

Review

Sustainability of Aqua Feeds in Africa: A Narrative Review

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Abstract: In recent decades, the aquaculture industry has seen exponential growth worldwide, surpassing other food production sectors. This review aims to explore the dynamics of aqua feed production, particularly the shift from conventional to local feed production in Africa, driven by cost-effectiveness and the availability of raw materials. This review examines various scientific publications on aqua feed, focusing on both conventional and novel feed formulations and their impact on both small-scale and large-scale aquaculture. Commonly used aqua feed ingredients among African farmers include cassava, maize gluten, groundnut oilcake, sunflower oilcake, soybean meal, kale, peas, garlic, shrimp wastes, and waste blood. Novel ingredients such as insect-based diets, micro-algae, and fish discard formulations are also explored. Aqua feed composition impacts aqua waste, water quality, algae, oxygen demand, fish mortality, and eutrophication, and findings from literature reiterate the need to reorient feed formulation methods and ingredients to achieve a circular economy in Africa. This will entail promoting increased fish production at minimal costs and creating employment while supporting climate adaptation and mitigation efforts. Ultimately, the aqua feed sector has the potential to grow sustainably through the adoption of feed alternatives that prioritize sustainable production and encourage beneficiation studies.

Keywords: fish; aquaculture; aqua feed; sustainable; environment; circular economy



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1. Introduction

For the past 20 years, aquaculture has experienced the fastest rate of growth among all food production sectors [1]. For the first time, aquaculture dominated worldwide fish production, reaching an unexpected 130.9 million and constituting 51% of the total aquatic animal production [2]. In Africa, production volumes have massively grown by 455% since the year 2000 but rank lowest when compared to other regions such as Asia, Latin America and the Caribbean, and Europe [3]. Although constituting fewer countries, the Northern African regions dominated the 2021 regional production volumes, contributing to 66.93% of the regional tonnage [3]. However, several nations in sub-Saharan Africa (SSA) have witnessed an increase in aquaculture production of 12–23% each year over the last two decades [4,5].

Fish production in Kenya alone, for example, has expanded over the past ten years, rising almost four-fold from over 5000 metric tonnes (MT) in 2009 to almost 19,000 MT in 2019 [5]. Countries such as Nigeria and Uganda are leading in SSA in terms of aquaculture, accounting for 34% of national fisheries output and contributing 4.5% and 3% of national GDPs, respectively [3]. Despite having one of the strongest economies in SSA, South Africa has performed poorly in aquaculture, contributing to less than 1% of Gross

Domestic Product (GDP) and 4% of agricultural GDP [6–8]. Overall, the most pressing question is whether the industry is expanding quickly and responsibly enough to satisfy the expected demand, a situation that is being worsened by a changing climate and a growing population [9]. Such rapid growth is not without challenges and consequences associated with environmental stress. Focus is therefore needed is assessing the sustainability and circularity of the aquaculture industry.

This paper provides a comprehensive literature review of aquafeeds, specifically in Africa, as a premise for sustainable food production. Much ado about improving our food systems to make them sustainable has been advocated for. Hence, aquaculture plays a significant role as it augments human nutrition, provides jobs, improves livelihoods along value chains, and lessens strain on wild aquatic resources [10,11]. In this paper, we define aquaculture as the practice of growing aquatic and freshwater organisms in a controlled environment where production is influenced by economic, technological, biological, and environmental factors [12,13]. Worldwide, demand for aquaculture goods is increasing due to declining wild fish returns. The current food production system is stated to be wasteful, environmentally destructive, and inefficient [14] due to its contribution to environmental degradation, greenhouse gases, and other pollutants. On the other hand, limited resources and energy costs, particularly from fossil fuels, continue to grow, putting a further burden on attaining sustainability.

Challenges such as food sanitation, governance, trade and markets [15], diseases, climate extremes, the use of wild stocks in feed production [16], and increasing human population and therefore higher demand [17] impede current aquaculture fish production from meeting demand. Additionally, the expansion of the aquaculture industry is hampered by high feed prices [4,13,18]. Increased fish feed costs are common across the African globe, with the largest producing countries, such as Egypt and Nigeria, facing this predicament. The high cost of imported feed in African countries has led fish farmers to adopt suboptimal alternatives such as termites, rice bran, and domestic wastes, resulting in underperformance in the aquaculture sector, highlighting the importance of high-quality fish feed for achieving growth, development, and profitability [19]. Other challenges related to fish feed include inadequate supply of quality fish feed, lack of trained feed nutritionists, and concerns over the nutritional value of novel fish feeds and feeds by small-scale farmers [20–22].

While imported feeds are becoming more widely available in sub-Saharan Africa, certain countries are boosting investments in local feed production to benefit from less expensive and more readily available raw materials [4]. The use of fish flour as a main protein source in aquafeeds (69% of ~41,000 tons in 2017) is precarious given that its production from the wild keeps decreasing annually, therefore making it costly to procure [23]. As a result, innovative methods of generating sustainable and ecologically friendly aqua-feed alternative ingredients at a lower cost are required. Aquaculture feed can be categorized as either artisanal or commercial, where artisanal feed is produced on a small scale using local raw materials and basic processing methods, while commercial feed manufacturers utilize bulk raw materials and advanced machinery for processing [24]. Novel fish feeds are set to largely benefit small-scale farmers who are under-resourced and struggle with importing feed to effectively produce stocks that can compete with the commercially fed breeds. This review presents an exposition and overview of the various feed alternatives under consideration for local farmers to provide cost-effective, nutritional, and sustainable feeds. Additionally, this paper discusses the potential of sustainable aquaculture in strengthening human food systems, creating employment, and minimizing pressure on wild aquatic resources through progressing towards circular economies.

2. Methods

A systematic literature search was developed using keywords such as ‘sustainable’, ‘aquaculture’, ‘aqua feeds’, and alternative terms such as ‘novel aqua feeds’, and ‘local aqua feeds’ with the advanced search restricting the search to Africa. The literature query search was combined with concepts such as ‘circular economy’ and ‘life cycle assessments’ across databases including Google Scholar, Scopus, Science Direct, PubMed, and FAOStats. Abstracts, results, and conclusions from review studies and grey literature were reviewed, with the final search conducted on 26 August 2024. This study was not limited to a specific number of studies but included all relevant documents that met the criteria of speaking to the sustainability of novel feeds in aquaculture systems, being written in English, and focusing on the circularity of aquafeeds that used local ingredients. The exclusion criteria included dated articles and duplicates.

3. Aqua Feed Alternatives

Novel ingredients and aquafeeds are needed as an alternative to the current unsustainable production and transportation of feed ingredients from sources that are procured from far away and, therefore, become costly. In 2018, the number of aqua farmers in Africa reached approximately 1.2 million, registering a ~30% growth from 920,000 in 2014 [25]. However, the growth of the sector is hindered by the heavy reliance on tilapia farming, which is sensitive to diseases and requires costly feed [26]. Additionally, feed ingredients tend to bear a high carbon footprint on the environment. As an alternative to conventional production processes and unsustainable sources of ingredients currently in practice, blue feeds can be the alternative and answer to inclusive, sustainable, and resilient (including climate-smart, carbon-neutral, or reduced-emission) aquaculture fish production. Replacing fishmeal with alternative protein sources, for example, is inevitable in ensuring sustainable, cost-effective, and quality aquaculture fish production. Most ingredients used in novel feeds are found abundantly and can easily be harvested, and therefore, have the potential to reduce feed costs [27]. However, whether fish feed ingredients in use are plant- or animal-based and less costly stems from how they are grown, produced, sourced, transported, and stored for use as feeds [7,28–30]. Issues regarding the quality of local ingredients are also a cause for concern, especially for small-scale manufacturing that is not under any monitoring [31]. This calls for the need for an exposition of fish feed and ingredients across the continent and recommendations of ways to enhance local ingredients and aquafeed to replace fish meal and fish-oil-based feeds where possible. However, several factors should be considered when selecting content for usage in aquaculture, including ingredient accessibility, availability, and nutrient content [32].

Several research initiatives are currently underway to evaluate various local components for commercial feed production, including insects and other new components [13,18,33,34]. Modern innovations, such as the nutritious pond concept, which makes use of underutilized local ingredients, hold the potential to increase productivity while creating environmental advantages and adding to a circular economy through the effective utilization of feed waste [35]. Advancing research and development to examine locally accessible ingredients and increase low-cost local manufacturing of fish feed is critical to the growth and sustainability of aquaculture in sub-Saharan Africa. Table 1 shows a summary of the cost-benefit analysis of different aqua feed options discussed in this study.

Managing alternatives and optimizing fish nutrition and growth are, however, complex undertakings. A highly digestible feed lowers production costs but can increase feed waste and eutrophication. Despite continuous and expanding research on novel and low-cost ingredients for commercial feeds, studies on the evaluation of farming practices, feed performance, and experimentation remain limited [4]. Some of the feed alternatives indicated in Table 1 are presented in more detail in the ensuing sections.

Table 1. Comparative analysis of the studied fish feed ingredients.

Aqua Feed	Average Cost per Ton	Availability	Potential Benefits	Challenges	References
Plant-based feed	USD 300–USD 700	High	<ul style="list-style-type: none"> - Readily available ingredients (e.g., soy, maize, cassava) - Sustainable reduces pressure on fish stocks. - High amino acids. 	<ul style="list-style-type: none"> - Lower digestibility than fishmeal. - May require supplementation due to anti-nutritional factors. 	[36–39]
Fishmeal Fish oil	USD 1600 USD 800–USD 1800	Moderate	<ul style="list-style-type: none"> - High protein content. - Promotes fast fish growth. 	<ul style="list-style-type: none"> - High cost, especially for small-scale farmers. - Environmental concerns about overfishing for fishmeal. 	[40–42]
Insect-based feed	USD 400–USD 700	Moderate	<ul style="list-style-type: none"> - High protein content (40%+), Ca (7.56%). - Sustainable, uses organic waste. - Potential to reduce costs long-term. - Larvae contain natural antibiotics. 	<ul style="list-style-type: none"> - Limited large-scale production in Africa. - Regulatory challenges and lack of widespread acceptance 	[40,43–46]
Algae-based feed	USD 1000–USD 1500	Low	<ul style="list-style-type: none"> - Sustainable alternative to fishmeal. - Excellent source of amino acids and omega-3 and omega-6 fatty acids. - Improves growth rates and overall animal health. - Promotes color and disease resistance. 	<ul style="list-style-type: none"> - High production cost. - Still in developmental stages in Africa. 	[40,47,48]
Fish-discard-based feed	USD 400–USD 600	High	<ul style="list-style-type: none"> - Inexpensive and readily available. - Utilizes by-products of fish processing, reducing waste. 	<ul style="list-style-type: none"> - Quality inconsistency. - Risk of contamination and lower nutritional value. 	[40,49–51]

3.1. Plant-Based Proteins

Recently, plant proteins, including agricultural waste and oil seeds, have received attention as alternative and sustainable sources of protein for aquafeeds. Agriculture alone produces 998 million tons of waste annually [52]. These include animal waste, food processing waste, field residue, abandoned vegetables, and fruit, among others. Fish feed can be made from these and organic scraps that are safe for human consumption. Protein is an essential nutrient crucial in the selection of fish feed ingredients [33]. Table 2 summarizes some of the identified benefits and challenges of plant-based protein feed from the reviewed literature.

Table 2. Advantages and disadvantages of plant-based proteins in fish feed.

