nazari MT, Rosseto M, Krein DDC, Loss RA, Dettmer A. From waste to value-added products: a review of opportunities for fish waste valorization. Environ Qual Manag. 2023;33(1):203-21. doi:10.1002/tqem.22040
45. Santos B, Freitas F, Sobral AJ, Encarnação T. Microalgae and circular economy: unlocking waste to resource pathways for sustainable development. Int J Sustain Eng. 2025;18(1):2501488. doi:10.1080/19397038.2025.2501488
46. Saviolidis NM, Ólafsdóttir G, Mehta S, Myhre MS, Strand AV, Bogason SG. Barriers in the transition to a more circular blue bioeconomy in Norway and Iceland: multistakeholder perspectives. J Clean Prod. 2025;521:146297. doi:10.1016/j.jclepro.2025.146297
47. Sharma NK, Govindan K, Lai KK, Chen WK, Kumar V. The transition from linear economy to circular economy for sustainability among SMEs: a study on prospects, impediments, and prerequisites. Bus Strategy Environ. 2021;30(4):1803-22. doi:10.1002/bse.2717
48. Sultan FA, Routroy S, Thakur M. Understanding fish waste management using bibliometric analysis: a supply chain perspective. Waste Manag Res. 2023;41(3):531-53. doi:10.1177/0734242X221122556
49. Triunfo M, Tafi E, Guarnieri A, Salvia R, Scieuzo C, Hahn T, Zibek S, Gagliardini A, Panariello L, Coltelli MB, De Bonis A. Characterization of chitin and chitosan derived from Hermetia illucens, a further step in a circular economy process. Sci Rep. 2022;12(1):6613. doi:10.1038/s41598-022-10423-5
50. Uzoagba C, Onwualu PA, Okoroigwe E, Kadivar M, Oribu WS, Mguni NG, Anye VC, Bello A, Mozie MC, Aperebo M, Adedeji IA. A review of biomass valorization for bioenergy and rural electricity generation in Nigeria. Cureus. 2024;1(1):1-16.