Chapter 4
Waste to Feed: An Emerging Technology to Improve Aquaculture in Africa

Kenneth Prudence Abasubong, Ndakalimwe Naftal Gabriel, Jean-Jacques Yao Adjoumani, and Aniefiokmkpong Okokon Okon

Abstract As a result of globalization, the quantity and generation rate of solid waste in Africa have increased tremendously. This calls for the need to salvage the situation before it gets out of hand. Most African countries dump waste in landfills where there is overflow and burnt, causing severe health and safety concerns. Therefore, instead of taking this waste to landfills, it is significant to reuse it to culture animal feed. From waste to feed might be an alternative feed ingredient to boost the African aquaculture industry. On the other hand, it enables sustainable aquaculture production with less reliance on fish meals. As a result, the aquaculture industry must ramp up its quest for alternative components made from renewable natural resources. Microbial and insect protein have been considered long-term components, owing to their ability to convert non-food lignocellulosic biomass into significant protein resources. This chapter outlined the importance of microbial and insect meals to aquatic animals and the steps involved in turning wastes into proteins. Furthermore, we discuss their nutritional capacity, growth promoters, and the immunoregulatory functions of these resources in aquaculture. However, several advancements in aquaculture nutrition and considerations for the future development of sustainable and safe aquaculture production are also discussed.

Keywords Aquaculture industry · Aquatic products · Fish meal replacement · Waste · Microbial resources · Insect

K. P. Abasubong (✉) · J.-J. Y. Adjoumani
Key Laboratory of Aquatic Nutrition and Feed Science of Jiangsu Province, College of Animal Science and Technology, Nanjing Agricultural University, Nanjing, China

N. N. Gabriel
Department of Fisheries and Ocean Sciences, Faculty of Agriculture, Engineering, and Natural Science, Sam Nujoma Campus, University of Namibia, Henties Bay, Namibia

A. O. Okon
Department of Animal and Environmental Biology, University of Uyo, Uyo, Akwa Ibom State, Nigeria

N. N. Gabriel et al. (eds.), *Emerging Sustainable Aquaculture Innovations in Africa*, Sustainable Agriculture and Food Security,
https://doi.org/10.1007/978-981-19-7451-9_4

4.1 Introduction

Aquaculture is the only way to meet the growing need for animal protein as wild fish and crustaceans become scarce (Daniel 2018; Stankus 2021). Therefore, it is significant to expand aquaculture to improve food security. However, aquaculture relies heavily on a steady source of fish meal (FM), a vital ingredient in commercial fish feeds. Aquaculture has put growing pressure on wild fish to support farmed fish, causing wild fish supplies to fall rapidly (Stankus 2021). The rising costs of aquafeeds, such as meat meals, and FM, representing 60–70% of the total production expenses, impede further aquaculture development. To alleviate this pressure, an alternative protein source that is low cost and ecologically friendly could provide additional nutritional positive health effects without affecting fish growth and health. However, plant-based protein sources have been suggested as possible FM substitutes. However, their major setbacks, such as detrimental consequences on microbial community and intestine structure, high anti-nutrient content, low digestibility, and lower feed intake, have made their utilization unacceptable in fish diets (Table 4.1) (Farhangi and Carter 2015; Øverland et al. 2009; Francis et al. 2001). Although animal protein by-products, such as fish blood meal (El-Haroun et al. 2012), processing wastes (Hardy et al. 2007), meat, bone, and feather meal (Bureau et al. 2000), have some unique features over plant-based alternatives, including better digestibility and the non-availability of anti-nutrient elements, they seem to be expensive and have limited availability (Karimi et al. 2018). However, using human food as an ingredient for fish could pose some challenges that could affect the standard of living.

In 2015, fish and other aquatic items comprised roughly 26% of animal protein consumption in the least developed countries (LDCs), compared to 11% in developed countries (FAO 2018). So, by 2050, when the world's population reaches nine billion people, Africa, Latin America, and Asia will need to boost food production by 300%, 80%, and 70%, respectively, to feed the estimated populations of two billion, 810 million, and 5.4 billion people in their respective regions (Anon 1997). So, fish consumption and demand for a cheap protein source are rising due to the rapid growth of the human population and increasing standard of living. Rapid urbanization, rising economic activity, and population increase in Africa have produced unprecedented levels of waste. Since the waste pollution from these sites has reached an emergency level across Africa, this has consequently expanded hazardous waste material sites. Waste generation in Africa is predicted to quadruple by 2050, rising from 174 million tonnes annually in 2016 to roughly 516 million tonnes annually (UNEP (2018). However, Africa's average rate of rubbish collection is just about 55% of the total amount of waste. Notably, more than 90% of waste in Africa is disposed of in unregulated dumps and landfills, frequently with open burning in the aftermath. Most significantly, 19 of the 50 largest dumpsites in the world are in Africa, particularly in Sub-Saharan Africa. According to composition, roughly 13% of the municipal solid trash produced in Africa is plastic, while 57% is organic waste (OECD 2016). Currently, landfills are where most of the organic

Table 4.1 The advantages and disadvantages of an alternative fish diet

Alternative feed	Advantages	Disadvantages	References
Soybean meal	• EAA profile is favourable, and the protein level is high • Possibility of making soy protein concentration (low in anti-nutritional factors, soluble carbohydrates)	• Contains saponins, phytic acid • Some processing techniques (solvent extraction) leave anti-nutrient molecules in the food	Bandara (2018)
Wheat gluten meals	• On a dry matter basis, it comprises 85% protein • Most fish species, such as Atlantic salmon, Coho salmon, and Rainbow trout, have a higher digestibility • Fish distal intestine tissues show no morphological alterations	• Deficiency in lysine, methionine, and arginine	Bandara (2018)
Sunflower meal	• Dehulling and other preprocessing processes remove a greater amount of fibre	• Higher content of fibre • Higher in protease inhibitors, arginase inhibitors, and phytic acids	Bandara (2018)
Canola/ Rapeseed	• Ability to produce canola protein concentrate by aqueous extraction of fibre (higher protein content) • Good source of linolenic acid and low levels of linoleic acid in rapeseed oil	• It contains a higher amount of fibre and glucosinolates • Higher content of phytic acids and glucosinolates	Bandara (2018)
Pulses	• Possibility of producing protein concentrates to boost protein intake	• Higher carbohydrate content than protein • Higher content of phytic acid and tannins	Bandara (2018)
Lupins	• Arginine and glutamic acid levels are high, but anti-nutritional factors are low	• Deficiency in methionine and lysine • Presence of alkaloids	Bandara (2018)
Rice protein concentrate	• High protein and lipid content	• Deficiency in lysine	Abasubong et al. (2018)
Guar meal	• Guar meal can be used in place of soy meal without affecting the growth of some fish	• Anti-nutritional and anti-digestive chemicals, such as phytate, protease, residual gum, saponin, and inhibitor tannin, are present • Gastrointestinal evacuation takes time • Indigestible amino acids • Guar meal availability is influenced by oil output and guar gum utilization	Nidhina and Muthukumar (2015); Ullah et al. (2016)

(continued)

Table 4.1 (continued)

Alternative feed	Advantages	Disadvantages	References
Wheat	• Cheaper to obtained	• Starch content is higher (usually more than 70%) • A lysine deficit is seen • The protein content is low (11%)	Draganovic et al. (2013); Sørensen et al. (2011)
Blood meal (Cow blood)	• Higher protein content • Relatively rice in lysine content	• They are deficiency Methionine content • Heat sensitivity and drying conditions have a big impact on protein digestion	Aladetohun and Sogbesan (2013); Hussain et al. (2011)
Feather meal (Hydrolysed)	• They are rich in cystine (74–61%) and protein content	• Very hard to digest • Low in lysine and methionine • During processing with application heat typically deteriorates hemoglobin and causes low palatability	Grazziotin et al. (2008); Yu et al. (2020)
Poultry by-products	• Free from anti-nutrient	• Expensive feed ingredient in aqua diets • Low level of lysine, methionine, and histidine	Bandara (2018)

waste is disposed of. However, producing insect and microbial proteins for feed through organic waste could offer the enormous socioeconomic potential for African nations to continue aquaculture operations.

In this situation, making use of waste could serve as a protein source that could be used in animal feed. Insect and microbial proteins have attracted much attention as animal feed ingredients (Matassa et al. 2016). However, waste proteins are similar to FM in protein concentration and amino acid composition, which are widely consumed by fish and crustaceans. Many wastes protein is considered good because they do not impair the host's health but have some biological activities that help the host thrive. Therefore, this chapter assessed the understanding of microbial resources as a future feed ingredient for sustainable FM replacement. Thus, the utilization of various microbial resources in the aquafeed industry was thoroughly discussed. Therefore, having a rudimentary understanding of how waste nutrients are used in aquatic species culture can be beneficial.

4.2 Waste Production in Africa

A rapid increase in municipal solid waste (MSW) is anticipated in Africa due to population growth, urbanization, and shifting consumption habits. By 2040, the population of Africa is projected to reach approximately two billion people.

Approximately 40% of Africa's population currently resides in cities (as of 2014). In 2040, the number of people living in urban areas is projected to double to over 1 billion, growing at a rate of 3.5% annually, faster than on any other continent (UNEP 2018). In 2015, urban Africa produced 124 million tonnes of garbage annually. It is anticipated to reach 368 million tonnes by 2040 (UNEP 2018). In other words, by 2040, urban waste will have increased by about 200%. South Africa and North African nations produce significantly more daily waste per person (UNEP 2018). This is mainly caused by these countries' higher consumption and purchasing power levels. However, the amount of trash created and the patterns of consumption and production in Africa are starting to shift. More individuals adopt Western consumption habits as their affluence rises, which raises the quantity of waste produced. Africa now produces more waste than it did in the past due to rising global waste trade and illegal waste trafficking from high-income nations to the continent (UNEP 2018).

Due to the informal nature of recycling, there is a severe lack of factual data on recycling in Africa. Only a few formal recycling programmes are in operation, and the average recycling rate in Sub-Saharan Africa is only thought to be around 4% (UNEP 2018). Additionally, there are significant differences between country to country and region to region. There is excellent potential for zero-waste management, given the considerable proportion of African organic waste. Dumping rubbish is one of the most popular waste disposal techniques. The ecology and locals' health are harmed by open waste burning, which usually occurs in conjunction with dumping (Wael Fahmi and Sutton 2010). Waste disposal facilities are frequently dangerously overloaded and insufficient in many cities. However, many towns prioritize landfill site improvement and expansion over waste reduction, reuse, and recycling as part of an integrated waste management strategy. In fact, a 2014 evaluation of the two main dumpsites in Freetown, Sierra Leone, revealed that people who lived there or nearby were exposed to diseases and contamination of their air, soil, streams, and sea. Without sorting the waste first, it is burned, which causes significant air pollution and the release of poisons into the environment. The urgent need for a redesigned and integrated waste management system in Africa is demonstrated by the hazardous situations many landfills and dumps are in and the harm they inflict to the environment and public health.