Plant Based Protein	References	
Benefits	Safer for human consumption	[37,53–56]
	Cost-effective	[4,57]
	Widely available	[4,57]
Disadvantages	Toxicity in cassava	[58]
	Reduced nutritional profile	[57,59]

Fish on food waste diets are generally safer for consumers as compared to fish-fed commercial diets, owing to greater pollutant concentrations in commercial diet fishmeal [55,56]. Conventional land-based foods have been recommended for some applications as alternatives for a portion of the fishmeal, but they can alter the nutritional content of the fish produced [60].

Wastes composed of cassava leaf flour, *Gliricidia* sp. (a nitrogen-fixing legume) leaves, and rice husk, enhanced with *Spirulina* sp. powder, are alternative sources of protein [32]. Cassava farming, for instance, is spread throughout several tropical countries, and it is widely grown across Africa, with an estimated yearly output of 291.9 million tons [61]. Cassava leaves contribute to the supply of proteins, micronutrients, and minerals and are a significant source of carbohydrates, but some varieties contain cyanogenic elements that must be detoxified before use [58].

Soybean and groundnuts are popular legumes in Africa but tend to be expensive compared to other legumes and tubers, such as sweet potato and cassava [4]. The choice and the combination of local ingredients depend on availability and affordability. A study conducted in Ghana showed that 43% of farmers use either yellow or white maize in the formulation of feed [4]. Nigerian plant commodities such as yam, plantain, banana, cowpeas, mucuna, maize, cassava, millet, sorghum, groundnut, sun hemp seed, and brewery wastes are being examined as viable fish feed materials [62]. In Kenya, farmers use plants such as spinach, cassava, vitamin mix, peas, carrots, garlic, kale, groundnuts, soybeans, and maize as feed ingredients [63]. However, some of the substances utilized in fish feed manufacturing, such as maize gluten, groundnut oilcake, sunflower oilcake, and soybean meal, can act as fungal growth sites [63]. Overall, plant-based proteins have been identified as reducing environmental impacts, having nutritional benefits for fish, and being relatively cheaper than traditional fishmeal. However, there is a need for careful formulations as some plants, such as cassava leaves, can be toxic while others promote fungal growth.

3.2. Insect-Based Protein

Insects have been studied widely as a viable protein source that can replace expensive and conventional ingredients such as fishmeal. Additionally, life cycle assessments have assisted in understanding the potential environmental impacts of using insects as feed sources. These assessments focus on parameters such as global warming potential, resource use (land, energy, water), eutrophication, acidification, economic fish-in-fish-out ratio, and solid waste output production [18,58]. Table 3 shows some of the advantages and disadvantages of using insect-based proteins in fish feed.

Table 3. Advantages and disadvantages of insect-based protein in fish feed.

	Insect-Based Protein	References
Benefits	Reduced land and water usage	[64]
	Increased weight in fish	[65]
	Increased profits	[65]
	Can convert organic material into essential nutrients for fish	[66,67]
	High in protein and lipids	[68–71]
	Reduced pressure on wild fish stocks	[72]
	High feed conversion efficiency	[72,73]
Disadvantages	Limited consumer acceptance	[74]
	Food safety concerns	[75]
	Allergen concerns	[70]
	Palatability may vary	[70,72]
	Higher carbon footprint	[76]

Manufacturing insect meal has environmental consequences that are measured using several indicators, including aquatic acidification potential (kgSO_2e), agricultural land occupation ($\text{m}^2 \text{org. arable}$), cumulative energy demand (MJ), global warming potential (kgCO_2e), aquatic eutrophication potential (kgPO_4e), water depletion (L deprived), and toxicity potential (ton TEG water/soil) [71]. These indicators reflect aspects such as acidification of aquatic ecosystems, land use, energy consumption, greenhouse gas emissions, eutrophication, water scarcity, and potential toxicity to water and soil. Studies by Alfiko support these assertions by showing the favorable impact on land usage for insect production. The downside is that insect production requires high energy use and has a larger carbon footprint than conventional protein sources [76] (see Figure 1).

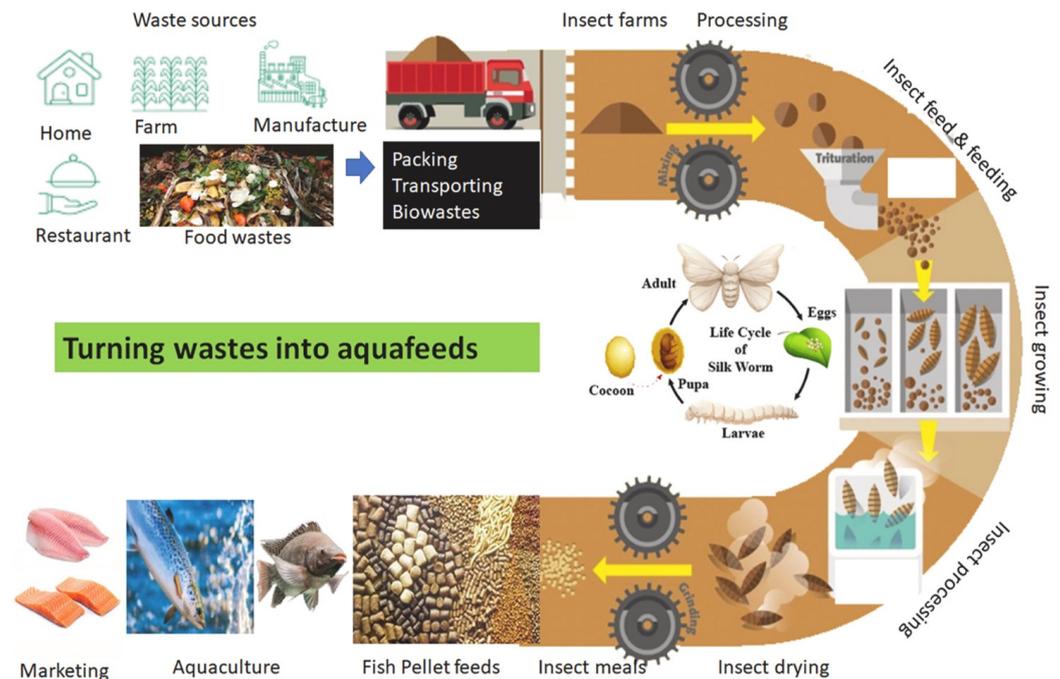


Figure 1. An illustration of how insect meal can be used to turn wastes into proteins for fishmeal. Source: [76] under Creative commons.

Studies have demonstrated that utilizing the Black Soldier Fly (BSF), *Hermetia illucens* L., can effectively transform various organic materials like food waste and manure into valuable nutrient sources for livestock and aquaculture feed. This presents a double win in novelty- where waste is minimized, and the environment is protected through nutrient recycling [46,66,77]. The treatment of bio-wastes originating from insect rearing presents an opportunity for the production of fertilizer critical for crop production [71]. In contrast, the inclusion of BSF, housefly (*Musca domestica*), mealworm (*Tenebrio molitor*), and grasshopper (*Zonocerus variegatus*) results in more solid nitrogen waste when compared to insect-free diets [78].

Using insect protein as a cost-effective alternative to fishmeal in tilapia aqua feed is viable. Studies demonstrated how feeding Nile tilapia fingerlings a diet with 33% black soldier fly larvae resulted in a larger gross profit margin compared to a diet with 100% black soldier fly larvae [65]. Additionally, the study found that fish on the insect diet experienced a 15% weight increase compared to those on controlled diets [65]. While Nile tilapia constitutes the majority of aquaculture production in sub-Saharan Africa, production costs and limited research on feed formulations have hindered its expansion [46,65]. Effective communication and farmer education are also lacking but key in enhancing farmers' awareness and understanding of the BSF diet and other novel fish feed ingredients among African smallholder farmers [43]. Although termites are abundant, their use is relatively low across Africa [43,79]. However, the promotion of the use of insect protein has multiple

benefits. Insect-based protein is environmentally friendly, has high nutritional value, and potential to free up arable land for food production and ultimately improve food security in Africa. This is because insect farming uses 50 to 90% less land per kg of protein produced, 40 to 80% less feed per kg of edible weight, produces 1.2 to 2.7 kg less greenhouse gas (GHG) emissions per kg of live weight gain, and 1000 L less water per kg of live weight gain compared to conventional livestock production systems [64,80]. Additionally, insect-based feed formulations have the potential to greatly benefit the animal husbandry and aquaculture industry in African communities, which serves as a critical economic and social asset. This growth in the industry not only supports the livelihoods of many individuals but also presents numerous synergistic opportunities for African economies.

Incorporating insects into fish feed holds promise for augmenting per capita fish consumption, thereby bolstering food security. Insect meal in aquaculture feed reduces energy requirements for synthesizing amino acids and proteins, enhancing metabolic activity and bolstering the immune system [67]. Its high protein content and superior lipid profile make it an excellent alternative to fishmeal for promoting the development of fry and juveniles [68]. Despite its potential growth, the current use of insect meal in aqua feed represents less than 1% of the global market [68]. In East Africa, multiple edible insect species such as *Acheta domesticus*, *Scapsipedus icipe*, *Gryllus bimaculatus*, *Schistocerca gregaria*, *Ruspolia differens*, *Hermetia illucens*, *Tenebrio molitor*, and *Rhynchophorus phoenicis* have the potential for farming [81–83], but the rapidly expanding industry lacks sufficient research attention. In South Africa, ensuring health and safety standards and implementing regulations for the farming and trade of edible insects and insect products are paramount considerations [72,75,84]. Additionally, some obstacles, including fostering consumer acceptance, addressing food safety apprehensions, and enacting suitable regulations, must be effectively addressed through collaborative endeavors involving the government, industry, and academia [74]. Also, certain difficult concerns, such as expenses and scaling up insect production, still persist across the continent [76].

3.3. Algae-Based Feed

Microalgae, which are aquatic unicellular microbes with approximately 50,000 species, can be used as sustainable fish feed. This is because they have the potential to reduce the strain on aquaculture based on fish flour and fish oil and help close the supply–demand gap for fish by increasing production [85]. Though these can fall under plant-based proteins, microalgae are a renewable resource and have a quick growth rate [86] thus we consider them separately. Table 4 provides a summary of some of the pros and cons of algae-based fish feed.

Table 4. Advantages and disadvantages of algae-based fish feed.

Algae-Based Feed		References
Benefits	Require minimal water and arable land	[85,87]
	Highly nutritious	[88]
	Ubiquitous and have higher biomass yields	[86,89]
	Multiple benefits, including wastewater treatment potential	[90]
	Job creation (coastal communities)	[91]
	Helps carbon sequestration and nutrient recycling	[91]
Disadvantages	Increased presence of metal bioaccumulation	[90]
	Not easily digestible	[90]
	Inconsistent biochemical composition and nutritional value	[25,90]

Microalgae biomasses are prospective feed source ingredients because their cell metabolites provide a combination of vital amino acids, healthy triglycerides, vitamins, and pigments [88]. Also, their production uses minimal land and water, making microalgae-based feed environmentally friendly. They are particularly well-suited to extensive production due to their high biomass yields per unit area and capacity to thrive in saltwater or non-potable water on non-arable terrain [87]. However, toxic metal bioaccumulation, poor microbial biomass digestion, and anti-nutrient effects must all be addressed before microalgae biomass and bio-products can be used as fish diets [90].

