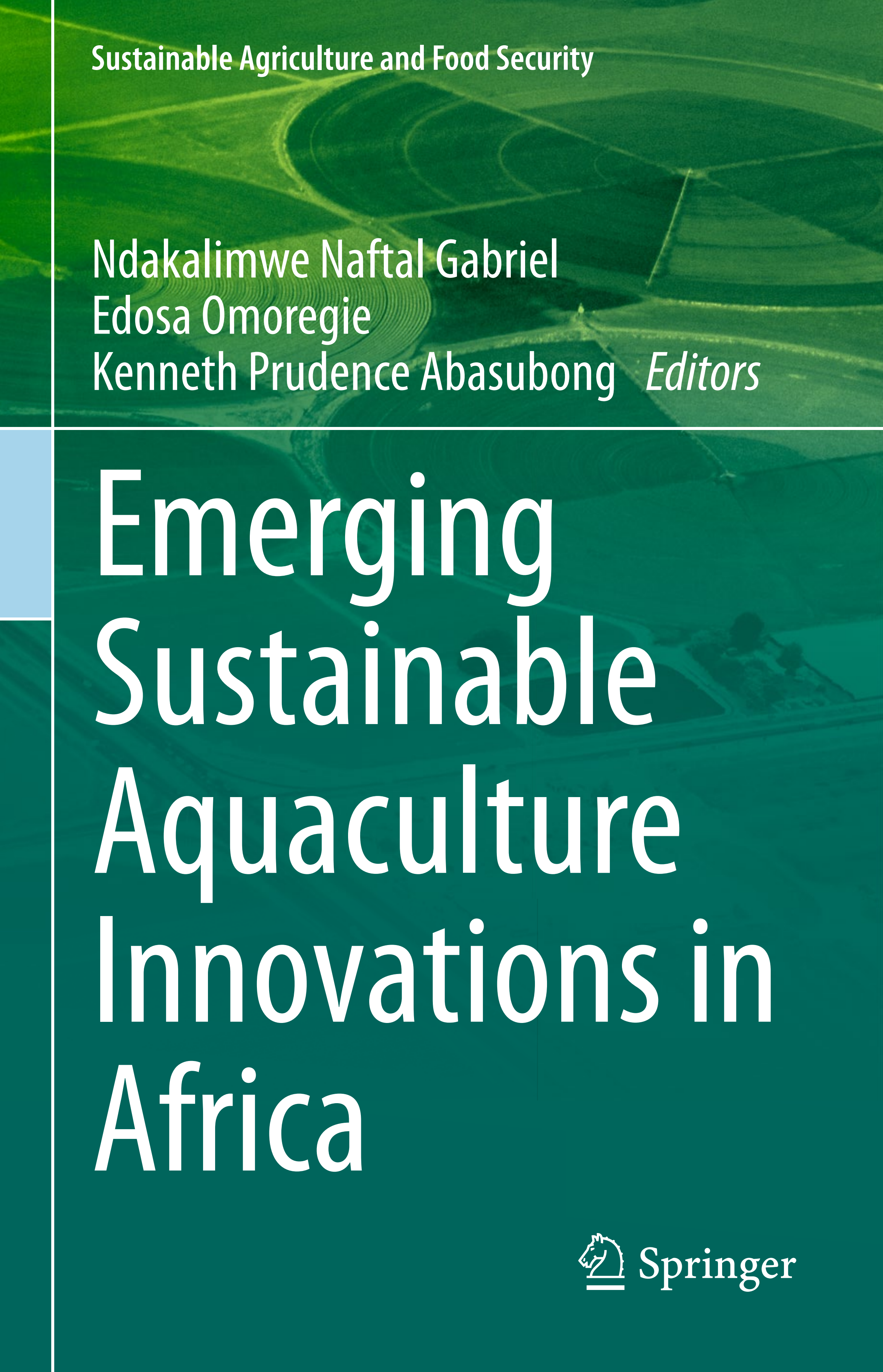

Sustainable Agriculture and Food Security

Ndakalimwe Naftal Gabriel
Edosa Omoregie
Kenneth Prudence Abasubong *Editors*

Emerging Sustainable Aquaculture Innovations in Africa

Springer

Sustainability Sciences in Asia and Africa

Sustainable Agriculture and Food Security

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Ndakalimwe Naftal Gabriel • Edosa Omoregie •
Kenneth Prudence Abasubong
Editors