Therefore, to prevent this waste from being dumped in landfills, which would increase climate change, increased circular systems that reuse feed nutrients can also lessen other adverse environmental effects of growing feed crops, such as those related to energy, water, and land use. Due to the rising cost of FM production and growing public awareness of FM's adverse environmental effects, it is imperative to develop sustainable alternatives to FM to satisfy the rising protein demands from the world's fastest-growing food-producing industry (Kim et al. 2019). Insect and microbial protein, which can be generated in vast quantities and possibly has a low carbon footprint, has proven to be a successful FM replacement for the latter (Jones et al. 2020; Matassa et al. 2016; Pikaar et al. 2017; Spalvins et al. 2018; Spalvins and Blumberga 2018). This is because low-value agricultural waste (such as waste from fruit, soy protein and rice concentrates, and dairy production) and

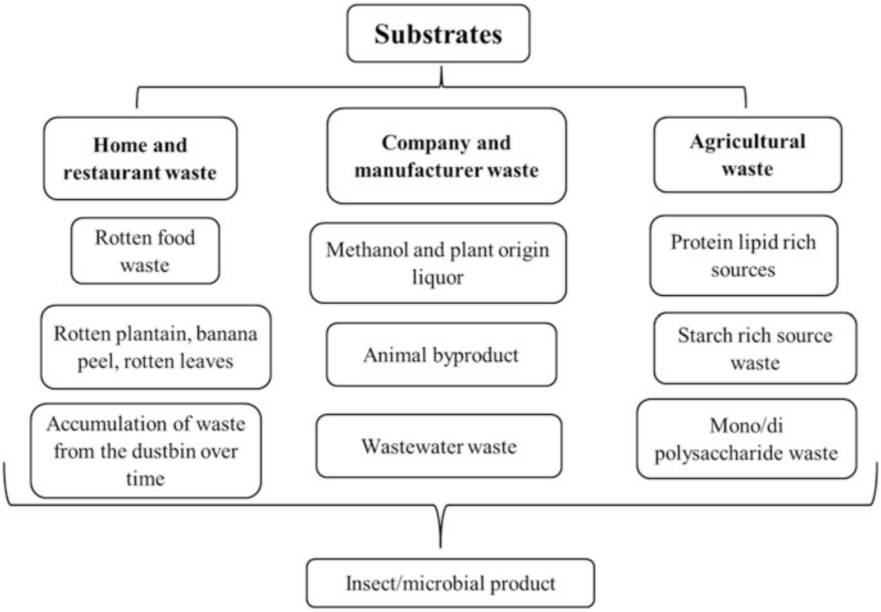

Fig. 4.1 Substrates are used for the culturing of insect and microbial species. (Adopted from Jannathulla et al. (2017))

industrial biomass residues (such as sulphite waste liquor, and lignin waste) can be inoculated and fermented to produce insect and microbial protein (Spalvins et al. 2018; Spalvins and Blumberga 2018) as shown in Fig. 4.1. It offers a strategy for developing a stable feed supply that regulates and turns waste from other industrial sectors into a valued commodity (Spalvins et al. 2018).

4.2.1 Waste to Microbial Resources

Microbial resources are the protein extracted from a single-cell protein or whole biomass from different single or mixed microbe cultures, such as algae, bacteria, fungi, and yeast from waste (home, restaurant, companies, etc.), that often have a crude protein (CP) content of about 40% by dry weight (Rajkumar et al. 2017; Matassa et al. 2016; García-Garibay et al. 2003). Compared to plant-based alternatives, the conversion of organics, nitrogen, and phosphorus to proteins is particularly effective (Matassa et al. 2016). Microbial resources are an excellent protein source and feed in aquaculture, and they help alleviate environmental issues caused by waste accumulation (Patil and Jadhav 2014). These substances are non-pathogenic to plants, humans, and animals, may be used for food and feed, have high nutritional value, are free of hazardous chemicals, and are inexpensive to produce. Overall, microbial components can potentially alleviate the strain on human food supplies. However, the production of microbial components is commercially under construction, and several start-up companies have been established, while current output quantities are unknown.

According to available data, Africa generated 125 million tonnes of MSW each year in 2012, with Sub-Saharan Africa accounting for 81 million tonnes (65%). This number is expected to increase to 244 million tonnes by 2025. With a waste collection rate of only 55% (68 million tonnes) (Scarlat et al. 2015), nearly half of all MSW generated in Africa is thrown on open fields, sidewalks, stormwater drains, and waterways. The issue is significantly worse in rural areas since formal waste collection services are frequently unavailable. This waste includes plastics, rotten food items, paper, wood, metal, etc. The waste from food and rotten greens accounted for roughly 44% (Scarlat et al. 2015). Therefore, biodegradable agro-industrial wastes and by-products should be considered sources of nutrients as potential substrates for microorganism cultivation to reduce environmental hazards and lower production costs.

The production of microbial resources is attained by submerged or solid-state fermentation to obtain microbial isolates and whole-cell biomass from various microorganisms, such as bacteria, fungus, and yeast. At the end of the process, the corresponding microorganisms' spores or cells are taken and subjected to multiple downstream operations, such as cell wall disruption washing, protein extraction, and purification (Rumsey et al. 2010). However, algae can be produced in indoor/outdoor, open/closed, axenic/non-axenic, and batch/continuous/semi-continuous methods. Although many factors influence the development of microbial resources, the substrates needed and the microorganisms used in this process must be standardized to achieve the best yield. For instance, fungus and yeast species thrive on lignocellulosic materials, including cellulose, hemicellulose, and lignin, primarily cultured in paper and wood waste, Corn cobs, maize, cotton stalk, plant, and animal wastes (Jannathulla et al. 2017). Carbon dioxide and sunlight are the essential parameters for culturing algal species, such as *Chlorella pyrenoidosa*, *Chlorella sorokiniana*, *Porphyrium sp*., etc. (Rumsey et al. 2010). However, specific fungi can be selected for this process according to dominant components present in the waste. By-products of industrial waste are mainly used for the cultivation of bacterial species.

4.3 Importance of Microbial Resources in Aquaculture

Microbial resources have been recommended as a viable ingredient in the worldwide feed business based on research on the compatibility of microbial resources in the diets of diverse aquatic species conducted over the last two decades (Pike et al. 1990; Bob Manuel and Alfred-Ockiya 2011). In aquaculture, microbial resources act as potential feed ingredients and serve as viable immunostimulants and probiotics, which improve growth, health, disease resistance, and immunity (Bharti et al. 2014). Microbial resources play a significant role in aquaculture by (1) changing the host-associated microbial ecology, (2) facilitating better feed utilization or increasing its nutritional value, such as biotin, fatty acids, and vitamin B12, which benefits an animal's health, (3) strengthening the host's disease resistance, and/or (4) improving the quality of its surrounding environment. On the other hand, this substance can be fed to the animal or added to the rising water, benefiting the host by boosting immunity and antioxidants capacities, improving health, growth performance, and feed utilization, as shown in Fig. 4.2. This is accomplished partly by enhancing the microbial balance of the host or the surrounding environment. According to Kolndadacha et al. (2011), one of the aquaculture's disease control options is using bacterial species as a probiotic, particularly gram-positive bacteria (Lactobacillus sp.), as an alternative to antibiotics. According to Fish Site (2019), using microbial products enhanced farmed animals' capability to absorb protein, resulting in a significant feed conversion ratio in aquaculture. Furthermore, according to Bharti et al. (2014), microbial resources play an essential role in ornamental fish farming by regulating the colour and size of the fish, primarily sourced from algae and bacteria rich in pigments, predominantly carotenoids.

The nutritional content of microbial resources is determined by the species, fermentation conditions, and post-harvest processing (Spalvins et al. 2018; Hansen et al. 2021; Lapea et al. 2020). Yeast has a CP level ranging from 38 to 60% DM, depending on yeast species and strains and the type of downstream processing employed after fermentation (Sharma et al. 2018). Yeast has a good amino acid composition than fish requirements; however, it is deficient in methionine and cysteine content (Agboola et al. 2020; Mahnken et al. 1980). Low lipid content is also associated with yeast, with unsaturated fatty acids predominating in the fatty acid composition (Halasz and Lasztity 1991), except for oleaginous yeast. The carbohydrate content of yeast contains a polysaccharide compound, with monosaccharides and oligosaccharides at a lower level. Fungi have a CP content of 55–63% and digestibility content of 87%. This was reported in monogastric animals. Their cell wall is rich with minerals and vitamin and comprises around one-third of the total biomass. Bacterial flour contains approximately 70% CP and 10% crude fat and is similar to a macronutrient composition of FM. The amino acid profile is comparable to that of the FM but with lower levels of lysine and methionine and higher levels of tryptophan. Microalgae can collect large amounts of n-3 PUFAs, accounting for 30–50% of their total fatty acid content and 50–65% of their CP biomass. Microalgae proteins have a similar amino acid content across species and

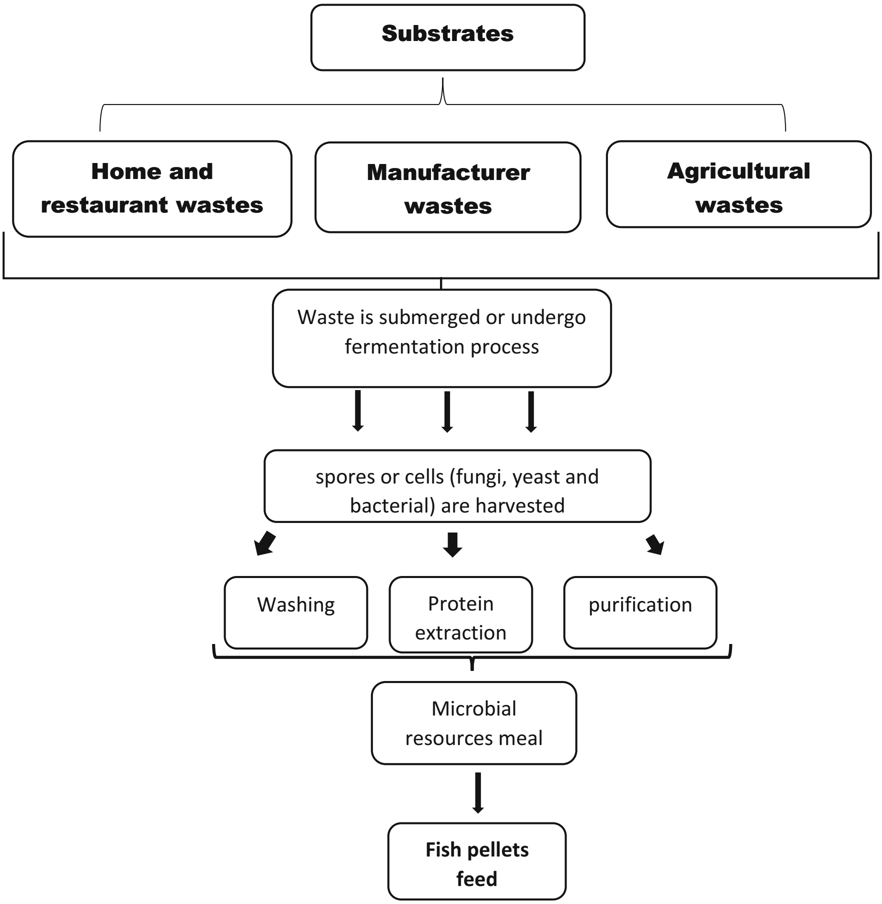

Fig. 4.2 Turning wastes into proteins using the microbial resources (bacterial fungi and yeast) to produce microbial meals to replace FM in aquafeeds for fish culture

are equivalent to traditional food and feed proteins, like soybean (Becker 2007). Algae were found to have lower nucleic acid content 4.0–6.0% dry weight. However, bacteria, fungal, and yeast species have 15.0–16.0, 9.7, and 7.1–12.0% dry weight, respectively. Of all the microbial species, fungi have a higher limiting amino acid content, particularly lysine (Jannathulla et al. 2017) (Fig. 4.3).