There is potential for the use of macroalgae as alternative plant-based feed sources. A study on coastal aquaculture in Zanzibar found that seaweed farming has achieved commercial-scale production, although challenges such as seaweed die-offs and economic constraints hinder its expansion [89]. Seaweed has rapid growth, high biomass production, and potential as a carbon sink before harvesting. It is therefore considered a novel alternative for fish food and feed, but consumer demand would need to be increased [89]. Seaweed cultivation in Africa has significant potential for job creation, value chain development, and export growth. Algae cultivation, predominantly red algae, has witnessed significant development in Tanzania, while other African nations such as Namibia, Mozambique, Madagascar, Kenya, and South Africa have also acknowledged the potential of cultivating seaweeds and have been actively developing their seaweed industries in recent decades [25]. The South African seaweed industry is a huge sector, and one of its crucial aquaculture products is the green seaweed *Ulva*, which plays a vital role as a feed source in South Africa and serves as a template for other coastal countries [92]. With affordable investment costs and increasing demand, seaweed farming offers an opportunity to improve living conditions across the continent. Unlike traditional agriculture and fish farming, seaweed cultivation, currently dominated by women, requires minimal land, water, and external inputs while contributing to social equity, coastal ecosystem restoration, carbon sequestration, and nutrient recycling [91].

Despite algae's potential for huge economic benefits due to lower input costs, low carbon footprint, and wastewater treatment ability, their biochemical composition knowledge is scarce and varied, while the nutritional value information is scattered or inconsistent [90]. The knowledge gap presents an opportunity for further research and development into feeds.

3.4. Fish-Waste-Based Feed

Fish discard is starting to emerge as a fish feed alternative for the aquaculture industry. World leaders' priority is not just to ameliorate the effects that have already occurred but also to tackle the demand to generate more food and energy for a global population that is projected to exceed 10 billion people by 2050 through fewer fossil fuels, lower harmful gas emissions, and zero waste [93,94]. Over the last decade, more than 40 countries have developed and implemented national policies, policy instruments, and strategies related to this new economic model of reduced and zero waste [95–98], which is primarily based on an efficient resource management system with the priority of extending the useful life of materials and products and preventing their loss of value by incorporating their waste into production processes [95,99]. Fish waste and feeding residue generate carbon dioxide (CO₂)-rich organic matter, while protein-rich residual feed and fish excretions release nitrous oxide (N₂O) and methane (CH₄) into the atmosphere through gas bubbling [7,100,101]. Utilizing fish waste in feed can reduce the amount of discard in the environment. Table 5 provides a summary of the merits and demerits of using fish waste in fish feed.

Table 5. Advantages and disadvantages of using fish waste in fish feeds.

Fish-Waste-Based Feed		References
Benefits	Efficient resource use	[102–105]
	Highly nutrient rich	[102,106–109]
	Lower environmental pollution	[106]
	Cost-effective	[106]
Disadvantages	Regulatory and safety concerns (e.g., pathogen risk)	[102]
	Risk of overconsumption of seafood	[106]

More than 60% of fish and shellfish by-products, including bones, trimmings, head, fins, skin, scales, and intestines, are discarded, whereas less than 40% of fish products are consumed by humans [107]. Collagen and gelatin can be found in fish skin offal. Fishbone is primarily cartilage that has been cemented with calcium phosphate. Fish spine waste is another good source of protein and minerals. Furthermore, fish scales contain both inorganic and organic components, principally hydroxyapatite and collagen [108]. Fishbone and fish spine waste can, therefore, be utilized as ingredients in fish feed, organic fertilizers, biogas production, extraction of bioactive compounds, and industrial applications such as the production of biomaterials and dental products, cutting production costs while increasing income [103,106,109]. The use of fishery discards as a secondary raw material is a resource-efficient approach that lowers production costs, mitigates potential environmental impacts, and contributes to maintaining fisheries sustainability [103]. It is important to consider in-depth studies on the valorization of fish discard in African contexts.

4. Feed Management in Aquaculture

Several studies have shown the importance of effective feed management approaches in reducing feed waste, lowering costs, promoting fast fish growth, and increasing profitability [109–111]. Proper feeding management can lower feed costs by 15–20% [110]. Underfeeding and overfeeding are both prevalent in multiple farming systems and nations [111]. Underfeeding wastes feed, resulting in stunted growth and reduced production, while overfeeding is equally detrimental to water quality [109,110]. A study conducted in Ghana indicated incidences of overfeeding and many cases of underfeeding in small-scale production systems [4]. A low percentage of aquatic animal survival is caused by the ammonification of extra feed and waste that is dumped at the bottom of the pond.

Species- and fish-size-specific possible efficacy of any diet must be known to facilitate labeling feed with the required data on feed digestibility and potential waste output, including the amount of solids, phosphorus, and nitrogen [112]. The researchers also proposed that the biomass of the fish in the system be known, as well as appropriate information on the fish's health and physiological status [112]. Uniformity in fish size is critical for them to ingest the same size of pellet; the feed should be sieved to eliminate dust and remove broken pellets; and the feed must be fed successfully to reduce waste from uneaten feed [113,114].

Aqua Feed Formulation Methods

Feed composition and chemical composition are essential for sustainable aquaculture [115]. Proper feed ingredient grinding, pelleting, and steam flaking increase nutritional availability, minimize undigested feed and fecal loss, and promote good water quality [116]. Production methods like extruded diets where aqua feed dry ingredients are moistened and heated through steaming ensure consistency and digestibility, reducing the amount of toxins expelled into the water [117]. Evidence suggests that extruded free-floating feeds are more appropriate than sinking feeds in reducing lake pollution [118]. Most small-scale feed producers from African countries still struggle with producing free-floating feed [119].

Highly digested feedstuff, for example, reduces solid waste outflow while improving water quality. Determining material for feed ingredients requires a study of digestibility. Feed with highly digestible components is connected with improved growth performance and lower feed waste, which may contaminate the environment [120]. As a result, it is advised to choose and consider adequate feed ingredients with sufficient digestible phosphorus and nitrogen levels to reduce phosphorus and nitrogen excretion while maintaining growth performance [121]. The number of necessary amino acids and their balance are important elements in defining the quality of fish feed. Excessive amino acid feeding causes ammonia excretion and energy loss [122]. The balance of protein intake and energy use reduces dissolved nitrogen waste. Dietary planning based on adequate phosphorus availability reduces phosphorus excretion and enhances water quality [123]. Nitrogen excretion can be decreased by including crystalline amino acids and other synthetic amino acids in fish diets to accurately match amino acid needs [124].

5. Navigating the Sustainability of Aqua Feed in Aquaculture

Aquaculture is impacted by several factors, including climate variability, sea level rise, infections, hazardous algal blooms, the unpredictability of external input supplies, and shifting sea surface salinity [125]. Approximately 71% of fishmeal and 74% of fish oil are from wild catches, particularly pelagic fish, with the remainder emanating from aquatic animal processing waste [126]. The aquaculture sector consumed approximately 86% of global fishmeal production in 2021 [2]. Given this high demand, the continued supply of fishmeal for increased future aquaculture fish production is unsustainable. In context, sustainably caught small pelagic fish cannot meet this demand as their availability continues on a downward trajectory [1]. Their availability is also challenged by climatic conditions [127]. As a result, aquaculture ought to minimize reliance on fishmeal and fish oil from small wild stocks, which support aquatic food chains and food security for the poor on many coastlines. The adoption of innovative fish feeds in aquaculture has the potential to support the nutritional demands of fish attributed to humans while having little environmental implications [52] (see Figure 2).

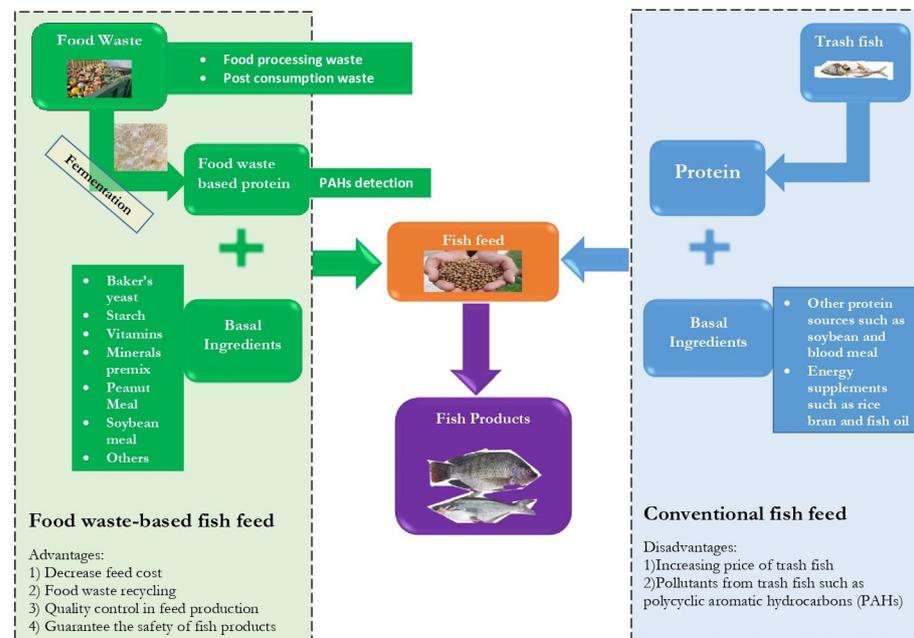


Figure 2. Upcycled aquafeed versus conventional aquafeeds [128].

The implications of novel fish feed for improving human livelihoods extend beyond profitability. However, they have several positive and negative implications on the socio-economic and environmental factors that affect sustainability. Demonstrating beneficitation

in attaining sustainability in aquaculture, particularly in SSA, where the fish farmers are mostly small-scale, is crucial. Table 6 provides a summary of some of the implications identified from the literature.

Table 6. Socio-economic and environmental implications of novel aqua feeds in Africa.

Identified Impacts	References
<i>Social</i>	
Poverty reduction	[129,130]
Reduced malnutrition	[91,131]
Increased food security	[130,132]
Gender empowerment	[133]
<i>Economic</i>	
Improved production (increase in fish size and quantity, reduced mortality, etc.)	[4,134]
Increase in local supply (increased access)	[91,135]
Increased profits	[4,134,136]
Increased employment opportunities for rural communities	[4,91,129,137]
Increased market inequalities	[91,133,138,139]
Poor payment over novel feeds	[91]
<i>Environmental</i>	
Increased resource efficiency	[33,140–142]
Reduced pressure on wild catches	[143–145]
Increased competition for resources with other industries	[146]
Eutrophication from aqua waste (nitrous oxide, methane, etc.)	[100,101,147,148]

Aquaculture possesses the potential for climate change adaptation and mitigation beyond its existing benefits in poverty reduction and food security [130]. Around 200 million individuals in Africa obtain affordable and nutritious proteins from fish, yet the utilization of fish as a means to address the “triple burden” of malnutrition—which encompasses obesity, undernutrition, and micronutrient deficiencies and significantly contributes to health issues in the area—is not maximized [149]. If properly produced, improved feeds result in improved production, which can end malnutrition and help build healthy, eco-friendly, and resilient food systems [91,131].