Emerging Sustainable Aquaculture Innovations in Africa

Springer

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Preface

The global food production systems require expanding their capacity to produce almost twice the current levels to safeguard the food security of the burgeoning population worldwide. More than 800 million suffering from undernourishment worldwide pose a great risk to the attainment of sustainable development goal (SDG) 2 of the UN that targets "End hunger, achieve food security and improved nutrition and promote sustainable agriculture" within the next 7 years. The challenge is further exacerbated by the rising weather extremities and unpredictability in rainfall patterns and pest-pathogen dynamics associated with global climate change that has profound negative impact on the agricultural productivity and farm incomes worldwide. Also, the future targets of food production should be secured in a resource-constrained agricultural setting and with least environment footprint, thus calling for sustainable innovations in agri-farming systems and enhanced participation of women in agriculture. The challenge to reduce hunger is alarming in the case of developing nations particularly in Asia and Africa that house the largest proportion of people suffering from malnutrition and other nutrition-related issues. Furthermore, the agri-food systems in Asia and Africa are severely constrained by subsistence nature of farming, declining land and other agricultural resources, increasing environmental pollution, soil and biodiversity degradation, and climate change. Therefore, this book series, "Sustainable Agriculture and Food Security," has been planned to support the global efforts towards sustainability by providing timely coverage of the progress, opportunities, and challenges of sustainable food production and consumption in Asia and Africa. The series narrates the success stories and research endeavours from the regions of Africa and Asia on issues relating to SDG 2: Zero hunger. It fosters research in transdisciplinary academic fields spanning across sustainable agriculture systems and practices, post-harvest and food supply chains. The focus of the series is to provide a comprehensive publication platform and act as a knowledge engine in the growth of sustainability sciences with a special focus on developing nations.

As per the UN's Food and Agriculture Organization (FAO), aquaculture is defined as the '*farming of aquatic organisms including fish, molluscs, crustaceans* *and aquatic plants. Farming implies some sort of intervention in the rearing process to enhance production, such as regular stocking, feeding, protection from predators, etc. Farming also implies individual or corporate ownership of the stock being cultivated, the planning, development and operation of aquaculture systems, sites, facilities and practices, and the production and transport.*' Although aquaculture has been around for millennia, it started to contribute significantly to the global food supply and rural livelihoods about 30–40 years ago. In the context of target geographic regions of the book series, Asia dominates global aquaculture accounting for 92% of global production, and Africa has <2% share in global production. However, in the last 20 years, aquaculture production in sub-Saharan Africa (SSA) has grown by 11% annually on average, almost twice as fast compared with the rest of the world, and some African countries with a growth of 12–23% per year. However, due to fish disease triggered by poor water and farm management practices in the beginning of 2015, the high cost of local production, competition from cheap fish imports, and then the recent addition of the COVID-19 pandemic, the production level has been stagnated. As per an estimate, the projected increase in demand for aquatic foods in SSA required that aquaculture produces an additional 5 million tonnes by 2030 and 10.6 million tonnes by 2050. However, such growth must not come at the cost of aquatic ecosystem health, increased pollution, animal welfare, biodiversity, or social equality. This requires new, sustainable and equitable aquaculture development strategies.

According to a joint report of Agence Française de Développement (AFD), European Commission, and German International Development Agency (GIZ), '*the aquaculture value chain—whether it be the primary production stage or the subsequent product supply chain—can contribute to achieving SDGs at both national and regional levels.*'

Among different kind of aquaculture types—subsistence aquaculture, small-scale commercial aquaculture, SME aquaculture, and industrial aquaculture—the subsistence aquaculture has the potential to contribute to most of the relevant SDGs. This is due to the family level of operations, where work is well distributed, meaningful, and empowering. Small-scale commercial aquaculture in terms of its contribution to the SDGs also has a greater opportunity to directly contribute to family income, and thus address poverty issues. This will assist to achieve other SDGs at community level, including good health and education opportunities. It can also generate some jobs, and being local, can be undertaken on a part-time basis by women. In the majority of the aquaculture sector in Africa, the above-mentioned two types of aquaculture farming are more common in Africa, and therefore improving aquaculture in Africa will significantly contribute to achieving SDGs.