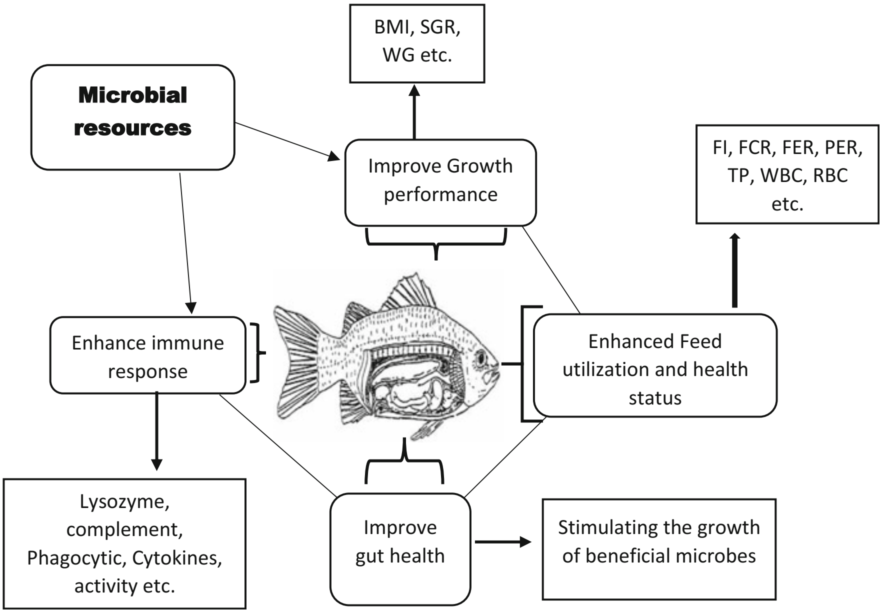

Fig. 4.3 The mode of action of microbial resources comprises of improved growth performance, feed utilization (macro-and micronutrients), health status, and enhanced immune and gut health. *BMI* body mass index, *SGR* specific growth rate, *WG* weight gain, *FI* feed intake, *FCR* feed conversion ratio, *FER* feed efficiency ratio, *PER* protein efficiency ratio, *TP* total protein, *WBC* white blood cell, *RBC* red blood cell

4.3.1 Stimulate Intestinal Enzymes to Promote a Growth Performance

The GI microbiota assists the host in a variety of ways. In mammals, their role in the nutritional provision, avoiding infectious agent colonization, energy balance, and maintaining adequate mucosal immunity is well recognized (Xu et al. 2003; Nicholson et al. 2005; Delzenne and Cani 2008). Fish GI tract microbial colonization, establishment, composition, and diversity is a complex process that is thought to reflect the microbial composition of the rearing water, nutrition, and environment (Korsnes et al. 2006; Fjellheim et al. 2007). Like mammals, hydrobionts' GI microbiota have been shown to promote physiological and nutritional health functions of the host by creating digestive enzymes, amino acids, vitamins, and metabolites (Skrodenyte Arbaeiauskiene 2000; Skrodenyte-Arbaciauskiene et al. 2006). When various chemicals, antibiotics, and pollutants enter an aquatic animal's digestive tract, they can drastically alter the composition of the dominant GI microbiota, potentially resulting in the extinction of individual species from the entire microbial community (Mickeniene and Syvokiene 2008; Navarrete et al. 2008). As a result, the composition of a fish's GI microbiota is strongly influenced by the meal and feeding conditions.

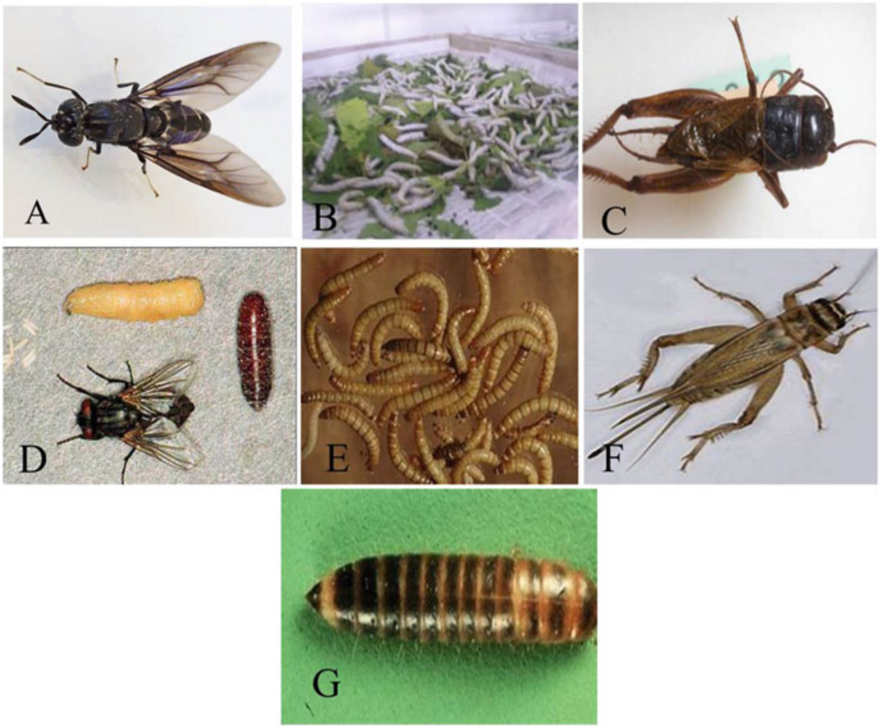

Fig. 4.4 Insect species used in producing meals to replace FM in aquafeeds. (**a**) Black soldier fly (*Hermetia illucens*), (**b**) Silkworms (*Bombyx mori*), (**c**) Jamaican field cricket (*Gryllus assimilis*), (**d**) housefly (Musca domestica) (Malik et al. 2007), (**e**) yellow mealworm (*Tenebrio molitor*), (**f**) house cricket (*Acheta domesticus*), (**g**) lesser mealworm (*Alphitobius diaperinus*)

A complex and integrated interaction of the modulation of GI enzymes is associated with nutrient absorption, and immune components are responsible for the fish's health and growth performance. On the other hand, feeding microbial resources is a better strategy for establishing and populating the probiont in fish's GI tract (Robertson et al. 2000). When microbial resources are fed to animals or added to water, they dramatically alter the gut microbiota composition by stimulating gastrointestinal bacteria to produce more enzymes. These enzymes can help increase nutrient digestibility and mineral absorption to enhance the host's growth performance, as seen in Fig. 4.4. However, besides enhancing enzymatic activities, it could stimulate B cell proliferation in gut-associated lymphoid tissues (GALT) or directly stimulate the innate immune system by increasing phagocytosis and antibacterial activity. This immune cell defends against harmful bacteria through competitive exclusion, the production of organic acids, and various other compounds, such as antibiotics (Gildberg et al. 1997; Gibson 1999; Gram et al. 1999). However, studies have shown that β-glucans (by-products from fungi and yeast), when digested, could stimulate the intestinal level via the production of cytokines, which influence fish's systemic immune response, thus hindering poisons, viruses, and harmful microorganisms from multiplying in the host (Volman et al. 2008).

The significance of microbial resources intake arises from their ability to selectively stimulate the growth and multiplication of indigenous bifidobacteria and lactobacilli in the intestine. For example, the Lactobacillus family of probiotics can produce lactase (which is responsible for breaking down lactose from dairy products), while the Bifidobacterium species can help break down fibre. The increase in healthy gut microflora is accompanied by several changes in the gut, including improved digesting enzyme activity. An increase in the synthesis of short-chain fatty acids (SCFAs) is frequently targeted and is the energy source of the colonocytes (van Immerseel et al. 2003). However, improved gut health in the host has been linked to increased SCFA production. As a result of the increased energy supply, the animal is stronger and more resistant to diseases. Besides, enhanced intestinal cell proliferation allows for improved uptake of nutrients from the meal, resulting in a higher feed uptake ratio and better growth (Vine et al. 2006). Nevertheless, there are reports concerning the interactive effect of microbial products on the digestive enzymes, growth performance, and immune response.

4.3.2 Improve Immune Response in Fish

The non-specific immune system, also known as the innate immune system, is the first line of defense, consisting of cells and mechanisms that protect the host from infection by other organisms. Immunomodulation can take several forms at the systemic level, including enhanced complement activity, increased lysozyme formation, phagocytic activity, peroxidase production, and respiratory burst activity. The GALT, a significant contributor to intestinal immune functions, have been revealed to be tightly connected with microbial resources bioactive chemicals or their metabolites (Saad et al. 2013). For example, the immunostimulatory capabilities of fungi and yeast is due to components, such as glucan, mannoproteins, and nucleic acids present in them (Ortuno et al. 2002) Meanwhile, β-glucans have been utilized in aquaculture to promote fish survival by regulating their innate immune system until adaptive immune responses develop enough to build effective anti-infection responses (Bricknell and Dalmo 2005; Meena et al. 2013). Suppose the β-glucans are administered as feed additives; they can exert their primary effects at the intestinal level through the induction of cytokines, affecting the systemic immune response in fish. As a result, its mode of action is dependent on dectin-1. β-glucan interacts with the dectin-1 receptor and activates NF-B via intracellular signaling, generating cytokines, phagocytosis, and respiratory burst (Volman et al. 2008). However, probiotics interact with immune cells, such as mononuclear phagocytes, neutrophils, and natural killer (NK) cells, to boost innate immune responses, thus increasing the number of erythrocytes, granulocytes, lymphocytes, and macrophages in different fishes (Kim and Austin 2006; Nayak et al. 2007). In fact, in fish fed microbial resources, a rise in the number of acidophilic granulocytes, T cells, Ig+

cells, and enhanced lysozyme synthesis and phagocytic activity has been noted at the gut level. Therefore, the immunomodulatory properties of these products could be achieved in the host by (1) stimulating specific and non-specific immune systems; (2) promoting phagocytic and lysozyme activities; (3) increasing the expression of various cytokines related to immunity; and (4) increasing immunoglobulin cells and acidophilic granulocytes in the fish's gut (Allameh et al. 2015).