Moreover, novel feeds have the potential for higher revenues due to faster growth, increased fish size and productivity, lower feed costs, reduced mortality, and enhanced management practices [4,134]. Affordably priced quality feed will make fish farming more appealing to small-scale farmers, inspiring them to begin or resume aquaculture or to take fish farming seriously again [4]. Improving aquaculture livelihoods is made possible by creating nutritious, affordable, and easily accessible feed [135]. The fish feed industry has the potential to create employment for both men and women in most African countries. Novel local feeds can augment local economies, especially for vulnerable groups and rural communities [137]. However, a study conducted in nine African countries [91] revealed that the fish-based feed industry, particularly in Guinea, has widespread issues of poor payment. Also, a review of studies in Nigeria found that literature on feed production gender dynamics remains scarce, and where available, indications show that men dominate feed production and supply, but the strengthening of such sectors does provide opportunities for both men and women [133].

The biggest barriers to aquaculture development in developing nations are feeding costs and quality, but this can make the venture unsustainable in terms of return on investments. Also, the adoption of creating their own feeds using cheaper and locally

accessible raw materials remains low in some African countries, and only a few do so when finances are tight, which may compromise beneficiation [4]. Some of the challenges cited in the adoption of novel fish technologies include limited knowledge, resource constraints, and traditional norms and beliefs, among other factors [150]. Experimentation is strongly suggested to determine suitable and cost-effective combinations of locally accessible raw materials and commercial feeds.

Aquaculture production must also prioritize environmentally sustainable practices [7,151]. Indirect and direct impacts of climate change on aquaculture include implications on targeted populations' range and productivity, habitats, and food webs, as well as impacts on fishery and aquaculture costs and productivity, as well as fishing community livelihoods and safety [152,153]. The promotion of aquaculture production has resulted in adverse consequences, such as increased GHG emissions from the production of fishmeal sourced from animal products and the loss of carbon sinks due to mangrove clearing, thereby amplifying atmospheric GHG persistence [130]. Sustainable aquaculture production can contribute to triple wins for increased production, climate mitigation, and climate adaptation. Mitigation and adaptation efforts can include innovations in feed formulation, feed management, and system design. The nutritional makeup of aqua feed is critical as it affects the quality of waste products, which have an impact on both the water quality in culture systems and the surrounding environment. The waste generated by fish can accumulate in the surrounding environment, leading to oxygen depletion in the water and the formation of algal blooms and dead zones [154].

Aqua wastes can affect the pH of the water, the number of algae in it, the biological oxygen demand (BOD), and even the fish mortality rate. Aqua-feed wastes promote eutrophication, which results in blooms of toxic algae [147]. Additionally, because fish cannot retain all the food they eat, a sizeable portion of the feed is left uneaten, resulting in massive amounts of aqua waste being expelled [147]. Solid waste and dissolved wastes from aquaculture result largely from feed uneaten, decomposed feed, fish droppings, dead fish carcasses, chemicals, pathogens, and other components [112].

Insufficient implementation of environmentally sustainable practices, which minimize the impact on the environment, emerges as a contributing factor hindering both economic growth and the intensification of aquaculture in SSA [155]. Effective management of feed in aquaculture can significantly reduce waste and minimize the environmental impact. Implementing strategies such as optimizing feed conversion ratios, providing feed digestibility and waste production information, sifting feed to remove dust and broken pellets, ensuring proper feeding practices, incorporating low-phytate grains, increasing phytase levels in fish feed formulation, and developing high-energy extruded feed can reduce waste, improve overall feed utilization, minimize phosphorus release into the water, and minimize nutrient leaching [112]. The dual benefits of economic growth and environmental sustainability can be realized through cleaner technologies and sustainable production practices [7].

Importance of Circularity of Aqua Feed

Over the last 50 years, agricultural production has tripled owing to soil expansion for agricultural use, the Green Revolution technologies, and increased human population increase [156]. The international regulatory framework for sustainable development has transformed agriculture's role, particularly policies and plans for the circular economy (CE) and bioeconomy. This has resulted in novel and enhanced techniques for agricultural waste, resource use efficiency, sustainable production, and reduced ecological impacts [93]. Egypt is forerunning in the integration of fish production and rice farming, maximizing efficient utilization of resources such as land and water while improving food security. The country leads in rice production across Africa and the Middle East [157], and the incentivized rice field aquaculture can be an opportunity for minimizing feed costs through novel fish feeds incorporating protein from rice.

The cost, quality, and nutritional value of feed are concerns for small-scale fish farmers, leading them to produce their own feed from agricultural by-products. However, the

resulting feed powder from most African small-scale fish farmers presents several physical and nutritional disadvantages for fish [20]. Good nutrition in aquaculture systems is essential to the economical production of a healthy and high-quality product. In addition, ingredients are often imported, and the distance that they need to cover in transportation for milling, feed production, distribution, wholesale, and retail means that costs become high. As such, production easily becomes unsustainable. Countries are challenged to re-orient production approaches in the context of climate change by minimizing costs through replacing conventional feed with novel protein and energy sources, including indigenous products with high protein and energy products such as indigenous wild fruit tree products [158].

A CE offers a primary sustainable alternative to traditional linear production practices such as reuse, recycling, and remanufacturing while reducing the negative externalities [95,159]. Elsewhere, the European food policy mandates CE in all production systems as it offers the best base for making cradle-to-cradle LCA assessments [160]. The circular economy and bio-economy make substantial contributions to the attainment of four sustainable development goals (SDGs), i.e., SDG 2: “Ending hunger, achieving food security, improving nutrition, and promoting sustainable agriculture”; SDG 11: “Making cities and human settlements inclusive, safe, resilient, and sustainable”; SDG 12: “Ensuring sustainable consumption and production patterns”, with the main goal of “doing more and better with fewer resources” [161]; and SDG 13: “Taking urgent action to combat climate change and its impacts” [93].

The increase in global agricultural production puts more strain on the environment, harming soil, air, and water resources [162]. The aquaculture industry requires an alternative business model, such as a circular economy, as the “take-make-dispose” paradigm is no longer appropriate in the context of shifts such as climate change. Using waste could, therefore, help society, the environment, and the economy. In the case of high-demand aquaculture commodities, efforts must be made to speed up production and fulfill rising demand, but there is concern about the rate of change and calls for the prudent use of natural resources. A life-cycle study comparing the environmental effects of standard mix feed with feed made from cruise ship food waste [163] was seen as a forerunner of the CE technique in aquaculture. Another study that backs up the CE concept is the replacement of fish oil with alternative sustainable resources generated not only from vegetable fats but also from animal fats [164]. A study on Integrated Trophic Aquaculture Systems (IMTA) conducted in Ireland, Brazil, and South Africa found that nutrient management and resource efficiency were the major circularity indications resulting in a 90% increase in water reticulation and 80–90% improvement in bioremediation effectiveness [165].

6. Limitations of This Study

The limitations of this review include the regional focus on Africa, in particular sub-Saharan Africa, which could mean that the findings cannot be generalized for other geographical regions. Also, the limitations in the literature available that provide evidence of the circularity of fish feeds were identified. Ultimately, this study did not comprehensively cover all existing research gaps in aquaculture but exposed key gaps for further scrutiny, such as the need for contextual life cycle assessments on various local feed alternatives in Africa and beyond.

7. Conclusions

Understanding the dynamics of the aquaculture industry through aqua feeds is critical in ensuring the sustainability of the livelihood, as feed constitutes the highest expense incurred during aquaculture fish production. Novel feed formulations promise multiple socio-economic and environmental benefits, albeit adoption is minimal in most African countries. The nutritional composition of aqua feed influences aqua waste, which has spiraling effects on the environment and fish production; hence, reorienting feed formulation methods and ingredients is crucial for achieving triple wins for fish farmers and support-

ing a circular economy. Other implications from this study include minimizing strain on wild aquatic resources through utilizing novel feed alternatives for both commercial and artisanal fish feed producers. There are prospects for cost and benefit analysis studies to pursue the sustainability of local feed alternatives other than plants and insects for an improved circular economy.

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References

1. FAO. The State of World Fisheries and Aquaculture 1998. In *The State of World Fisheries and Aquaculture (SOFIA)*; FAO: Rome, Italy, 1999; ISBN 925104187.
2. FAO. The State of World Fisheries and Aquaculture 2024: Blue Transformation in Action. In *The State of World Fisheries and Aquaculture (SOFIA)*; FAO: Rome, Italy, 2024; ISBN 978-92-5-138763-4.
3. FAO. The State of World Fisheries and Aquaculture 2020. In *Sustainability in Action*; FAO: Rome, Italy, 2020; Volume 32, p. 244. [[CrossRef](#)]
4. Ragasa, C.; Osei-Mensah, Y.O.; Amewu, S. Impact of Fish Feed Formulation Training on Feed Use and Farmers' Income: Evidence from Ghana. *Aquaculture* **2022**, *558*, 738378. [[CrossRef](#)]
5. Kenya National Bureau of Statistics. *Kenya Population and Housing Census Reports. Kenya National Bureau of Statistics KNBS*; ISO: Geneva, Switzerland, 2019.
6. Madibana, M.; Fouché, C.; Mnisi, C. Challenges Facing Emerging Aquaculture Entrepreneurs in South Africa and Possible Solutions. *Afr. J. Food Agric. Nutr. Dev.* **2020**, *20*, 16689–16702. [[CrossRef](#)]
7. Ngarava, S.; Zhou, L.; Nyambo, P.; Chari, M.M.; Bhungeni, O. Aquaculture Production, GHG Emission and Economic Growth in Sub-Sahara Africa. *Environ. Chall.* **2023**, *12*, 100737. [[CrossRef](#)]
8. SADC-EU. South African Fisheries and the SADC-EU Economic Partnership Agreement. Available online: <https://sadc-epa-outreach.com/images/files/sadc-eu-epa-fisheries-july-2017.pdf> (accessed on 17 July 2024).
9. Muala, W.C.B.; Desobgo, Z.S.C.; Jong, N.E. Optimization of Extraction Conditions of Phenolic Compounds from *Cymbopogon Citratus* and Evaluation of Phenolics and Aroma Profiles of Extract. *Heliyon* **2021**, *7*, e06744. [[CrossRef](#)] [[PubMed](#)]
10. Little, D.; Newton, R.; Beveridge, M. Aquaculture: A Rapidly Growing and Significant Source of Sustainable Food? Status, Transitions and Potential. *Proc. Nutr. Soc.* **2016**, *75*, 274–286. [[CrossRef](#)]
11. Nasr-Allah, A.; Gasparatos, A.; Karanja, A.; Dompok, E.B.; Murphy, S.; Rossignoli, C.M.; Phillips, M.; Charo-Karisa, H. Employment generation in the Egyptian aquaculture value chain: Implications for meeting the Sustainable Development Goals (SDGs). *Aquaculture* **2020**, *520*, 734940. [[CrossRef](#)]
12. Jang, H.G.; Yamazaki, S. Community-Level Analysis of Correlated Fish Production in Fisheries and Aquaculture: The Case of Japan. *Mar. Policy* **2020**, *122*, 104240. [[CrossRef](#)]
13. Kaleem, O.; Sabi, A.F.B.S. Overview of Aquaculture Systems in Egypt and Nigeria, Prospects, Potentials, and Constraints. *Aquac. Fish.* **2021**, *6*, 535–547. [[CrossRef](#)]
14. Ellen Macarthur Foundation. *Cities in the Circular Economy: An Initial Exploration*; Ellen Macarthur Foundation: Cowes, UK, 2017.
15. Subasinghe, R.; Soto, D.; Jia, J. Global Aquaculture and Its Role in Sustainable Development. *Rev. Aquac.* **2009**, *1*, 2–9. [[CrossRef](#)]