In view of this, the present book, *Emerging Sustainable Aquaculture Innovations in Africa,* provides a platform to appreciate current efforts and plan future work on this important topic. The book contains 26 chapters written by various experts and practitioners in aquaculture in Africa. The chapters are written under four parts: Aquaculture Nutrition and Feed Management, Water Quality Management, Aquaculture Development and Innovations in Africa, and Aquaculture Animal Welfare. I would like to congratulate the editors, Ndakalimwe Naftal Gabriel, Edosa Omoregie, and Kenneth Prudence Abasubong, and all authors for their valued contributions. I am sure that this book is a great resource for students, researchers, aquaculture farmers, aquaculture educators and extension agents, policy makers, and other stakeholders engaged in transforming aquaculture in Africa and possibly other parts of the world.

I wish to extend my sincere thanks and gratitude to the Springer staff, particularly Aakanksha Tyagi, Senior Editor (Books), Life Sciences, and Naren Aggarwal, Editorial Director, Medicine, Biomedical and Life Sciences Books Asia, for their constant support for the accomplishment of this compendium. The cooperation received from my senior colleagues and research leaders such as David Morrison, Peter Davies, and Daniel Murphy and my laboratory colleagues Anu Chitikineni, Abhishek Bohra, and Vanika Garg from Murdoch University (Australia) is also gratefully acknowledged. I would like to thank my family members Monika Varshney, Prakhar Varshney, and Preksha Varshney for their love and support to discharge my duties as Series Editor.

Perth, WA, Australia Rajeev K. Varshney

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About the Editors

Ndakalimwe Naftal Gabriel is a senior lecturer in the Department of Fisheries and Ocean Sciences at the University of Namibia (UNAM). He has a PhD in Fisheries and Aquatic Sciences from UNAM. From 2013 to 2015, he attended Nanjing Agricultural University in Jiangsu, China (MSc-aquaculture) and UNAM for his bachelor's degree in Biological Sciences. He has received numerous awards, including a Fulbright scholarship, TWAS fellowship, Nanjing Municipal People's Government international student scholarship, Distinguished Foreign Student Scholarship–2015, Chinese Government Scholarship, and recognition as one of the best students at Nanjing Agricultural University in 2014 and 2015. He has over 10 years of expertise as a researcher in aquaculture and 7 years as a lecturer at UNAM. He has over 30 published research pieces, including book chapters and 2 books. He has also evaluated numerous peer-reviewed articles from renowned journals and supervised several graduate students in the area of aquaculture and fishery sciences.

Edosa Omoregie obtained his PhD degree in Zoology (Fisheries) from the University of Jos, Nigeria, in 1995. He is an NSRIC (Nature Science Research and Innovation Centre, Canada) distinguished professor of fisheries and currently with the Namibia University of Science and Technology. His academic career started in 1990 with the Department of Zoology, University of Jos, Nigeria, where he rose to the rank of professor of fisheries in 2004. From 2005 to 2008, he was FAO expert lecturer in fisheries for the University of The Gambia. Between 2011 and 2015, he was the director of the Sam Nujoma Marine and Coastal Resources Research Centre, University of Namibia. He is actively involved in fisheries and aquatic science research on the African continent and has supervised over 50 postgraduate research students. He has served as a review editor for several journals with focus on fisheries and aquatic sciences and has contributed to over 150 scholarly works, including more than 75 peer-reviewed research papers.

Kenneth Prudence Abasubong holds an MSc in Animal Nutrition and Feed Science in 2018 and is a final year PhD candidate at Nanjing Agricultural University (NAU), China. His specialisation areas are aquaculture nutrition, molecular biology, feed science, animal and aquatic physiology, and nutrient metabolism. He has attended several international conferences and symposiums in aquaculture and fisheries sciences. He studied at the University of Uyo, Uyo, Nigeria (PGD Aquatic Environmental Management) from 2012 to 2013 and at the University of Calabar for his bachelor's degree in Animal Sciences. He has published more than 20 articles and reviewed several high-impact international journals in aquaculture. He has received several awards, including the best international student in NAU in 2018. He has supervised several undergraduate and graduate students in fisheries and aquaculture. He has over 8 years of experience as a researcher in aquaculture.