4.3.3 Prevent Spoilage in Aquatic Products

Aquatic items have high water and protein content, making them tasty, nutritious, and prone to spoiling. Every year, the rotting of aquatic items causes significant economic losses and poses a health concern to consumers. As a result, many chemical preservatives have been created to preserve aquatic items during storage. According to Wang et al. (2020), their use may pose secondary health and environmental risks, and their application is limited to specific product categories and storage methods. Beneficial bacteria can prevent spoilage bacteria and diseases of aquatic animals through similar processes. As a result, it can be employed in addition to conventional preservatives. Fermentation is a widespread and traditional food processing method for aquatic goods that can help avoid spoiling and generate a distinct flavour. Because of the hypertonic or anaerobic environment, fermentation generally inhibits the growth of most spoilage microorganisms. Furthermore, the anti-spoilage effect is aided by the helpful microorganisms engaged in fermentation. These bacteria produce various products, primarily organic acids, alcohol, and CO_2, by oxidizing carbohydrates during metabolism. These products dramatically impact the environment and serve as a preservative by preventing the spread of pathogenic flora and/or deterioration in the food product (Ray and Montet 2015).

4.3.4 Improve Water Quality

Good water quality is essential to aquaculture as any deterioration in water quality causes stress and makes the cultured organism more vulnerable to deadly pathogens. Intensification in aquaculture, poor feed management, and indiscriminate disposal of fish waste is associated with improper mineralization of excess nutrients, affecting water quality (Edwards 2015). These poor water conditions threaten aquatic organisms' survival and render ground and surface water unsafe for other organisms. Notwithstanding the exact aquaculture system, sustaining balanced water quality levels is fundamental for farmed aquatic species' health and growth. However, water exchange/supplementation and chemicals, such as Biolite plus, Bio-tuff, Geotox, Green zeolite, JV zeolite, Pontox plus (Shamsuzzaman and Biswas 2012), Well Zeolite, and Aquazet (Faruk et al. 2008), have been the traditional methods used in solving those problems. Besides, this method is usually accompanied by pond-contaminated effluence directly discharging into adjacent water, thus causing a series of issues such as pollution diffusion, water environment deterioration, and water eutrophication. As a result, it is critical to maintaining water quality characteristics that allow for disease-free fish production.

Improving water quality and avoiding the accumulation of organic, nitrogen, ammonia, and nitrite waste are continual challenges. However, high concentrations of these compounds can be highly damaging and cause massive mortalities (Das et al. 2017). The oxidizing bacteria of ammonia (ammonia to nitrite) and nitrites (nitrite to nitrate) turn these hazardous compounds into less harmful forms in nature (Qi et al. 2009). Microbial resources, such as probiotic bacteria, have been proposed as ecological biocontrol or bioremediation agents in aquaculture (Dimitroglou et al. 2011; Iribarren et al. 2012). Benefits attributed to probiotics include increased bacterial populations, suppression of possible pathogens, and increased dissolved oxygen concentration (Ibrahem 2015). For instance, Bacillus bacteria have been considered probiotics in water treatment due to their unique ability to convert organic waste to CO_2 (Dalmin et al. 2001). Lalloo et al. (2010) found that three *Bacillus* isolates reduced the amounts of nitrite, nitrate, and ammonium in ornamental fish water. Probiotics can be administered in several ways, including (1) directly to the culture water or mixed with the inoculum of "green water", a high concentration of microalgae often employed in fish culture for food consumption in the early stages of larval development (2 days after hatching); (2) by live feed given to rotifers (up to day 19 after hatching), followed by the addition of Artemia (until about day 25 of culture after hatching). Probiotics can colonize the surface layer of the fish's skin and then infiltrate through it. As a result, probiotics can be discovered in water, sediment, and cultured organisms after inoculation in culture systems.

4.3.5 Several Advancements in Aquaculture Nutrition

Furthermore, the bacteria can produce flocculated material, providing an extra food supply while improving water quality and increasing breeding density (Schryver et al. 2008). In Pacific white shrimp (Litopenaeus vannamei), dry bioflocculant material obtained from aquaculture can partially replace FM; replacing more than 20% of FM with biofloc meal may facilitate faster growth of shrimp (Dantas et al. 2016). Other aquatic animals, such as flatfish (*Paralichthys olivaceus*) and sea cucumber (*Apostichopus japonicus*), have also shown better growth performance in similar tests and applications (Chen et al. 2018).

In Nile and blue tilapia, Viola (1984) discovered that up to 50% FM inclusion using a commercial bacterial-based microbial product (Pruteen with 70% protein) created from *Methylophilus methylotrophus* produced equal growth to the control group (no FM substitute). *Penaeus chinensis*, on the other hand, had a similar outcome (Daniel 2018). Rainbow trout fed a diet that replaced 25% of the dietary FM with a bacterial-based microbial product exhibited no negative impacts on growth, feed intake, or absorption efficiency (Perera et al. 1995). A similar outcome was seen in Atlantic salmon using bacterial and algal-based microbial products (*Desmodesmus sp.*) (Storebakken et al. 2004; Aas et al. 2006; Kiron et al. 2016). In Cobia fish, a commercial yeast (*S. cerevisiae*) derived source (NuPro) at a level of 40% may replace a control diet with 65.9% FM. Nevertheless, the percentage of FM substituted in the diet was increased to 50%, while a control diet made up of 54.4% FM was being fed (Lunger et al. 2007). When *P. vannamei* was fed an algal-based microbial product made from *Spirulina platensis*, it was found to partially replace FM similarly (Hanel et al. 2007).

For instance, *M. rosenbergii,* given *Turbinaria ornate,* and *Gracilaria corticata*-included diet, had higher activity of digestive enzymes, such as amylase, protease, and lipase, than the control group (Rajkumar et al. 2017). The addition of *Bacillus sp.* to *P. indicus* boosted the specific activity of amylase, protease, and lipase (Ziaei-Nejad et al. 2006). This enhanced enzyme activity could be attributable to exogenous enzyme release by microbes, which aids in growth and survival by improving food absorption and digesting. In the intestine of *P. vannamei* fed basic meal supplemented with *Rhodobacter sphaeroides* and *B. coagulans* at various doses of 0.1, 1, and 2%, Wang (2008) discovered a steady rise in protease and amylase activity. Although there was no difference in lipase or cellulose activity between the treated groups, the groups fed a bacteria-supplemented meal had a much greater value than the control group. Rengpipat et al. (1998) found that using the appropriate probiotics and administering them accurately improved the intestinal microbiota balance, resulting in improved digestion and absorption of cultivated species and positive results in farmed species growth.

Compared to oral supplementation, Taoka et al. (2006) study of *O. niloticus* revealed considerably higher levels of lysozyme in the skin mucosa when commercial probiotics were added to the water. These findings imply that fish given probiotic supplements can afford to resist bacterial illnesses due to enhanced lysozome activity. After 30 days of ingesting Epinephelus coioides grouper, blood C3 levels of probiotic treated group, according to Sun et al. (2010), were considerably greater than those of the control. The maximum activity against *Vibrio anguillarum* was seen in rainbow trout 2 weeks after the probiotic feeding, and after 4 weeks, there was an increase in activity compared to the control (Sharifuzzaman and Austin 2009). Yuan et al. (2019) indicated that dietary replacement of FM by 3% YH (yeast hydrolysate) could improve antioxidant capability and enhance the non-specific immunity of juvenile Jian carp. Purified β-glucan product fed to Atlantic cod (Gadus morhua L.) for 5 weeks increased the expression of IL-1 β in the anterior intestine and rectum when challenged with *V. anguillarum* (Lokesh et al. 2012). Schizochytrium fed to Atlantic salmon for 12 weeks improved goblet cell proliferation, mucus production, and inducible nitric oxide synthase activity in those given the control diet. Brewer's yeast and Spirulina increased serum proteins, notably albumin and globulin, after exposure to Aeromonas hydrophila challenge in Rohu Labeo rohita after 60 days when compared to the control group.

4.4 Waste to Insect Feed Meal

Insects are the most diverse group of animals, and a natural food source for fish, especially for carnivorous and omnivorous fish, as these fish species need a relatively high number of proteins in their diets (van Huis 2019). For more than 2000 years, people have used insects as a food source in numerous nations. For thousands of years, numerous societies have engaged in entomophagy, gathering insects for nourishment (Evans et al. 2015). Insect rearing was practiced thousands of years ago when silkworms (*Bombyx mori*) were first cultivated in China to produce silk. During the collection of the silk, the pupae by-product was fed to carp fish in ponds. Insects are a relatively recent method of producing high-quality protein for animal feeds from food waste or cow feces and pee slurry. Since then, increased research efforts and sector expenditures have resulted in more industrialized insect breeding for food and feed (van Huis 2019). Insect output is currently insufficient for the widespread use of insects in aquafeed production in Africa, despite significant research advancements and an increase in insect productivity. Numerous areas, like handling insects, production automation, and raw materials, require greater attention (Liland et al. 2017).

In Africa, Orders, including Lepidoptera, Orthoptera, Coleoptera, Isoptera, Hymenoptera, and Hemiptera, contain the greatest diversity of edible insect species. According to recent studies, the protein and calorie content of insects may be comparable to that of traditional meat sources. In Africa, crickets and acridians are the Orthoptera species most frequently ingested. More than 850 insect farms that produce food and feed are already present in Africa, along with hydroponic farms. Africa may produce up to \$2.6 billion in CP and \$19.4 billion in biofertilizers per year from insect farming using agricultural waste as feed. The protein meal would be sufficient to provide up to 14% of the CP required to raise fish in Africa.

The following insect species have been studied and used to produce industrial aquafeed: silkworms (*Bombyx mori*) (Duan et al. 2010); black soldier fly (*Hermetia illucens*) (Barry 2004); Jamaican field cricket (*Gryllus assimilis*) (Masson et al. 2020); housefly (*Musca domestica*) (Malik et al. 2007); yellow mealworm (*Tenebrio molitor*) (Li et al. 2013); house cricket (*Acheta domesticus*) (Hessler Frelinckx 2019), and lesser mealworm (*Alphitobius diaperinus*) (Rumbos et al. 2019). The ideal dietary inclusion varies considerably depending on the fish or crustacean species and their nutrient requirements. Therefore, insect meals are unquestionably a good substitute for animal protein in aquaculture feed.

In nature, insects are responsible for converting rotting food into high-quality nutrients. The larvae of some species, like the black soldier fly (BSF) species, can ingest low-quality feed and function at scales that traditional mechanical systems have not yet attained. These initiatives improve regional food security by focusing on local reuse, which lowers the pollution brought on by transportation.