16. Naylor, R.L.; Hardy, R.W.; Buschmann, A.H.; Bush, S.R.; Cao, L.; Klinger, D.H.; Little, D.C.; Lubchenco, J.; Shumway, S.E.; Troell, M. A 20-Year Retrospective Review of Global Aquaculture. *Nature* **2021**, *591*, 551–563. [CrossRef]
17. Belghit, I.; Liland, N.S.; Waagbø, R.; Biancarosa, I.; Pelusio, N.; Li, Y.; Krogdahl, Å.; Lock, E.J. Potential of Insect-Based Diets for Atlantic Salmon (*Salmo salar*). *Aquaculture* **2018**, *491*, 72–81. [CrossRef]
18. Obwanga, B.; Rurangwa, E.; Duijn, A.; Soma, K. A Comparative Study of Aquaculture Sector Development in Egypt, Ghana and Nigeria: Insights for Kenya’s Sustainable Domestic Sector Development. *Wageningen. Mar. Res.* **2018**, *6*, 14–18.
19. Olapade, O.J.; Saboleh, P. Development of Fish Feeds for African Catfish (*Clarias gariepinus* Burchell 1822) Farming in Sierra Leone, West Africa. *Int. J. Fish. Aquac.* **2022**, *14*, 15–21. [CrossRef]
20. Mustapha, A. Improving the Quality of Aquafeed for an Effective Food Security in Small Scale African Aquaculture. *World J. Adv. Res. Rev.* **2020**, *7*, 274–282. [CrossRef]
21. Hasimuna, O.J.; Maulu, S.; Mphande, J. Aquaculture Health Management Practices in Zambia: Status, Challenges and Proposed Biosecurity Measures. *J. Aquac. Res. Dev.* **2020**, *11*, 1–6.
22. Udoh, J.P.; Ekpo, I.E. Diet-Morphology Relationships of Some Fish Species in the Cross-River Estuary, Southeast Nigeria. *Int. J. Fish. Aquac. Res.* **2017**, *3*, 10–29.
23. Rosas, V.T.; Poersch, L.H.; Romano, L.A.; Tesser, M.B. Feasibility of the Use of Spirulina in Aquaculture Diets. *Rev. Aquac.* **2019**, *11*, 1367–1378. [CrossRef]
24. Avadí, A.; Bolaños, C.; Sandoval, I.; Ycaza, C. Life Cycle Assessment of Ecuadorian Processed Tuna. *Int. J. Life Cycle Assess.* **2015**, *20*, 1415–1428. [CrossRef]
25. Mbaka, M.M.; Cox, J.H.; Ronan, S. Aquaculture in Africa: Aquatic Animal Welfare, Impact on the Environment and the Sustainability of the Sector. 2022. Available online: https://www.wellbeingintlstudiesrepository.org/aw_farm_aqua/1/ (accessed on 17 July 2024).
26. AU-IBAR. *Africa Blue Economy Programme*; African Union: Nairobi, Kenya, 2019; p. 48.
27. Nyamukonda, V.; Ndlovu, L. Indigenous and Underutilized Fruits for Food and Nutritional Security in Southern Africa. *J. Ethn. Foods* **2019**, *6*, 17–26.
28. Barange, M.; Bahri, T.; Beveridge, M.C.; Cochrane, K.L.; Funge-Smith, S.; Poulain, F. Impacts of Climate Change on Fisheries and Aquaculture. *United Nations’ Food Agric. Organ.* **2018**, *12*, 628–635.
29. Goyal, S.; Ott, D.; Liebscher, J.; Höfling, D.; Müller, A.; Dautz, J.; Gutzeit, H.O.; Schmidt, D.; Reuss, R. Sustainability Analysis of Fish Feed Derived from Aquatic Plant and Insect. *Sustainability* **2021**, *13*, 7371. [CrossRef]
30. Gephart, J.A.; Henriksson, P.J.G.; Parker, R.W.R.; Shepon, A.; Gorospe, K.D.; Bergman, K.; Eshel, G.; Golden, C.D.; Halpern, B.S.; Hornborg, S.; et al. Environmental Performance of Blue Foods. *Nature* **2021**, *597*, 360–365. [CrossRef] [PubMed]
31. Munguti, J.; Kirimi, J.; Obiero, K.; Ogello, E.; Sabwa, J.; Kyule, D.; Liti, D.; Musalia, L. Critical Aspects of Aquafeed Value Chain in the Kenyan Aquaculture Sector. *Rev. Sustain. Agric. Res.* **2021**, *10*, 87. [CrossRef]
32. Carmona, M.; Rendón-Castrillón, L.; Ocampo-Lopez, C.; Sánchez-Osorno, D. Fish Food Production Using Agro-Industrial Waste Enhanced with *Spirulina* sp. *Sustainability* **2022**, *14*, 6059. [CrossRef]
33. Adeyemi, A.D.; Kayodé, A.P.P.; Chabi, I.B.; Odouaro, O.B.O.; Nout, M.J.; Linnemann, A.R. Screening Local Feed Ingredients of Benin, West Africa, for Fish Feed Formulation. *Aquac. Rep.* **2020**, *17*, 100386. [CrossRef]
34. Ssepuyaya, G.; Mukisa, I.M.; Nakimbugwe, D. Nutritional Composition, Quality, and Shelf Stability of Processed Ruspolia Nitidula (Edible Grasshoppers). *Food Sci. Nutr.* **2017**, *5*, 103–112. [CrossRef]
35. Verdegem, M.; Yossa, R.; Chary, K.; Schrama, J.W.; Beveridge, M.C.M.; Marwaha, N. *Sustainable and Accessible Fish Feeds for Small-Scale Fish Farmers*; CGIAR Research Program on Fish Agri-Food Systems: Penang, Malaysia, 2021.
36. Zakaria, M.K.; Kari, Z.A.; Van Doan, H.; Kabir, M.A.; Che Harun, H.; Mohamad Sukri, S.A.; Goh, K.W.; Wee, W.; Khoo, M.I.; Wei, L.S. Fermented Soybean Meal (FSBM) in African Catfish (*Clarias gariepinus*) Diets: Effects on Growth Performance, Fish Gut Microbiota Analysis, Blood Haematology, and Liver Morphology. *Life* **2022**, *12*, 1851. [CrossRef]
37. Kari, Z.A.; Kabir, M.A.; Razab, M.K.A.A.; Munir, M.B.; Lim, P.T.; Wei, L.S. A Replacement of Plant Protein Sources as an Alternative of Fish Meal Ingredient for African Catfish, *Clarias gariepinus*: A Review. *J. Trop. Resour. Sustain. Sci. JTRSS* **2020**, *8*, 47–59.
38. Santillan, E.; Yasumaru, F.; Vethathirri, R.S.; Thi, S.S.; Hoon, H.Y.; Sian, D.C.P.; Wuertz, S. Microbial Community-Based Protein from Soybean-Processing Wastewater as a Sustainable Alternative Fish Feed Ingredient. *Sci. Rep.* **2024**, *14*, 2620. [CrossRef]
39. Roslan, N.A.; Sukri, S.A.M.; Wei, L.S.; Shahjahan, M.; Rohani, M.F.; Yea, C.S.; Kabir, M.A.; Guru, A.; Goh, K.W.; Kallem, P. Replacement of Fishmeal by Fermented Spent Coffee Ground: Effects on Growth Performance, Feed Stability, Blood Biochemistry, Liver, and Intestinal Morphology of African Catfish (*Clarias gariepinus*). *Aquac. Rep.* **2024**, *36*, 102073. [CrossRef]
40. Hodar, A.; Vasava, R.; Mahavadiya, D.; Joshi, N. Fish Meal and Fish Oil Replacement for Aqua Feed Formulation by Using Alternative Sources: A Review. *J. Exp. Zool. India* **2020**, *23*, 13–21.
41. Oliva-Teles, A.; Enes, P.; Couto, A.; Peres, H. Replacing Fish Meal and Fish Oil in Industrial Fish Feeds. *Feed. Pract. Aquac.* **2022**, 231–268. [CrossRef]
42. Kok, B.; Malcorps, W.; Tlusty, M.F.; Eltholth, M.M.; Auchterlonie, N.A.; Little, D.C.; Davies, S.J. Fish as Feed: Using Economic Allocation to Quantify the Fish In: Fish Out Ratio of Major Fed Aquaculture Species. *Aquaculture* **2020**, *528*, 735474. [CrossRef]