Part I
Aquaculture Nutrition and Feed Management

Chapter 1
Fish Nutrition: An African Aquaculture Perspective

Samwel Mchele Limbu

Abstract Aquaculture production is an essential industry in many African countries as a source of protein, income, and employment. The industry is expected to grow because the demand for fish products is increasing while the supply from natural sources is decreasing or has stagnated. Therefore, aquaculture in Africa is required to increase production while ensuring industry sustainability. One of the most important aspects required to increase aquaculture production and ensure the sustainability of the industry in Africa is fish nutrition. Fish nutrition plays a critical role in the expansion of aquaculture because it influences not only production costs but also fish growth, health and waste production. Under current production economics, feed is the most expensive item in African fish production, frequently amounting to more than 50% of the total variable costs depending on the intensity of culture. Accordingly, the success of African aquaculture partly depends on formulating affordable feeds, which guarantee fast growth and survival of cultured fish without causing environmental pollution. Extensive research has been conducted on African aquaculture on various aspects of fish nutrition by using various feeding strategies and technologies, ingredients to replace expensive and limited availability fishmeal and soybean meal by using cheap alternatives, use of affordable locally available feed ingredients and supplementation by using different feed additives for various purposes. The effects of these approaches on growth performance, feed utilization, organ indices, water quality, immunity and economic benefits have been documented. However, information is currently scattered and unorganized. This chapter critically analyses and discusses the available information in the literature on fish nutrition in cultured fish species in Africa. The chapter findings pave the way towards aquaculture development in Africa through proper fish nutrition to meet the needs of the industry for increased production and environmental sustainability in the era of blue economy.

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Keywords Fish nutrition · African aquaculture · Growth performance · Immunity response · Feed additives

1.1 Introduction

One of the critical aspects required for future human development is food security. The unprecedented human population growth has caused increasing pressure on human food sources (Dunbar et al. 2014). Across the world, hunger and malnutrition are still challenging to tackle by 2030 (FAO 2022). Asia and Sub-Saharan Africa currently have many people who are food and nutrition insecure (Beveridge et al. 2013). Most inhabitants in the two Asia and Sub-Saharan Africa depend on fish as a rich source of protein, micronutrients and essential fatty acids. Fish is among the aquatic foods, which are increasingly recognized as significant contributors to the food security and nutrition (FAO 2022). Accordingly, one of the objectives of Africa is to increase the dietary intake of fish to provide the energy and protein sufficient to fight against wasting and stunting (Delarue 2019). Fish contributes to Africa's food and nutrition security, but future directions for the wild fish sector remain uncertain (Chan et al. 2019). Therefore, aquaculture is the potential industry to narrow the gap between fish demand and supply in Africa.

Aquaculture is the primary fish production sector projected to contribute largely to the expected increase in fishery products by a further 15% in the year 2030 (FAO 2022). Such projections are based on the intensification and expansion of sustainable aquaculture production. For the African aquaculture industry to meet the projected growth sustainably, effective feeding at affordable cost is a prerequisite. Affordable feed is important to the African aquaculture industry because fish feed constitutes 40% to 60% of the total operational costs depending on intensity of production (Limbu and Jumanne 2014). Accordingly, the African aquaculture has been using various methods and technologies to produce fish.

One of the potential approaches used in African aquaculture is the development of appropriate feeding methods and technologies for improved fish growth performance and general health at a reasonable cost. Indeed, the African aquaculture industry uses various approaches to achieve the production of high-quality fish for food consumption. These include mixed protein levels, restriction and re-feeding (Limbu and Jumanne 2014; El-Araby et al. 2020), on-farm made feeds (Limbu 2020b) and supplemental feeds with fertilization (Limbu et al. 2016; Lundeba et al. 2022). Moreover, feed supplementation by using different additives has also been reported as an important approach to sustain the African aquaculture industry (Abdel-Tawwab et al. 2021c). The projected expansion and diversification of aquaculture (FAO 2022) is expected to cause stress and compromise fish immunity, leading to disease outbreaks (Awad and Awaad 2017). Such effects require supplementation by using growth and immunity stimulants as antioxidant agents for protecting fish against xenobiotics (Abdel-Tawwab et al. 2020b). Extensive studies have been conducted in African aquaculture, covering an array of functional feed additives for various purposes. However, information on the feeding methods, technologies and feed additives used in African aquaculture is currently scattered and unorganized, consequently limiting the industry's growth.