4.4.1 The Nutritional Capacity of Insect Meals

The nutritional value of insect proteins is widely known. According to feeding experiments with various fish and crab species, insect meal additions do not negatively affect development and performance. Adding insect protein to aquafeeds has improved FCRs in several aquatic species. Most insect species have high CP levels, ranging from 42.1 to 63.3%. Although it is like soybean meal (SM), this level of CP is lower than that in FM (Allegretti et al. 2017; Henry et al. 2015). Various insects in these species had different amino acid profiles. Except for silkworms, sulphur amino acid concentrations in insects are lower than those in FM. While other insect species have equal quantities of threonine, silkworms have higher levels (Henry et al. 2015; Sanchez-Muros et al. 2014). Tryptophan concentrations in other insect species are often lower than those in silkworms and housefly maggot meal. Depending on the fish species' specific needs, synthetic amino acid supplements may be advised for optimum growth. An amino acid profile superior to SM is found in silkworms, black army flies, and houseflies. These insects are, therefore, preferable to SM for replacing FM in aquafeeds (Henry et al. 2015; Sanchez-Muros et al. 2014).

In comparison to FM, these species contain less fat. After researching various insect species, van Huis stated in 2020 that the fat content ranged from 8% for mature locusts to 36% for mealworm larvae. The development stage and the food that insects consume are two aspects that impact the fat content (Barros-Cordeiro et al. 2014; Barroso et al. 2019). Omega-3 fatty acids are substantially more prevalent in fish oil than in insect meals (Makkar et al. 2014); however, there are significant amounts of saturated fatty acids in insect meals. Compared to other insect species, mealworm, and housefly maggot diets have higher quantities of unsaturated fatty acids (between 60 and 70%). At the same time, approximately 19–37% of black soldier fly larvae (BSFL) contain unsaturated fatty acids (Gasco et al. 2020; Hawkey et al. 2021; van Huis 2019). These insects have lower concentrations of EPA (eicosapentaenoic acid 20:5n-3) and DHA (docosahexaenoic acid 22:6n-3) than fish oil but greater concentrations of polyunsaturated fatty acids (PFA), specifically n-6 PFA (Gasco et al. 2020; Hawkey et al. 2021; van Huis 2019). Therefore, their usefulness as an oil source in aquafeeds is restricted by the dearth of EPA and DHA in the five insect species.

4.4.2 Insect Meal as an Immunostimulant

In addition, there is growing interest in the naturally occurring bioactive compounds found in insects and the nutritional advantages of eating insects. Insect chitin in food has been linked to beneficial effects on intestinal health in rainbow trout, Jian carp, Siberian sturgeon, and marron crayfish. The precise function of chitin in fish diets is still up for debate and is dependent on the amount of chitin present in the diet; chitin may act as a prebiotic, immunostimulant, and anti-inflammatory molecule in fish when present at low levels, but when present in high doses, it may inhibit fish growth and induce intestinal inflammation. More than 50 potential active peptides have been found in BSF larvae, indicating that insects are a significant source of antimicrobial peptides (AMPs) (Pastor et al. 2015). A wide range of bacteria, fungi, certain parasites, and viruses can be attacked by AMPs, which are essential parts of the innate immune system in most animals. Due to their immunostimulant, antioxidant, and antibacterial qualities, insect meals can improve the health and performance of fish and crustaceans even at modest inclusion levels. The functionalities of premium insect meal can be used in particular formulations targeting high-value species, like sturgeons, shrimp, salmonids, juveniles, or broodstock with distinct needs.

4.4.3 Production of Insect Meal

Insect farming in a controlled or indoor environment is a suitable technique to make them available all year round because many insects are only present in nature during specific seasons or months (Cadinu et al. 2020; van Huis 2019; Hawkey et al. 2021). Collecting significant amounts of organic matter, preserving progenitors, and ensuring efficient egg production in number and quality are all crucial steps in insect farming (Pastor et al. 2015). Indoor rearing of insects necessitates the management of ambient environmental conditions (temperature, relative humidity, photoperiod), premium feed, and avoidance of parasites and diseases for the best possible insect growth and development (Hawkey et al. 2021; van Huis 2019). Long-term intensive insect farming can be carried out under technical supervision in such cases.

Various crucial phases are involved in producing insect meals (van Huis 2019). Since the nutrient composition of growing substrates significantly impacts crucial production factors, like total larvae yield, individual larva body weight, and nutrient composition of yielded insect larvae, the first step is to ensure biomass availability, which should be continuously available (Tschirner and Simon 2015). Decontamination, which involves thermal or radiation techniques, is the next phase. The final phase involves drying the insect pupa or entire body through convection, contact, and radiation. The fourth stage involves crushing the insects or pupa into tiny pieces. Defatting, the fourth step in extracting fat from insects, is crucial for particular insect species (like yellow mealworms). Defatting is often accomplished by mechanical pressing, aqueous solutions, and solvents (Soxhlet and supercritical carbon dioxide) (Rumpold et al. 2017). Numerous methods for extracting proteins include enzyme-, microwave-, ultrasound-, pulsed electric energy-, and high-pressure-aided extraction methods (Pojić et al. 2018). It is crucial to eliminate chitin from meals for some species since their bodies contain chitin. Chitin can be extracted chemically or biologically in various ways; one illustration is fermentation using microbes and enzymes (Rumpold et al. 2017). Energy costs are a significant problem for preparing insect meals. Modern technologies, such as automation with IOT, must be used to maximize every stage of the processing (Yue and Shen 2021).

4.5 Several Advancements in Aquaculture Nutrition

The effects of including insect meals into aquafeeds on various aquaculture species have recently been the subject of an increasing number of research that involved feeding trials. Here, we provide a concise summary of what is currently known about employing the eight insects as aquafeeds.

Studies have demonstrated that it is theoretically possible to grow insects on a big scale and use them as a sustainable protein substitute in the diet of birds, pigs, cattle, and aquatic animals (Veldkamp et al. 2012). However, several uses of insects to feed fish have been thoroughly studied. These include house fly larvae (*Musca domestica*) (Ogunji et al. 2008a, b; Ezewudo et al. 2015), larvae of butterflies (*Bematistes macaria*) (Nwamba and Ogunji 2012); and *Tenebrio molitor* (Ng et al. 2001; Piccolo et al. 2014; Belforti et al. 2015; Gasco et al. 2016; MªJ et al. 2016; Freccia et al. 2016).

Silkworm pupae meal can replace FM in common carp and Japanese sea bass (*Lateolabrax japonicus*) without sacrificing growth performance (Jeyachandran and Paulraj 1976). Feeding trials showed that Silkworm pupae meal might replace up to 30% of FM in the diet of rainbow sharks (*Epalzeorhynchos frenatum*) (Raja et al. 2020). When the two amino acids Lys and Met were added to the meals containing Silkworm pupae meal, the growth performance of olive flounder (*Paralichthys olivaceus*) was unaffected (Lee et al. 2012). The results of an eight-week feeding experiment on juvenile yellow catfish (*Pelteobagrus fulvidraco*) showed that BSFL meal could replace 20% of the FM in the fish feed without negatively affecting growth outcomes, including weight gain, FCR, as well as a whole body and proximate muscle composition. Dry matter, CP, crude lipids, gross energy, and ADCs (amino acid's apparent digestibility coefficients) remained unchanged among the other metrics. According to feeding research on Atlantic salmon, the quality of the fillets was unaffected when FM was replaced entirely with BSFL meal. For example, in the fillets of Atlantic salmon fed diets containing BSFL meal, neutral n-3 PUFA (polyunsaturated fatty acids) increased considerably. The impact of BSFL meal on diets was examined in African catfish (*Clarias gariepinus*). FM can be substituted with BSFL meal up to 50% without harming the growth, nutrient uptake, survival rate, or welfare of *C. gariepinus* fingerlings (Adeoye et al. 2020).

Numerous feeding studies have been conducted on two catfish species (*Clarias gariepinus* and *Heterobranchus longifilis*) and their hybrids to explore the impact of adding housefly maggots to their meals on their growth performance. Overall, the results of feeding trials for catfish species are favourable. However, maggot meal inclusion cannot exceed 30% because greater inclusion rates tend to reduce growth performance (Aniebo et al. 2009; Fasakin et al. 2003; Okore et al. 2016; Saleh 2020). A study substituted housefly maggots grown from chicken waste for FM in aquafeeds at varied inclusion levels of 0, 25, 50, 75, and 100% of maggot inclusions. The study suggests that *C. gariepinus* juveniles can effectively consume wet maggots; 75% of them should be utilized in commercial fish feed (Ipinmoroti et al. 2019). The best growth performance and survival rate were seen at 34% substitution of FM, with no adverse effects on homeostasis, when maggot meal was substituted for FM in the diet at a rate of 15–68%. It was discovered that n-6 and n-3 fatty acids must be included in the diet and maggot meal to improve fish's fatty acid profile (Ogunji et al. 2008a, b).

Using up to 25% mealworm as a meal replacement for FM demonstrated no detrimental effects on weight gain in European sea bass (*Dicentrarchus labrax*). While protein efficiency, feed consumption, and body composition were unaffected, growth and feed consumption ratios were reduced when FM was replaced with mealworm meal to 50%. Tenebrio meal at a 25% inclusion rate had no adverse effects on young European sea bass (*D. labrax*), but at a 50% inclusion rate, the specific growth rate was decreased (Gasco et al. 2014). With an outstanding replacement value of 25%, which equates to the inclusion of 7.5% of giant tenebrio meal in the diet, studies testing the replacement of FM with giant tenebrio (*Zophobas morio*) for Nile tilapia obtained a better feed conversion ratio and weight gain than the control (Abd Rahman Jabir et al. 2012).

According to Elia et al. (2018), eating BSFL meals increased the oxidative stress biomarkers SOD and CAT levels in rainbow trout (*Oncorhynchus mykiss*). The activity of serum immune-related enzymes, such as LZM and SOD in yellow catfish (*P. fulvidraco*), increased when BSF meals were included in the diet. The fish's serum levels of SOD, nitric acid, malondialdehyde (MDA), ceruloplasmin, myeloperoxidase, and glutathione peroxidase (GPx) could cause all rise if yellow meal worm is added to their diet (Su et al. 2017; Sankian et al. 2018; Henry et al. 2018). When treated with dietary supplementation of Silkworm pupae meal, *O. mykiss'* WBCs were considerably high, according to Shakoori et al. (2015) in another investigation on the innate immunity of finfish. WBC production would boost the body's defenses against viruses as they become more prevalent (Shakoori et al. 2015).

4.6 Conclusion

Although novel ingredients are required to bridge the gap in aquaculture feed resources, several obstacles must be overcome before these can be implemented in the African aquaculture industry. Aside from nutritional value, technical quality, accessibility, affordability, and environmental sustainability must all be considered. Most novel protein sources discussed in this paper are currently unavailable to the aquaculture feed industry, and several factors limit their immediate use as feed ingredients. It is significant to note that the use of these proteins (insect and microbial) may be associated with contamination with allergens and toxins (such as enterotoxins and cytotoxins) during the production process (Linder 2019; Ritala et al. 2017). So, they should not be widely used until more study and testing is finished. However, such contaminations can be managed and avoided in a closed fermentation system by following industrial verification and validation, adhering to food safety production standards (for instance, HACCP systems and ISO standards), and maintaining traceability throughout the production cycle. As a result, before large-scale industrial applications, credible and adequate examinations of resource's potential side effects, including hazardous consequences, should be conducted.