43. Ouko, K.O.; Mboya, J.B.; Obiero, K.O.; Ogello, E.O.; Mukhebi, A.W.; Muthoka, M.; Munguti, J.M. Determinants of Fish Farmers' Awareness of Insect-Based Aquafeeds in Kenya; the Case of Black Soldier Fly Larvae Meal. *Cogent Food Agric.* **2023**, *9*, 2187185. [CrossRef]
44. Ondiba, R.N.; Ogello, E.O.; Kembenyua, E.; Gichana, Z.; Obiero, K. Future Demand and Supply of Aquafeed Ingredients: Outlines to Commercialize Non-Conventional Protein Ingredients to Enhance Aquaculture Production for Food Security in Sub-Saharan Africa. *Aquat. Ecosyst. Health Manag.* **2022**, *25*, 75–84. [CrossRef]
45. Lisboa, H.M.; Nascimento, A.; Arruda, A.; Sarinho, A.; Lima, J.; Batista, L.; Dantas, M.F.; Andrade, R. Unlocking the Potential of Insect-Based Proteins: Sustainable Solutions for Global Food Security and Nutrition. *Foods* **2024**, *13*, 1846. [CrossRef]
46. Limbu, S.M.; Shoko, A.P.; Ulotu, E.E.; Luvanga, S.A.; Munyi, F.M.; John, J.O.; Opiyo, M.A. Black Soldier Fly (*Hermetia illucens*, L.) Larvae Meal Improves Growth Performance, Feed Efficiency and Economic Returns of Nile Tilapia (*Oreochromis niloticus*, L.) Fry. *Aquac. Fish Fish.* **2022**, *2*, 167–178. [CrossRef]
47. Sarker, P.K.; Kapuscinski, A.R.; McKuin, B.; Fitzgerald, D.S.; Nash, H.M.; Greenwood, C. Microalgae-Blend Tilapia Feed Eliminates Fishmeal and Fish Oil, Improves Growth, and Is Cost Viable. *Sci. Rep.* **2020**, *10*, 19328. [CrossRef]
48. Ansari, F.A.; Guldhe, A.; Gupta, S.K.; Rawat, I.; Bux, F. Improving the Feasibility of Aquaculture Feed by Using Microalgae. *Environ. Sci. Pollut. Res.* **2021**, *28*, 43234–43257. [CrossRef]
49. Gasco, L.; Acuti, G.; Bani, P.; Dalle Zotte, A.; Danieli, P.P.; De Angelis, A.; Fortina, R.; Marino, R.; Parisi, G.; Piccolo, G. Insect and Fish By-Products as Sustainable Alternatives to Conventional Animal Proteins in Animal Nutrition. *Ital. J. Anim. Sci.* **2020**, *19*, 360–372. [CrossRef]
50. Apaza, A.C.M. Utilization of Acid Whey as a Fermentation Aid to Process Fish Waste and Develop an Enriched Feed Ingredient. Doctoral Dissertation, The Ohio State University, Columbus, OH, USA, 2022.
51. Fernández-Arias, M.; Álvarez-Olcina, I.; Malvido-Fresnillo, P.; Vázquez, J.A.; Boutinguiza, M.; Comesaña, R.; Pou, J. Biogenic Calcium Phosphate from Fish Discards and By-Products. *Appl. Sci.* **2021**, *11*, 3387. [CrossRef]
52. Obi, F.O.; Ugwuishiwu, B.O.; Nwakaire, J.N. Agricultural waste concept, generation, utilization and management. *Niger. J. Technol.* **2016**, *35*, 957–964. [CrossRef]
53. Marwaha, N.; Beveridge, M.; Phillips, M.; Komugisha, B.; Notere Boso, D.; Chan, C.; Kabir, K.; Sulser, T.; Wiebe, K. *Alternative Seafood: Assessing Food, Nutrition and Livelihood Futures of Plant-Based and Cell-Based Seafood*; WorldFish: Penang, Malaysia, 2020.
54. Salter, A.M.; Lopez-Viso, C. Role of Novel Protein Sources in Sustainably Meeting Future Global Requirements. *Proc. Nutr. Soc.* **2021**, *80*, 186–194. [CrossRef]
55. Sotolu, A.O. Comparative Utilizations of Fish Waste Meal with Imported Fishmeal by African Catfish (*Clarias gariepinus*). *Am.-Eurasian J. Sustain. Agric.* **2009**, *4*, 285–289.
56. Wong, M.H.; Mo, W.Y.; Choi, W.M.; Cheng, Z.; Man, Y.B. Recycle Food Wastes into High Quality Fish Feeds for Safe and Quality Fish Production. *Environ. Pollut.* **2016**, *219*, 631–638. [CrossRef]
57. Jatta, S.; Fall, J.; Diouf, M.; Ndour, P.M.; Fall, S.K.L. The Effects of Substituting Fishmeal Based-Diet With Plant Based-Diet on Nile Tilapia (*Oreochromis niloticus*) Fish Growth, Feed Efficiency and Production Cost-Effectiveness. *J. Biol. Life Sci.* **2022**, *13*, 29–39. [CrossRef]
58. Lansche, J.; Awiszus, S.; Latif, S.; Müller, J. Potential of Biogas Production from Processing Residues to Reduce Environmental Impacts from Cassava Starch and Crisp Production—a Case Study from Malaysia. *Appl. Sci.* **2020**, *10*, 2975. [CrossRef]
59. Hardy, H. Utilisation of Plant Proteins in Fish Diets: Effects of Global Demand and Supplies of Fish Meal. *Aquac. Res.* **2010**, *41*, 770–776. [CrossRef]
60. Shah, M.R.; Lutzu, G.A.; Alam, A. Microalgae in Aquafeeds for a Sustainable Aquaculture Industry. *J. Appl. Phycol.* **2018**, *30*, 197–213. [CrossRef]
61. Shackelford, G.E.; Haddaway, N.R.; Usieta, H.O. Cassava Farming Practices and Their Agricultural and Environmental Impacts: A Systematic Map Protocol. *Environ. Evid.* **2018**, *7*, 30. [CrossRef]
62. Audu, R.; Yola, I. Contemporary Issues in Fisheries and Aquaculture: A Review on Non-Conventional Feed Ingredients for Fish Feed in Nigeria. *Bayero J. Pure Appl. Sci.* **2021**, *13*, 22–28. [CrossRef]
63. Nyamwaka, I.; Monda, E.; Ombori, R. Prevalence and Characterization of Moulds Associated with Fish Feeds Sold in Kisii County, Kenya. *J. Adv. Microbiol.* **2020**, *20*, 31–41. [CrossRef]
64. Buitrago, P.A.E.; Hernández, L.M.; Burkart, S.; Palmer, N.; Arango, J.A.C. Forage-Fed Insects as Food and Feed Source: Opportunities and Constraints of Edible Insects in the Tropics. *Front. Sustain. Food Syst.* **2021**, *5*, 724628. [CrossRef]
65. Wachira, M.N.; Osuga, I.M.; Munguti, J.M.; Ambula, M.K.; Subramanian, S.; Tanga, C.M. Efficiency and Improved Profitability of Insect-Based Aquafeeds for Farming Nile Tilapia Fish (*Oreochromis niloticus* L.). *Animals* **2021**, *11*, 2599. [CrossRef]
66. Pechal, J.L.; Benbow, M.E.; Kamng'ona, A.W.; Safalaoh, A.; Masamba, K.; Kang'ombe, J. The Need for Alternative Insect Protein in Africa. *Ann. Entomol. Soc. Am.* **2019**, *112*, 566–575. [CrossRef]
67. Mousavi, S.; Zahedinezhad, S.; Loh, J.Y. A Review on Insect Meals in Aquaculture: The Immunomodulatory and Physiological Effects. *Int. Aquat. Res.* **2020**, *12*, 100–115. [CrossRef]
68. Fletcher, R. Why Insect Production May Have Minimal Impact on Aquaculture Sustainability. Available online: <https://thefishsite.com/articles/why-insect-production-may-have-minimal-impact-on-aquaculture-sustainability> (accessed on 23 July 2024).
69. Kolobe, S.D.; Manyelo, T.G.; Malematja, E.; Sebola, N.A.; Mabelebele, M. Fats and Major Fatty Acids Present in Edible Insects Utilised as Food and Livestock Feed. *Vet. Anim. Sci.* **2023**, *22*, 100312. [CrossRef]

70. Maiolo, S.; Parisi, G.; Biondi, N.; Lunelli, F.; Tibaldi, E.; Pastres, R. Fishmeal Partial Substitution within Aquafeed Formulations: Life Cycle Assessment of Four Alternative Protein Sources. *Int. J. Life Cycle Assess.* **2020**, *25*, 1455–1471. [[CrossRef](#)]
71. Smetana, S.; Schmitt, E.; Mathys, A. Sustainable Use of *Hermetia Illucens* Insect Biomass for Feed and Food: Attributional and Consequential Life Cycle Assessment. *Resour. Conserv. Recycl.* **2019**, *144*, 285–296. [[CrossRef](#)]
72. Kleyn, E. The Environmental Impact of Fishmeal and *Hermetia Illucens* (Black Soldier Fly) Larvae Meal in Aquaculture Feed, Utilising Life Cycle Assessment under South African Conditions. Master's Thesis, Stellenbosch University, Stellenbosch, South Africa, 2023.
73. Bosch, G.; Van Zanten, H.; Zamprogna, A.; Veenenbos, M.; Meijer, N.; Van der Fels-Klerx, H.; Van Loon, J. Conversion of Organic Resources by Black Soldier Fly Larvae: Legislation, Efficiency and Environmental Impact. *J. Clean. Prod.* **2019**, *222*, 355–363. [[CrossRef](#)]
74. Mulumpwa, M. The Potential of Insect Meal in Improving Food Security in Malawi: An Alternative of Soybean and Fishmeal in Livestock Feed. *J. Insects Food Feed* **2018**, *4*, 301–312. [[CrossRef](#)]
75. Nakimbugwe, D.; Ssepuuya, G.; Male, D.; Lutwama, V.; Mukisa, I.M.; Fiaboe, K.K.M. Status of the Regulatory Environment for Utilization of Insects as Food and Feed in Sub-Saharan Africa: A Review. *Crit. Rev. Food Sci. Nutr.* **2021**, *61*, 1269–1278. [[CrossRef](#)] [[PubMed](#)]
76. Alfiko, Y.; Xie, D.; Astuti, R.T.; Wong, J.; Wang, L. Insects as a Feed Ingredient for Fish Culture: Status and Trends. *Aquac. Fish.* **2021**, *7*, 166–178. [[CrossRef](#)]
77. Chia, S.Y.; Tanga, C.M.; van Loon, J.J.; Dicke, M. Insects for Sustainable Animal Feed: Inclusive Business Models Involving Smallholder Farmers. *Curr. Opin. Environ. Sustain.* **2019**, *41*, 23–30. [[CrossRef](#)]
78. Tran, H.Q.; Van Doan, H.; Stejskal, V. Environmental consequences of using insect meal as an ingredient in aquafeeds: A systematic view. *Rev. Aquac.* **2021**, *14*, 237–251. [[CrossRef](#)]
79. Adeoye, A.A.; Akegbejo-Samsons, Y.; Fawole, F.J.; Davies, S.J. Preliminary Assessment of Black Soldier Fly (*Hermetia illucens*) Larval Meal in the Diet of African Catfish (*Clarias gariepinus*): Impact on Growth, Body Index, and Hematological Parameters. *J. World Aquac. Soc.* **2020**, *51*, 1024–1033. [[CrossRef](#)]
80. Payne, C.L.R.; Scarborough, P.; Rayner, M.; Nonaka, K. Are Edible Insects More or Less 'healthy' than Commonly Consumed Meats? A Comparison Using Two Nutrient Profiling Models Developed to Combat over- and Undernutrition. *Eur. J. Clin. Nutr.* **2016**, *70*, 285–291. [[CrossRef](#)]
81. Mlček, J.; Rop, O.; Borkovcova, M.; Bednářová, M. A Comprehensive Look at the Possibilities of Edible Insects as Food in Europe—a Review. *Pol. J. Food Nutr. Sci.* **2014**, *64*, 147–157. [[CrossRef](#)]
82. Govorushko, S. Global Status of Insects as Food and Feed Source: A Review. *Trends Food Sci. Technol.* **2019**, *91*, 436–445. [[CrossRef](#)]
83. Tanga, C.M.; Waweru, J.W.; Tola, Y.H.; Onyoni, A.A.; Khamis, F.M.; Ekesi, S.; Paredes, J.C. Organic Waste Substrates Induce Important Shifts in Gut Microbiota of Black Soldier Fly (*Hermetia illucens* L.): Coexistence of Conserved, Variable, and Potential Pathogenic Microbes. *Front. Microbiol.* **2021**, *12*, 635881. [[CrossRef](#)]
84. Niassy, S.; Ekesi, S.; Hendriks, S.L.; Haller-Barker, A. Legislation for the Use of Insects as Food and Feed in the South African Context. In *Edible Insects in Sustainable Food Systems*; Springer: Cham, Switzerland, 2018; pp. 457–470.
85. Dineshbabu, G.; Goswami, G.; Kumar, R.; Sinha, A.; Das, D. Microalgae—Nutritious, Sustainable Aqua- and Animal Feed Source. *J. Funct. Foods* **2019**, *62*, 103545. [[CrossRef](#)]
86. Ampofo, J.; Abbey, L. Microalgae: Bioactive Composition, Health Benefits, Safety and Prospects as Potential High-Value Ingredients for the Functional Food Industry. *Foods* **2022**, *11*, 1744. [[CrossRef](#)] [[PubMed](#)]
87. Torres-Tiji, Y.; Fields, F.J.; Mayfield, S.P. Microalgae as a future food source. *Biotechnol. Adv.* **2020**, *41*, 107536. [[CrossRef](#)] [[PubMed](#)]
88. Nagappan, S.; Das, P.; AbdulQuadir, M.; Thaher, M.; Khan, S.; Mahata, C.; Al-Jabri, H.; Vatland, A.K.; Kumar, G. Potential of Microalgae as a Sustainable Feed Ingredient for Aquaculture. *J. Biotechnol.* **2021**, *341*, 1–20. [[CrossRef](#)] [[PubMed](#)]
89. Charisiadou, S.; Halling, C.; Jiddawi, N.; von Schreeb, K.; Gullström, M.; Larsson, T.; Nordlund, L.M. Coastal aquaculture in Zanzibar, Tanzania. *Aquaculture* **2021**, *546*, 737331. [[CrossRef](#)]
90. Ahmad, A.; Hassan, S.W.; Banat, F. An Overview of Microalgae Biomass as a Sustainable Aquaculture Feed Ingredient: Food Security and Circular Economy. *Bioengineered* **2022**, *13*, 9521–9547. [[CrossRef](#)]
91. Thiao, D.; Bunting, S.W. *Socio-Economic and Biological Impacts of the Fish-Based Feed Industry for Sub-Saharan Africa*; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 2022. [[CrossRef](#)]
92. Amosu, A.O.; Robertson-Andersson, D.V.; Maneveldt, G.W.; Anderson, R.J.; Bolton, J.J. African Journal of Agricultural Research Review South African Seaweed Aquaculture: A Sustainable Development Example for Other African Coastal Countries. *Afr. J. Agric. Res.* **2013**, *8*, 5268–5279.
93. Duque-Acevedo, M.; Belmonte-Ureña, L.J.; Cortés-García, F.J.; Camacho-Ferre, F. Agricultural Waste: Review of the Evolution, Approaches and Perspectives on Alternative Uses. *Glob. Ecol. Conserv.* **2020**, *22*, 00902. [[CrossRef](#)]
94. United Nations. *The Sustainable Development Goals Report 2019*; United Nations Publications: New York, NY, USA, 2019.
95. Molina-Moreno, V.; Leyva-Díaz, J.; Llorens-Montes, F.; Cortés-García, F. Design of Indicators of Circular Economy as Instruments for the Evaluation of Sustainability and Efficiency in Wastewater from Pig Farming Industry. *Water* **2017**, *9*, 653. [[CrossRef](#)]
96. Molina-Sánchez, E.; Leyva-Díaz, J.; Cortés-García, F.; Molina-Moreno, V. Proposal of Sustainability Indicators for the Waste Management from the Paper Industry within the Circular Economy Model. *Water* **2018**, *10*, 1014. [[CrossRef](#)]