References

Aas TSV, Hatlen B, Grisdale-Helland B, Terjesen BF, Bakke-Mckellep AM, Helland SLJ (2006) Effects of diets containing a bacterial protein meal on growth and feed utilisation in rainbow trout (*Oncorhynchus mykiss*). Aquaculture 261:357–368

Abasubong KP, Liu WB, Adjoumani Y, Xia SL, Xu C, Li XF (2018) Xylooligosaccharides benefits the growth, digestive functions and TOR signaling in *Megalobrama amblycephala* fed diets with fish meal replaced by rice protein concentrate. Aquaculture 500:417–428

Abd Rahman Jabir MD, Abd Rahman Jabir SA, Vikineswary S (2012) Nutritive potential and utilization of super worm (*Zophobas morio*) meal in the diet of Nile tilapia (*Oreochromis niloticus*) juvenile. Afr J Biotechnol 11:6592–6598

Adeoye AA, Akegbejo-Samsons Y, Fawole FJ, Davies SJ (2020) 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 51:1024–1033

Agboola JO, Verland M, Skrede A, Hansen JV (2020) Yeast as major protein-rich ingredient in aquafeeds: a review of the implications for aquaculture production. Rev Aquac 13:949–970

Aladetohun N, Sogbesan O (2013) Utilization of blood meal as a protein ingredient from animal waste product in the diet of *Oreochromis niloticus*. Int J Fish Aquac 5:234–237

Allameh SK, Ringø E, Yusoff FM, Daud HM, Ideris A (2015) Dietary supplement of *Enterococcus faecalison* digestive enzyme activities, short-chain fatty acid production, immune system response and disease resistance of Javanese carp (*Puntius gonionotus*, Bleeker 1850). Aquac Nutr 23:331–338

Allegretti G, Schmidt V, Talamini E (2017) Insects as feed: species selection and their potential use in Brazilian poultry production. Worlds Poult Sci J 73:928–937

Aniebo AO, Erondu ES, Owen OJ (2009) Replacement of fish meal with maggot meal in African catfish (Clarias gariepinus) diets. Revista Científica UDO Agrícola 9:666–671

Anon (1997) Communication from the Commission to the council and the European parliament commission European Commission Brussels, p 20

Bandara T (2018) Alternative feed ingredients in aquaculture: opportunities and challenges. J Entomol Zool Stud 6:3087–3094

Barros-Cordeiro KB, Bao SN, Pujol-Luz JR (2014) Intra-puparial development of the black soldier-fly, *Hermetia illucens*. J Insect Sci 14:83

Barroso FG, Sanchez-Muros MJ, Rincon MA, Rodriguez-Rodriguez M, Fabrikov D, Morote E, Torres A, Ramos R, Gui JL (2019) Production of n-3-rich insects by bioaccumulation of fishery waste. J Food Compos Anal 82:103237

Barry T (2004) Evaluation of the economic, social, and biological feasibility of bioconverting food wastes with the black soldier fly (Hermetia illucens). University of North Texas, Denton, Texas

Becker EW (2007) Micro-algae as a source of protein. Biotechnol Adv 25:207–210

Belforti M, Gai F, Lussiana C, Renna M, Malfatto V, Rotolo L (2015) *Tenebrio molitor* meal in rainbow trout (*Oncorhynchus mykiss*) diets: effects on animal performance, nutrient digestibility and chemical composition of fillets. Ital J Anim Sci 14:4170

Bharti V, Pandey PK, Koushlesh SK (2014) Single cell proteins: a novel approach in aquaculture systems. World Aquacult 45:62–63

Bob Manuel FG, Alfred-Ockiya JF (2011) Evaluation of yeast single cell protein (SCP) diets on growth performance, feed conversion and carcass composition of Tilapia *Oreochromis niloticus* (L.) fingerlings. Afr J Biotechnol 10:9473–9478

Bricknell I, Dalmo RA (2005) The use of immunostimulants in fish larval aquaculture. Fish Shellfish Immunol 19:457–472

Bureau DP, Harris AM, Bevan DJ, Simmons LA, Azevedo PA, Cho CY (2000) Feather meals and meat and bone meals from different origins as protein sources in rainbow trout (*Oncorhynchus mykiss*) diets. Aquaculture 181:281–291

Cadinu LA, Barra P, Torre F, Delogu F, Madau FA (2020) Insect rearing: potential, challenges, and circularity. Sustainability 12:4567

Chen J, Liu P, Li Y, Li M, Xia A (2018) Effects of dietary biofloc on growth, digestibility, protein turnover and energy budget of sea cucumber *Apostichopus japonicus* (Selenka). Anim Feed Sci Technol 241:151–162

Dalmin G, Kathiresan K, Purushothaman A (2001) Effect of probiotics on bacterial population and health status of shrimp in culture pond ecosystem. Indian J Exp Biol 39:939–942

Daniel N (2018) A review on replacing fish meal in aqua feeds using plant protein sources. Int J Fish Aquat Stud 6:164–179

Dantas EM, Valle B, Brito C, Calazans N, Peixoto S, Soares RB (2016) Partial replacement of fishmeal with biofloc meal in the diet of postlarvae of the Pacific white shrimp *Litopenaeus vannamei*. Aquac Nutr 22:335–342

Das S, Mondal K, Haque S (2017) A review on application of probiotic, prebiotic and synbiotic for sustainable development of aquaculture. J Entomol Zool Stud 5:422–429

Delzenne NM, Cani PD (2008) Gut micro£ora is a key player in host energy homeostasis. Med Sci (Paris) 24:505–510

Dimitroglou A, Merrifield DL, Carnevali O, Picchietti S, Avella M, Daniels C, Güroy D, Davies SJ (2011) Microbial manipulations to improve fish health and production—a Mediterranean perspective. Fish Shellfish Immunol 30:1–16

Draganovic V, van der Goot A, Boom R, Jonkers J (2013) Wheat gluten in extruded fish feed: effects on morphology and on physical and functional properties. Aquac Nutr 19:845–859

Duan J, Li R, Cheng D, Fan W, Zha X, Cheng T et al (2010) SilkDB v2. 0: a platform for silkworm (Bombyx mori) genome biology. Nucleic Acids Res 38:D453–D456

Edwards P (2015) Aquaculture environment interactions: past, present and likely future trends. Aquaculture 447:2–14

El-Haroun ER, Azevedo PA, Bureau DP (2012) High dietary incorporation levels of rendered animal protein ingredients on performance of rainbow trout *Oncorhynchus mykiss* (Walbaum, 1972). Aquaculture 290:269–274

Elia AC, Capucchio MT, Caldaroni B, Magara G, Dörr AJM, Biasato I, Gai F (2018) Influence of *Hermetia illucens* meal dietary inclusion on the histological traits, gut mucin composition and the oxidative stress biomarkers in rainbow trout (*Oncorhynchus mykiss*). Aquaculture 496:50–57

Evans J, Alemu MH, Flore R (2015) 'Entomophagy': an evolving terminology in need of review. J Insects Food Feed 1:293–305

Ezewudo BI, Monebi CO, Ugwumba AAA (2015) Production and utilization of Musca domestica maggots in the diet of *Oreochromis niloticus* (Linnaeus, 1758) fingerlings. Afr J Agric Res 10: 2363–2371

FAO (2018) The state of world fisheries and aquaculture 2018. FAO, Rome

Farhangi M, Carter CG (2015) Growth, physiological and immunological responses of rainbow trout (*Oncorhynchus mykiss*) to different dietary inclusion levels of dehulled lupin (*Lupinus angustifolius*). Aquac Res 32:329–340

Faruk MAR, Ali MM, Patwary ZP (2008) Evaluation of the status of use of chemicals and antibiotics in freshwater aquaculture activities with special emphasis to fish health management. J Bangladesh Agric Univ 6:381–390

Fasakin EA, Balogun AM, Ajayi OO (2003) Evaluation of full-fat and defatted maggot meals in the feeding of clariid catfish *Clarias gariepinus* fingerlings. Aquac Res 34:733–738

Fjellheim AJ, Playfoot KJ, Skjermo J, Vadstein O (2007) Vibrionaceae dominates the microflora antagonistic towards *Listonella anguillarum* in the intestine of cultured Atlantic cod (*Gadus morhua* L.) larvae. Aquaculture 269:98–106

Francis G, Makkar H, Becker K (2001) Antinutritional factors present in plant-derived alternate fish feed ingredients and their effects in fish. Aquaculture 199:197–227

Freccia A, Meurer ES, Jerônimo GT, Emerenciano MGC (2016) Insect meal in diets of tilapia fingerlings. Zootechn Arch 65:541–547

García-Garibay M, Gómez-Ruiz L, Cruz-Guerrero AE, Bárzana E (2003) Single-cell proteinl algae. In: Encyclopedia of food sciences and nutrition, 2nd edn. pp 5269–5276

Gasco L, Gai F, Piccolo G, Rotolo L, Lussiana C, Molla P (2014) Substitution of fish meal by *Tenebrio molitor* meal in the diet of *Dicentrarchus labrax* juveniles. In: Insects to feed the world, vol. 80. The Netherlands, pp 14–17

Gasco L, Henry M, Piccolo G, Marono S, Gai F, Renna M (2016) *Tenebrio molitor* meal in diets for European sea bass (*Dicentrarchus labrax* L.) juveniles: growth performance, whole body composition and in vivo apparent digestibility. Anim Feed Sci Technol 220:34–45

Gasco L, Biancarosa I, Liland NS (2020) From waste to feed: a review of recent knowledge on insects as producers of protein and fat for animal feeds. Curr Opin Green Sustain Chem 23:67–79

Gibson LF (1999) Bacteriocin activity and probiotic activity of *Aeromonas* media. J Appl Microbiol 85:2445–2485

Gildberg A, Mikkelsen A, Sandaker E, Ring E (1997) Probiotic effect of lactic acid bacteria in the feed on growth and survival of fry of Atlantic cod (*Gadus morhua*). Hydrobiology 352:279–285

Gram L, Melchiorsen J, Sanggard B, Hubber I, Nielsen T (1999) Inhibition of *Vibrio anguillarum* by *Pseudomonas fuorescens* AH2 a possible probiotic treatment of fish. Appl Environ Microbiol 65:969–973

Grazziotin A, Pimentel FA, Jong EVD (2008) Poultry feather hydrolysate as a protein source for growing rats. Braz J Vet Res Anim Sci 45:61–67

Halasz A, Lasztity R (1991) Use of yeast biomass in food production, 1st edn. CRC Press, Boca Raton

Hanel R, Broekman D, Graaf SD, Schnack D (2007) Partial replacement of fishmeal by lyophylized powder of the microalgae Spirulina platensis in Pacific white shrimp diets. Open Mar Biol J 1:1–5

Hansen JV, Lagos L, Peng L, Reveco F, Verland M (2021) Down-stream processing of baker's yeast (*Saccharomyces cerevisiae*)—effect on nutrient digestibility and immune response in Atlantic salmon (*Salmo salar*). Aquaculture 530:735707

Hardy RW, Sealey WM, Gatlin DM (2007) Fisheries by-catch and by-product meals as protein sources for rainbow trout *Oncorhynchus mykiss*. J World Aquacult Soc 36:393–400

Hawkey KJ, Lopez-Viso C, Brameld JM, Parr T, Salter AM (2021) Insects: a potential source of protein and other nutrients for feed and food. Annu Rev Anim Biosci 9:333–354

Henry M, Gasco L, Piccolo G, Fountoulaki E (2015) Review on the use of insects in the diet of farmed fish: Past and future. Anim Feed Sci Technol 203:1–22

Henry MA, Gasco L, Chatzifotis S, Piccolo G (2018) Does dietary insect meal affect the fish immune system? The case of mealworm, *Tenebrio molitor* on European sea bass, *Dicentrarchus labrax*. Dev Comp Immunol 81:204–209

Hessler Frelinckx J-C (2019) Behavioural study of the house cricket (*Acheta domesticus*): behavioural study of the house cricket (*Acheta domesticus*). Swedish University of Agricultural Science, Uppsala

Hussain SM, Afzal M, Salim M, Javid A, Khichi TAA, Hussain M, Raza SA (2011) Apparent digestibility of fish meal, blood meal and meat meal for *Labeo rohita* fingerlings. J Anim Plant Sci 21:807–811

Ibrahem MD (2015) Evolution of probiotics in aquatic world: potential effects, the current status in Egypt and recent prospective. J Adv Res 6:765–791

Ipinmoroti M, Akanmu O, Iyiola A (2019) Utilisation of house fly maggots (Musca domestica) as replacement for fish meal in the diets of *Clarias gariepinus* juveniles. J Insects Food Feed 5:69–76

Iribarren D, Dagá P, Moreira MT, Feijoo G (2012) Potential environmental effects of probiotics used in aquaculture. Aquacult Int 20:779–789

Jannathulla R, Dayal JS, Vasanthakumar D, Ambasankar K, Muralidhar M (2017) Effect of fermentation methods on amino acids, fiber fractions and anti-nutritional factors in different plant protein sources and essential amino acid index for Penaeus (*Litopenaeus) vannamei*. Indian J Fish 64:40–44

Jeyachandran P, Paulraj S (1976) Experiments with artificial feeds on Cyprinus carpio fingerlings. J Inland Fish Soc India 8(1976):33–37

Jones SW, Karpol A, Friedman S, Maru BT, Tracy BP (2020) Recent advances in single cell protein use as a feed ingredient in aquaculture. Curr Opin Biotechnol 61:189–197

Karimi S, Soofiani NM, Mahboubi A, Taherzadeh M (2018) Use of organic wastes and industrial by-products to produce filamentous fungi with potential as aqua-feed ingredients. Sustainability 10:1–19

Kim DH, Austin B (2006) Cytokine expression in leucocytes and gut cells of rainbow trout, *Oncorhynchus* mykiss Walbaum, induced by probiotics. Vet Immunol Immunopathol 114: 297–304

Kim SW, Less JF, Wang L, Yan T, Kiron V, Kaushik SJ, Lei XG (2019) Meeting global feed protein demand: challenge, opportunity, and strategy. Annu Rev Anim Biosci 7:221–243

Kiron V, Sørensen M, Huntley M, Vasanth GK, Gong Y, Dahle D, Palihawadana AM (2016) Defatted biomass of the microalga, *Desmodesmus sp.*, can replace fishmeal in the feeds for Atlantic salmon. Front Mar Sci 3:67

Kolndadacha OD, Adikwu IA, Okaeme AN, Atiribom RY, Mohammed A, Musa YM (2011) The role of probiotics in aquaculture in Nigeria-a review. Cont J Fish Aq Sci 5:8–15

Korsnes K, Nicolaisen O, Skar CK, Nerland AH, Bergh Ø (2006) Bacteria in the gut of juvenile cod *Gadus morhua* fed live feed enriched with four different commercial diets. Front Mar Sci 63: 296–301

Lalloo R, Ramchuran S, Rgens JG, Gardiner N, Maharajh D (2010) Isolation and selection of *Bacillus* spp. as potential biological agents for enhancement of water quality in culture of ornamental fish. J Appl Microbiol 103:1471–1479

Lapea D, Olsen PM, Arntzen M, Kosa G, Passoth V, Eijsink V, Horn SJ (2020) Spruce sugars and poultry hydrolysate as growth medium in repeated fed-batch fermentation processes for production of yeast biomass. Bioprocess Biosyst Eng 43:723–736

Lee J, Choi I, Kim K, Cho S, Yoo J (2012) Response of dietary substitution of fishmeal with various protein sources on growth, body composition and blood chemistry of olive flounder (Paralichthys olivaceus, Temminck & Schlegel, 1846). Fish Physiol Biochem 38(2012):735–744

Li L, Zhao Z, Liu H (2013) Feasibility of feeding yellow mealworm (Tenebrio molitor L.) in bioregenerative life support systems as a source of animal protein for humans. Acta Astronaut 92(2013):103–109

Liland NS, Biancarosa I, Araujo P (2017) Modulation of nutrient composition of black soldier fly (*Hermetia illucens*) larvae by feeding seaweed-enriched media. PLoS One 12:e0183188

Linder T (2019) Making the case for edible microorganisms as an integral part of a more sustainable and resilient food production system. Food Security 11:265–278

Lokesh J, Fernandes JMO, Korsnes K, Bergh O, Brinchmann MF, Kiron V (2012) Transcriptional regulation of cytokines in the intestine of Atlantic cod fed yeast derived mannan oligosaccharide or beta-glucan and challenged with *Vibrio anguillarum*. Fish Shellfish Immunol 33:626–631

Lunger AN, McLean E, Craig SR (2007) The effects of organic protein supplementation upon growth, feed conversion and texture quality parameters of juvenile cobia (*Rachycentron canadum*). Aquaculture 264:342–352

Mahnken C, Spinelli J, Waknitz FW (1980) Evaluation of an alkane yeast (Candida sp.) as a substitute for fish meal in Oregon moist pellet: feeding trials with coho salmon (*Oncorhynchus kisutch*) and rainbow trout (*Salmo gairdneri*). Aquaculture 20:41–56

MªJ SM, Haro C, Sanz A, Braided CE, Villareces S, Barroso FG (2016) Nutritional evaluation of *Tenebrio molitor* meal as fishmeal substitute for tilapia (*Oreochromis niloticus*) diet. Aquac Nutr 22:943–955

Makkar HPS, Tran G, Henze V, Ankers P (2014) State-of-the-art on use of insects as animal feed. Anim Feed Sci Tech 197:1–33

Malik A, Singh N, Satya S (2007) House fly (Musca domestica): a review of control strategies for a challenging pest. J Environ Sci Health Part B 42:453–469

Masson MV, de Souza Tavares W, Alves JM, Ferreira-Filho PJ, Barbosa LR, Wilcken CF et al (2020) Bioecological aspects of the common black field cricket, *Gryllus assimilis* (Orthoptera: Gryllidae) in the laboratory and in Eucalyptus (Myrtaceae) plantations. J Orthop Res 29:83

Matassa S, Boon N, Pikaar I, Verstraete W (2016) Microbial protein: future sustainable food supply route with low environmental footprint. Microb Biotechnol 9:568–575

Meena DK, Das P, Kumar S, Mandal SC, Prusty AK, Singh SK (2013) Beta-glucan: an ideal immunostimulant in aquaculture (a review). Fish Physiol Biochem 39:431–457

Mickeniene L, Syvokiene J (2008) The impact of zinc on the bacterial abundance in the intestinal tract of rainbow trout (*Oncorhynchus mykiss*) larvae. Ekologija 54:5–9

Navarrete P, Mardones P, Opazo R, Espejo R, Romero J (2008) Oxytetracycline treatment reduces bacterial diversity of intestinal microbiota of Atlantic salmon. J Aquat Anim Health 20:177–183

Nayak SK, Swain P, Mukherjee SC (2007) Effect of dietary supplementation of probiotic and vitamin C on the immune response of Indian major carp, *Labeo rohita* (Ham.). Fish Shellfish Immunol 23:892–896

Ng WK, Liew FL, Ang LP, Wong KW (2001) Potential of mealworm (*Tenebrio molitor*) as an alternative protein source in practical diets for African catfish, *Clarias gariepinus*. Aquac Res 32:273–280

Nicholson JK, Holmes E, Wilson ID (2005) Gut microorganisms, mammalian metabolism and personalized health care. Nat Rev Microbiol 3:431–438

Nidhina N, Muthukumar S (2015) Antinutritional factors and functionality of protein-rich fractions of industrial guar meal as affected by heat processing. Food Chem 173:920–926

Nwamba H, Ogunji JO (2012) Evaluating butterfly larvae (*Bematistes macaria*) meal as fishmeal substitute in diets of African catfish hybrid (*Heteroclarias*). Indian J Soc Nat Sci 1:78–84

OECD (2016) The cost of air pollution in Africa. https://www.oecd-ilibrary.org/development/thecost-of-air-pollution-in-africa_5jlqzq77x6f8-en

Ogunji JO, Kloas W, Wirth M, Neumann N, Pietsch C (2008a) Effect of housefly maggot meal (magmeal) diets on the performance, concentration of plasma glucose, cortisol and blood characteristics of *Oreochromis niloticus* fingerlings. J Anim Physiol Anim Nutr 92:511–518

Ogunji J, Schulz C, Kloas W (2008b) Growth performance, nutrient utilization of Nile tilapia *Oreochromis niloticus* fed housefly maggot meal (magmeal) diets. Turk J Fish Aquat Sci 8:141–147

Okore O, Ekedo C, Ubiaru P, Uzodinma K (2016) Growth and haematological studies of African catfish (*Clarias gariepinus*) juveniles fed with Housefly larva (*Musca dometica*) as feed supplement. Int J Agric Earth Sci 2:21–30

Ortuno J, Cuesta A, Rodriguez A, Esteban MA, Meseguer J (2002) Oral administration of yeast, *Saccharomyces cerevisiae,* enhances the cellular innate immune response of gilt-head seabream (*Sparus aurata* L.). Vet Immunol Immunopathol 85:41–50

Øverland MS, Rensen M, Storebakken T, Penn M, Krogdahl Å, Skrede A (2009) Pea protein concentrate substituting fish meal or soybean meal in diets for Atlantic salmon (*Salmo salar*)-

effect on growth performance, nutrient digestibility, carcass composition, gut health, and physical feed quality. Aquaculture 288:305–311

Pastor B, Velasquez Y, Gobbi P, Rojo S (2015) Conversion of organic wastes into fly larval biomass: bottlenecks and challenges. J Insects Food Feed 1:179–193

Patil NS, Jadhav JP (2014) Single cell protein production using penicillium ochrochloron chitinase and its evaluation in fish meal formulations. J Microb Biochem Technol S4:005

Perera W, Carter CG, Houlihan DF (1995) Apparent absorption efficiencies of amino acids in rainbow trout, *Oncorhynchus mykiss* (Walbaum), fed diets containing bacterial single-cell protein. Aquac Nutr 2:95–103