97. Dietz, T.; Börner, J.; Förster, J.J.; Von Braun, J. Governance of the Bioeconomy: A Global Comparative Study of National Bioeconomy Strategies. *Sustainability* **2018**, *10*, 3190. [\[CrossRef\]](#)
98. Valenti, W.C.; Barros, H.P.; Moraes-Valenti, P.; Bueno, G.W.; Cavalli, R.O. Aquaculture in Brazil: Past, Present and Future. *Aquac. Rep.* **2021**, *19*, 100611. [\[CrossRef\]](#)
99. Blomsma, F.; Brennan, G. The Emergence of Circular Economy: A New Framing Around Prolonging Resource Productivity. *J. Ind. Ecol.* **2017**, *21*, 603–614. [\[CrossRef\]](#)
100. Raul, C.; Pattanaik, S.S.; Prakash, S.; Sreedharan, K.; Bharti, S. Greenhouse Gas Emissions from Aquaculture Systems. *World Aquac.* **2020**, *57*, 57–61.
101. Yang, Z.; Zhu, D.; Zhu, Q.; Hu, L.; Wan, C.; Zhao, N.; Liu, H.; Chen, X. Development of New Fish-Based Indices of Biotic Integrity for Estimating the Effects of Cascade Reservoirs on Fish Assemblages in the Upper Yangtze River, China. *Ecol. Indic.* **2020**, *119*, 106860. [\[CrossRef\]](#)
102. Tugiyono, T.; Febryano, I.G.; Yuwana, P.; Suharso, S. Utilization of Fish Waste as Fish Feed Material as an Alternative Effort to Reduce and Use Waste. *Pak. J. Biol. Sci.* **2020**, *23*, 701–707. [\[CrossRef\]](#)
103. Caruso, G.; Floris, R.; Serangeli, C.; Paola, L. Fishery Wastes as a Yet Undiscovered Treasure from the Sea: Biomolecules Sources, Extraction Methods and Valorization. *Mar. Drugs* **2020**, *18*, 622. [\[CrossRef\]](#)
104. Ryder, J.; Balaban, M.O. *Second International Congress on Seafood Technology on Sustainable, Innovative and Healthy Seafood*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2011.
105. Fadeeva, Z.; Van Berkel, R. Towards Circular Economy of Food Systems: An Explorative Appraisal of Opportunities in Fish, Seafood Value Chains. In *Sustainable Food Value Chain Development: Perspectives from Developing and Emerging Economies*; Springer: London, UK, 2023; pp. 61–86.
106. Afreen, M.; Ucak, I. Fish Processing Wastes Used as Feed Ingredient for Animal Feed and Aquaculture Feed. *J. Surv. Fish. Sci.* **2020**, *6*, 55–64. [\[CrossRef\]](#)
107. Coppola, D.; Lauritano, C.; Palma Esposito, F.; Riccio, G.; Rizzo, C.; Pascale, D. Fish Waste: From Problem to Valuable Resource. *Mar. Drugs* **2021**, *19*, 116. [\[CrossRef\]](#)
108. Iskakov, R.; Sugirbay, A. Technologies for the Rational Use of Animal Waste: A Review. *Sustainability* **2023**, *15*, 2278. [\[CrossRef\]](#)
109. Kebe, N.N.; Rieker, C.; Fall, P.A.; Diouf, D.; Ndiaye, D.; Mockenhaupt, T.; Beuel, P.; Bursche, J. Anaerobic Co-Digestion of Fish Processing Waste with Cow Manure and Waste of Market (Rests of Fruits and Vegetables): A Lab Scale Batch Test. *J. Sustain. Bioenergy Syst.* **2021**, *11*, 45–59. [\[CrossRef\]](#)
110. Munguti, J.M.; Musa, S.; Orina, P.S.; Kyule, D.N.; Opiyo, M.A.; Charo-Karisa, H.; Ogello, E.O. An Overview of Current Status of Kenyan Fish Feed Industry and Feed Management Practices, Challenges and Opportunities. *Int. J. Fish. Aquat. Stud.* **2014**, *1*, 128–137.
111. Gule, T.T.; Geremew, A. Dietary Strategies for Better Utilization of Aquafeeds in Tilapia Farming. *Aquac. Nutr.* **2022**, *2022*, 1–11. [\[CrossRef\]](#)
112. Dauda, A.K.; Ajadi, A.; Tola-Fabunmi, A.S.; Akinwale, A.O. Waste Production in Aquaculture: Sources, Components, and Management in Different Culture Systems. *Aquac. Fish.* **2019**, *4*, 81–88. [\[CrossRef\]](#)
113. Gabriel, U.U.; Akinrotimi, O.A.; Bekibele, D.O.; Onunkwo, D.N.; Anyanwu, P.E. Locally Produced Fish Feed: Potentials for Aquaculture Development in Sub-Saharan Africa. *Afr. J. Agric. Res.* **2007**, *2*, 287–295.
114. Tumwesigye, Z.; Tumwesigye, W.; Opio, F.; Kemigabo, C.; Mujuni, B. The Effect of Water Quality on Aquaculture Productivity in Ibanda District, Uganda. *Aquac. J.* **2022**, *2*, 23–36. [\[CrossRef\]](#)
115. Idenyi, J.N.; Eya, J.C.; Nwankwegu, A.S.; Nwoba, E.G. Aquaculture Sustainability through Alternative Dietary Ingredients: Microalgal Value-Added Products. *Eng. Microbiol.* **2022**, *2*, 100049. [\[CrossRef\]](#)
116. Hlavac, D.; Adámek, Z.; Hartman, P.; Másílko, J. Effects of Supplementary Feeding in Carp Ponds on Discharge Water Quality: A Review. *Aquac. Int.* **2013**, *22*, 299–320. [\[CrossRef\]](#)
117. Bogevik, A.S.; Samuelsen, T.A.; Aspevik, T.; Romarheim, O.H.; Aas, T.S.; Kalanathan, T.; Rønnestad, I. Disintegration Stability of Extruded Fish Feed Affects Gastric Functions in Atlantic Salmon (*Salmo salar*). *Aquaculture* **2021**, *543*, 737006. [\[CrossRef\]](#)
118. Njiru, J.M.; Aura, C.M.; Okechi, J.K. Cage fish culture in Lake Victoria: A boon or a disaster in waiting? *Fish. Manag. Ecol.* **2018**, *26*, 426–434. [\[CrossRef\]](#)
119. Mwema, C.M.; Mudege, N.; Lundeba, M.; Nankwenya, B.; Kakwasha, K.; Phiri, M.; Komugisha, B.; Siamudaala, V. *A Review of Aquafeed Business Models and the Feed Value Chain in Zambia and Malawi*; WorldFish: Penang, Malaysia, 2021.
120. Suryaningrum, L.; Jusadi, D.; Setiawati, M.; Sunarno, M. Nutrient Composition and Apparent Digestibility Coefficient of Ulva Lactuca Meal in the Nile Tilapia (*Oreochromis niloticus*). *J. Aquac. Res. Dev.* **2017**, *10*, 77–86.
121. Pomar, C.; Andretta, I.; Remus, A. Feeding Strategies to Reduce Nutrient Losses and Improve the Sustainability of Growing Pigs. *Front. Vet. Sci.* **2021**, *8*, 742220. [\[CrossRef\]](#)
122. Gao, N.; Zhu, L.; Guo, Z.; Yi, M.; Zhang, L. Effects of chronic ammonia exposure on ammonia metabolism and excretion in marine medaka *Oryzias melastigma*. *Fish Shellfish Immunol.* **2017**, *65*, 226–234. [\[CrossRef\]](#)
123. Dalsgaard, J.; Ekmann, K.S.; Jensen, M.D.; Pedersen, P.B. Reducing Phosphorus Emissions from Net Cage Fish Farming by Diet Manipulation. *J. Environ. Manag.* **2023**, *334*, 117445. [\[CrossRef\]](#)
124. Furuya, W.M.; da Cruz, T.P.; Gatlin III, D.M. Amino Acid Requirements for Nile Tilapia: An Update. *Animals* **2023**, *13*, 900. [\[CrossRef\]](#)

125. Maulu, S.; Hasimuna, O.J.; Haambiya, L.H.; Monde, C.; Musuka, C.G.; Makorwa, T.H.; Nsekanabo, J.D. Climate Change Effects on Aquaculture Production: Sustainability Implications, Mitigation, and Adaptations. *Front. Sustain. Food Syst.* **2021**, *5*, 609097. [[CrossRef](#)]
126. Boyd, C.E.; McNevin, A.A.; Davis, R.P. The Contribution of Fisheries and Aquaculture to the Global Protein Supply. *Food Secur.* **2022**, *14*, 805–827. [[CrossRef](#)]
127. Pennino, M.G.; Coll, M.; Albo-Puigserver, M.; Fernandez-Corredor, E.; Steenbeek, J.; Giraldez, A.; Gonzalez, M.; Esteban, A.; Belindo, J.M. Current and Future Influence of Environmental Factors on Small Pelagic Fish Distributions in the Northwestern Mediterranean Sea. *Front. Mar. Sci.* **2020**, *7*. [[CrossRef](#)]
128. Yu, B.M.; Wing, Y.M.; Feng, Z.; Ming, H.W. Health Risk Assessments Based on Polycyclic Aromatic Hydrocarbons in Freshwater Fish Cultured Using Food Waste-Based Diets. *Environ. Pollut.* **2020**, *256*, 113380. [[CrossRef](#)]
129. Chan, C.Y.; Tran, N.; Pethiyagoda, S.; Crissman, C.C.; Sulser, T.B.; Phillips, M.J. Prospects and Challenges of Fish for Food Security in Africa. *Glob. Food Secur.* **2019**, *20*, 17–25. [[CrossRef](#)]
130. Oyebola, O.O.; Olatunde, O.M. Climate Change Adaptation through Aquaculture: Ecological Considerations and Regulatory Requirements for Tropical Africa. In *Agriculture and Ecosystem Resilience in Sub Saharan Africa: Livelihood Pathways Under Changing Climate*; Springer: Cham, Switzerland, 2019; pp. 435–472, ISBN 978-3-030-12974-3.
131. Azam-Ali, S.; Ahmadzai, H.; Choudhury, D.; Goh, E.; Jahanshiri, E.; Mabhaudhi, T.; Olutayo, A. Marginal Areas and Indigenous People: Priorities for Research and Action. In *Science and Innovations for Food Systems Transformation*; Springer: Cham, Switzerland, 2021; pp. 261–279.
132. Asiedu, G.A.; Oduro-Yeboah, C.; Akonor, P.; Saka, E.; Arthur, W.; Boateng, C.; Padi, A. *Training for Small-Scale Fish Processors*; CSIR-Food Research Institute: Accra, Ghana, 2020.
133. Adam, R.; Njogu, L. A Review of Gender Inequality and Women’s Empowerment in Aquaculture Using the Reach-Benefit-Empower-Transform Framework Approach: A Case Study of Nigeria. *Front. Aquac.* **2023**, *1*, 1052097. [[CrossRef](#)]
134. Munguti, J.M.; Nairuti, R.; Iteba, J.O.; Obiero, K.O.; Kyule, D.; Opiyo, M.A.; Abwao, J.; Kirimi, J.G.; Outa, N.; Muthoka, M.; et al. Nile Tilapia (*Oreochromis niloticus* Linnaeus, 1758) Culture in Kenya: Emerging Production Technologies and Socio-Economic Impacts on Local Livelihoods. *Aquac. Fish Fish.* **2022**, *2*, 265–276. [[CrossRef](#)]
135. Crona, B.I.; Wassénus, E.; Jonell, M. Four Ways Blue Foods Can Help Achieve Food System Ambitions across Nations. *Nature* **2023**, *616*, 104–112. [[CrossRef](#)]
136. Abro, Z.; Macharia, I.; Mulungu, K.; Subramanian, S.; Tanga, C.M.; Kassie, M. The Potential Economic Benefits of Insect-Based Feed in Uganda. *Front. Insect Sci.* **2022**, *2*, 968042.
137. Chisoro, P.; Jaja, I.F.; Assan, N. Incorporation of Local Novel Feed Resources in Livestock Feed for Sustainable Food Security and Circular Economy in Africa. *Front. Sustain.* **2023**, *4*, 1251179. [[CrossRef](#)]
138. Ahern, M.B.; Thilsted, S.H.; Kjelleovold, M.; Overå, R.; Toppe, J.; Doura, M.; Kalaluka, E.; Wismen, B.; Vargas, M.; Franz, N. Locally-Procured Fish Is Essential in School Feeding Programmes in Sub-Saharan Africa. *Foods* **2021**, *10*, 2080. [[CrossRef](#)]
139. Khan, A.; Ahmed, S.M.; Sarr, C.; Kabore, Y.; Kahasha, G.; Bangwe, L.; Odhiambo, W.; Gahunga, N.; Mclean, B.; Diop, H. Nourishing Nations during Pandemics: Why Prioritize Fish Diets and Aquatic Foods in Africa. *Marit. Stud.* **2021**, *20*, 487–500. [[CrossRef](#)]
140. Feleke, S.; Cole, S.M.; Sekabira, H.; Djouaka, R.; Manyong, V. Circular Bioeconomy Research for Development in Sub-Saharan Africa: Innovations, Gaps, and Actions. *Sustainability* **2021**, *13*, 1926. [[CrossRef](#)]
141. Maiolo, S.; Cristiano, S.; Gonella, F.; Pastres, R. Ecological Sustainability of Aquafeed: An Emergy Assessment of Novel or Underexploited Ingredients. *J. Clean. Prod.* **2021**, *294*, 126266. [[CrossRef](#)]
142. Mmanda, F.P.; Mulokozi, D.P.; Lindberg, J.E.; Norman Haldén, A.; Mtolera, M.; Kitula, R.; Lundh, T. Fish Farming in Tanzania: The Availability and Nutritive Value of Local Feed Ingredients. *J. Appl. Aquac.* **2020**, *32*, 341–360. [[CrossRef](#)]
143. Asche, F.; Eggert, H.; Oglend, A.; Roheim, C.A.; Smith, M.D. Aquaculture: Externalities and Policy Options. *Rev. Environ. Econ. Policy* **2022**, *16*, 282–305. [[CrossRef](#)]
144. Cowx, I.G.; Ogutu-Owhayo, R. Towards Sustainable Fisheries and Aquaculture Management in the African Great Lakes. *Fish. Manag. Ecol.* **2019**, *26*, 397–405. [[CrossRef](#)]
145. Okeke-Ogbuafor, N.; Stead, S.; Gray, T. Is Inland Aquaculture the Panacea for Sierra Leone’s Decline in Marine Fish Stocks? *Mar. Policy* **2021**, *132*, 104663. [[CrossRef](#)]
146. Muthoka, M.; Ouko, K.O.; Mboya, J.B.; Ndambuki, M.N.; Outa, N.; Ogello, E.; Obiero, K.; Ogola, R.J.; Midamba, D.C.; Njogu, L. Socio-economic Impacts of Climate Change and Adaptation Actions among Smallholder Fish Farmers in Sub-Saharan Africa. *Aquac. Fish Fish.* **2024**, *4*, e182. [[CrossRef](#)]
147. Munguti, J.; Kirimi, J.; Obiero, K.; Ogello, E.; Kyule, D.; Liti, D.; Musalia, L. Aqua-Feed Wastes: Impact on Natural Systems and Practical Mitigations—A Review. *J. Agric. Sci.* **2020**, *13*, 111. [[CrossRef](#)]
148. Ngarava, S.; Zhou, L.; Slayi, M.; Ningi, T.; Nguma, A.; Ncetani, N. Aquaculture Production in the Midst of GHG Emissions in South Africa. *Water* **2023**, *15*, 1253. [[CrossRef](#)]
149. Obiero, K.; Meulenbroek, P.; Drexler, S.; Dagne, A.; Akoll, P.; Odong, R.; Kaunda-Arara, B. The Contribution of Fish to Food and Nutrition Security in Eastern Africa: Emerging Trends and Future Outlooks. *Sustainability* **2019**, *11*, 1636. [[CrossRef](#)]
150. Dube, S.; Mabika, N. Factors Affecting the Adoption of Modern Fish Farming Technologies in Gokwe South District, Zimbabwe. *Int. J.* **2023**, *9*, 11. [[CrossRef](#)]

151. Adegbeye, M.J.; Elghandour, M.M.; Monroy, J.C.; Abegunde, T.O.; Salem, A.Z.; Barbabosa-Pliego, A.; Faniyi, T.O. Potential Influence of Yucca Extract as Feed Additive on Greenhouse Gases Emission for a Cleaner Livestock and Aquaculture Farming-A Review. *J. Clean. Prod.* **2019**, *239*, 118074. [CrossRef]
152. Daw, T.; Adger, W.N.; Brown, K.; Badjeck, M.C. Climate Change and Capture Fisheries: Potential Impacts, Adaptation and Mitigation. Available online: <https://digitalarchive.worldfishcenter.org/server/api/core/bitstreams/f6ed6527-08c1-4fd8-82d3-fb3c2668f6fb/content> (accessed on 17 July 2024).
153. Badjeck, M.C.; Allison, E.H.; Halls, A.S.; Dulvy, N.K. Impacts of Climate Variability and Change on Fishery-Based Livelihoods. *Mar. Policy* **2010**, *34*, 375–383. [CrossRef]
154. Global Seafood Alliance. What Is the Impact of Aquaculture on the Environment? Available online: <https://www.globalseafood.org/blog/what-is-the-environmental-impact-of-aquaculture/> (accessed on 23 July 2024).
155. Bohnes, F.A.; Laurent, A. LCA of Aquaculture Systems: Methodological Issues and Potential Improvements. *Int. J. Life Cycle Assess.* **2019**, *24*, 324–337. [CrossRef]
156. OECD/FAO. *OECD-FAO Agricultural Outlook 2019–2028*; OECD Publishing: Paris, France, 2019. [CrossRef]
157. Adeleke, B.; Robertson-Andersson, D.; Moodley, G.; Taylor, S. Aquaculture in Africa: A Comparative Review of Egypt, Nigeria, and Uganda Vis-À-Vis South Africa. *Rev. Fish. Sci. Aquac.* **2020**, *29*, 167–197. [CrossRef]
158. Kinyuru, J.N.; Nyangena, D.; Kamau, E.; Ndiritu, A.; Muniu, J.; Kipkoeh, C.; Weru, J.; Ndung'u, N.; Mmari, M. *The Role of Edible Insects in Diets and Nutrition in East Africa*; Springer: Cham, Switzerland, 2018; pp. 93–108.
159. Gorecki, J.; Núñez-Cacho, P.; Corpas-Iglesias, F.A.; Molina, V. How to Convince Players in Construction Market? Strategies for Effective Implementation of Circular Economy in Construction Sector. *Cogent Eng.* **2019**, *6*, 1690760. [CrossRef]
160. Kusumowardani, N.; Tjahjono, B. Circular Economy Adoption in the Aquafeed Manufacturing Industry. *Procedia CIRP* **2020**, *90*, 43–48. [CrossRef]
161. United Nations. Responsible Consumption & Production: Why It Matters. Available online: https://www.un.org/sustainabledevelopment/wp-content/uploads/2019/07/12_Why-It-Matters-2020.pdf (accessed on 23 July 2024).
162. Bedekar, P.A.; Bhalkar, B.N.; Patil, S.M.; Govindwar, S.P. Moringa Oleifera-Mediated Coagulation of Textile Wastewater and Its Biodegradation Using Novel Consortium-BBA Grown on Agricultural Waste Substratum. *Environ. Sci. Pollut. Res.* **2016**, *23*, 20963–20976. [CrossRef]
163. Strazza, C.; Magrassi, F.; Gallo, M.; Del Borghi, A. Life Cycle Assessment from Food to Food: A Case Study of Circular Economy from Cruise Ships to Aquaculture. *Sustain. Prod. Consum.* **2015**, *2*, 40–51. [CrossRef]
164. Monteiro, M.; Matos, E.; Ramos, R.; Campos, I.; Valente, L. A Blend of Land Animal Fats Can Replace up to 75% Fish Oil without Affecting Growth and Nutrient Utilization of European Seabass. *Aquaculture* **2018**, *487*, 22–31. [CrossRef]
165. Checa, D.; Macey, B.M.; Bolton, J.J.; Brink-Hull, M.; O'Donohoe, P.; Cardozo, A.; Poersch, L.H.; Sánchez, I. Circularity Assessment in Aquaculture: The Case of Integrated Multi-Trophic Aquaculture (IMTA) Systems. *Fishes* **2024**, *9*, 165. [CrossRef]

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