Piccolo G, Marono S, Gasco L, Iannaccone F, Bovera F, Nizza A (2014) Use of Tenebrio Molitor larvae meal in diets for Gilthead Sea bream Sparus aurata juveniles. In: Insects to feed the world. The Netherlands, pp 14–17

Pikaar I, Matassa S, Rabaey K, Bodirsky BL, Popp A, Herrero M, Verstraete W (2017) Microbes and the next nitrogen revolution. Environ Sci Technol 51:7297–7303

Pike IH, Andorsdottir G Mundheim H (1990) The role of fishmeal in diets for salmonids. International association of fishmeal manufacturers. https://www.iffo.net/es/system/files/TB24%20FM%20Salmon.PDF. Accessed 23 Aug 2019

Pojić M, Mišan A, Tiwari B (2018) Eco-innovative technologies for extraction of proteins for human consumption from renewable protein sources of plant origin. Trends Food Sci Technol 75:93–104

Qi Z, Zhang XH, Boon N, Bossier P (2009) Probiotics in aquaculture of China—current state, problems and prospect. Aquaculture 290:15–21

Raja PK, Aanand S, Sampathkumar JS, Padmavathy P (2020) Effect of silkworm (*Bombyx mori*) pupae on the growth and maturation of rainbow shark *Epalzeorhynchos frenatum* (Fowler, 1934) under captive rearing. Indian J Fish 67:89–96

Rajkumar G, Bhavan PS, Srinivasan V, Udayasuriyan R, Satgurunathan T (2017) Partial replacement of fishmeal with marine algae *Turbinaria ornata* and *Gracilaria corticata* for sustainable culture of the freshwater prawn *Macrobrachium rosenbergii*. Int J Res Stud Zool 3:32–44

Ray RC, Montet D (eds) (2015) Microorganisms and fermentation of traditional foods. CRC Press, New York

Rengpipat S, Phianphak W, Piyatiratitivorakul S, Menasveta P (1998) Effects of a probiotic bacterium on black tiger shrimp *Penaeus monodon* survival and growth. Aquaculture 167:301–313

Ritala A, Häkkinen ST, Toivari M, Wiebe MG (2017) Single cell protein—state-of the-art, industrial landscape and patents 2001–2016. Front Microbiol 8:2009

Robertson PAW, Dowd CO, Burrels C, Williams P, Austin B (2000) Use of *Carnobactrium sp*. as a probiotic for Atlantic Salmon (*Salmo salar* L.) and rainbow trout (*Oncorhynchus mykiss*, Walbaum). Aquaculture 18:235–243

Rumbos CI, Karapanagiotidis IT, Mente E, Athanassiou CG (2019) The lesser mealworm Alphitobius diaperinus: a noxious pest or a promising nutrient source? Rev Aquac 11 (2019):1418–1437

Rumpold BA, Klocke M, Schluter O (2017) Insect biodiversity: underutilize bioresource for sustainable applications in life sciences. Reg Environ Chang 17:1445–1454

Rumsey GL, Hughes SG, Kinsella JL (2010) Use of dietary yeast *Saccharomyces cerevisiae* nitrogen by Lake trout. J World Aquacult Soc 21:205–209

Saad N, Delattre C, Urdaci M, Schmitter JM, Bressollier P (2013) An overview of the last advances in probiotic and prebiotic field. LWT Food Sci Technol 50:1–16

Saleh HH (2020) Effect of feeding on fresh (wet) housefly maggots (*Musca domestica*) with or without artificial diet on water quality and growth rates of African catfish (*Clarias gariepinus* Burchell, 1822) fry under laboratory conditions. J Zool Res 2:2053

Sanchez-Muros MJ, Barroso FG, Manzano-Agugliaro F (2014) Insect meal as renewable source of food for animal feeding: a review. J Clean Prod 65:16–27

Sankian Z, Khosravi S, Kim YO, Lee SM (2018) Effects of dietary inclusion of yellow mealworm (*Tenebrio molitor*) meal on growth performance, feed utilization, body composition, plasma biochemical indices, selected immune parameters and antioxidant enzyme activities of mandarin fish (*Siniperca scherzeri*) juveniles. Aquaculture 496:79–87

Scarlat N, Motola V, Dallemand JF, Monforti-Ferrario F, Mofor L (2015) Evaluation of energy potential of municipal solid waste from African urban areas. Renew Sust Energ Rev 50:1269–1286

Schryver PD, Crab R, Defoirdt T, Boon N, Verstraete W (2008) The basics of bio-flocs technology: the added value for aquaculture. Aquaculture 277:125–137

Shakoori M, Gholipour H, Naseri S (2015) Effect of replacing dietary fish meal with silkworm (*Bombyx mori*) pupae on hematological parameters of rainbow trout *Oncorhynchus mykiss*. Comp Clin Path 24:139–143

Shamsuzzaman MM, Biswas TK (2012) Aqua chemicals in shrimp farm: a study from south-west coast of Bangladesh. Egypt J Aquat Res 38:275–285. https://doi.org/10.1016/j.ejar.2012.12.008

Sharifuzzaman SM, Austin B (2009) Influence of probiotic feeding duration on disease resistance and immune parameters in rainbow trout. Fish Shellfish Immunol 27:440–445

Sharma S, Hansen LD, Hansen JØ, Mydland LT, Horn SJ, Øverland M, Eijsink VGH, Vuoristo KS (2018) Microbial protein produced from brown seaweed and spruce wood as a feed ingredient. J Agric Food Chem 66:8328–8335

Skrodenyte-Arbaeiauskiene V (2000) Proteolytic activity of the roach (Rutilus rutilus L.) intestinal micro£ora. Acta Zool Litu 10(3):69–77

Skrodenyte-Arbaciauskiene V, Sruoga A, Butkauskas D (2006) Assessment of microbial diversity in the river trout *Salmo trutta fario* L. intestinal tract identified by partial 16S rRNA gene sequence analysis. Fish Sci 72:597–602

Sørensen M, Morken T, Kosanovic M (2011) Pea and wheat starch possess different processing characteristics and affect physical quality and viscosity of extruded feed for Atlantic salmon. Aquac Nutr 17:326–336

Spalvins K, Blumberga D (2018) Production of fish feed and fish oil from waste biomass using microorganisms: overview of methods analyzing resource availability. Environ Clim Technol 22:149–164

Spalvins K, Ivanovs K, Blumberga D (2018) Single cell protein production from waste biomass: review of various agricultural by-products. Agron Res 16:1493–1508

Stankus A (2021) State of world aquaculture 2020 and regional reviews: FAO webinar series. In: FAO aquaculture newsletter, pp 17–18

Storebakken T, Baeverfjord G, Skrede A, Olli JJ, Berge GM (2004) Bacterial protein grown on natural gas in diets for Atlantic salmon, *Salmo salar*, in freshwater. Aquaculture 241:413–425

Su J, Gong Y, Cao S, Lu F, Han D, Liu H, Xie S (2017) Effects of dietary *Tenebrio molitor* meal on the growth performance, immune response and disease resistance of yellow catfish (Pelteobagrus fulvidraco). Fish Shellfish Immunol 69:59–66

Sun YZ, Yang HL, Ma RL, Lin WY (2010) Probiotic applications of two dominant gut *Bacillus* strains with antagonistic activity improved the growth performance and immune responses of grouper *Epinephelus coioides*. Fish Shellfish Immunol 29:803–809

Taoka Y, Maeda H, Jo JY, Kim SM, Park S, Yoshikawa T (2006) Use of live and dead probiotic cells in tilapia Oreochromis niloticus. Fish Sci 72:55–66

Tschirner M, Simon A (2015) Influence of different growing substrates and processing on the nutrient composition of black soldier fly larvae destined for animal feed. J Insects Food Feed 1:249–259

Ullah Z, Ahmed G, Nisa MU (2016) Standardized ileal amino acid digestibility of commonly used feed ingredients in growing broilers. Asian Australas J Anim Sci 29:1322

UNEP (2018) Africa waste management outlook. UN Environment Programme, Nairobi, p 153

van Huis A (2019) Insects as food and feed, a new emerging agricultural sector: a review. J Insects Food Feed 6:27–44 van Immerseel F, de Buck J, Pasmans F, Velge P, Bottreau E, Fievez V (2003) Invasion of Salmonella enteritidis in avian intestinal epithelial cells in vitro is influenced by short-chain fatty acids. Int J Food Microbiol 85:237–248

Veldkamp T, Van Duinkerken G, Van Huis A, Lakemond CMM, Ottevanger E, Bosch G (2012) Insects as a sustainable feed ingredient in pig and poultry diets—a feasibility study. In: Wageningen UR livestock research, pp 1570–8616

Vine NG, Leukes WD, Kaiser H (2006) Probiotics in marine larviculture. FEMS Microbiol Rev 30:404–427

Viola SGZ (1984) Nutrition studies with market size hybrids of tilapia (*Oreochromis*) in intensive culture. Isr J Aquacult 36:3–15

Volman JJ, Ramakers JD, Plat J (2008) Dietary modulation of immune function by β-glucans. Physiol Behav 94:276–284

Wael Fahmi W, Sutton K (2010) Cairo's contested garbage: sustainable solid waste management and the Zabaleen's right to the city. Sustainability 2:1174

Wang YB (2008) Effect of probiotics on growth performance and digestive enzyme activity of the shrimp *Penaeus vannamei*. Aquaculture 269:259–264

Wang C, Chuprom J, Wang Y, Fu L (2020) Beneficial bacteria for aquaculture: nutrition, bacteriostasis and immunoregulation. J Appl Microbiol 128:28–40

Xu J, Bjursell MK, Himrod J, Deng S, Carmichael LK, Chiang HC, Hooper LV, Gordon JI (2003) A genomic view of the human- Bacteroides thetaiotaomicron symbiosis. Science 299:2074–2076

Yu R, Cao H, Huang Y, Peng M, Kajbaf K, Kumar V, Tao Z, Yang G, Wen C (2020) The effects of partial replacement of fishmeal protein by hydrolysed feather meal protein in the diet with high inclusion of plant protein on growth performance, fillet quality and physiological parameters of Pengze crucian carp (*Carassius auratus* var. Pengze). Aquac Res 51:636–647

Yuan XY, Jiang GZ, Wang CC, Abasubong KP, Zou Q, Zhou YY, Liu WB (2019) Effects of partial replacement of fish meal by yeast hydrolysate on antioxidant capability, intestinal morphology, and inflammation-related gene expression of juvenile Jian carp (*Cyprinus carpio* var. Jian). Fish Physiol Biochem 45:187–197

Yue K, Shen Y (2021) An overview of disruptive technologies for aquaculture. Aquac Fish 7:111–120

Ziaei-Nejad S, Rezaei MH, Takami GA, Lovett DL, Mirvaghefi AMS (2006) The effect of Bacillus spp. bacteria used as probiotics on digestive enzyme activity, survival and growth in the Indian white shrimp *Fenneropenaeus indicus*. Aquaculture 252:516–524