This chapter organizes and synthesizes the available information in the literature on the African aquaculture industry feeding perspectives. The chapter first analyses the various methods used in the feeding of cultured fish in various African countries. Second, it discusses the feeding technologies used in the African aquaculture industry. Third, the chapter explains the approaches undertaken by the African fish nutritionists to solve feed costs by focusing on replacing expensive and limited access ingredients. Lastly, the chapter explores the various feed additives used in African aquaculture for feed production to ensure enhanced fish growth performance, immunity and general health. On each of the four aspects, future perspectives are highlighted. The information generated could transform the African aquaculture industry fish production for sustainable food production required by the continent and global population in the blue economy era.

1.2 The Feeding Practices Used in African Aquaculture

Feeding practices aim to ensure optimum growth rates, feed efficiencies and cost-effective utilization of feeds. These are essential aspects for increased production and revenue generation. African aquaculture uses various feeding practices to achieve the above objectives (Table 1.1). One such approach is mixed feeding schedules with different dietary crude protein levels designed as low protein, medium protein and high protein. Such a practice was conducted in African Sharp tooth catfish, *Clarias gariepinus* fingerlings (Morenike and Akinola 2010). Feeding the *C. gariepinus* on high protein resulted in higher growth, and feed utilization consequently led to more economic returns. Other feed practices used in African aquaculture are feed restriction and re-feeding. Restriction and re-feeding strategy has been reported in Nile tilapia, *Oreochromis niloticus* in Tanzania (Limbu and Jumanne 2014) and Egypt (El-Araby et al. 2020). In both studies, fish fasted compensated for weight during re-feeding. Furthermore, restricted feeding improved antioxidant status (El-Araby et al. 2020) and reduced feed cost up to 20% (Limbu and Jumanne 2014). This feeding strategy is simple, easy, practically applicable and affordable means of reducing feeding costs in African aquaculture.

Locally produced fish feed has long been recognized as potential for aquaculture development in Sub-Saharan Africa (Gabriel et al. 2007). Therefore, another approach commonly used in African aquaculture is to formulate cost-effective feeds at the farm level by using locally available ingredients. This approach was evident in Uganda in the culture of *C. gariepinus* (Limbu 2020b). The on-farm formulated diet reduced feed cost up to 30%, leading to better protein retention and healthier fish. Moreover, fish farmers in Africa feed the supplemental feeds and fertilization in semi-intensive production due to unaffordable commercial feeds. Accordingly, *O. niloticus* farmers in Tanzania fed their fish on mixed ingredients and rice bran alone (RB) diets complemented with fertilization in earthen ponds

Table 1.1 The feeding practices used in African aquaculture

Feeding approach; country	Species and growth stage; study time	Effects	References
Mixed feeding schedules with low and high protein; Nigeria	*Clarias gariepinus* fingerling; 8 weeks	Feeding continuously with high protein was more economical	Morenike and Akinola (2010)
Different feeding regimes; Egypt	*Oreochromis niloticus* fingerling; 10 weeks	Fasted and re-fed once or twice every other day and fasted and re-fed twice every third day compensated for growth Fasting improved antioxidant status	El-Araby et al. (2020)
Restricted and re-feeding regime; Tanzania	*Oreochromis niloticus* fingerling; 8 weeks	Reduced feeding cost by 10 and 20% for depriving feed for 1 and 2 days, respectively	Limbu and Jumanne (2014)
On-farm and industrially manufactured feeds; Uganda	*Clarias gariepinus* juveniles; 8 weeks	On-farm feed reduced feed cost up to 30%, had better protein retention and healthier fish	Limbu (2020b)
Mixed ingredients and rice bran alone diets; Tanzania	*Oreochromis niloticus* and *Clarias gariepinus* juveniles; 38 weeks	No effect on performance in semi-intensive earthen ponds with fertilization	Limbu et al. (2016)
Three different feeding regimes; Zambia	*Oreochromis macrochir*; 34 weeks	Feed and manure increased fish growth	Lundeba et al. (2022)

(Limbu et al. 2016). In this study, no differences on growth and feed utilization were evident, indicating that semi-intensively cultured fish can be reared on simple feeds when fertilization is conducted. In a relatively related fashion, Lundeba et al. (2022) conducted a participatory on-field study on tilapia, *Oreochromis macrochir* in Zambia utilizing three feeding regimes namely formulated feed only, fertilization and formulated feed and fertilization together. The fish maintained by feeding and fertilization increased survival rate, weight gain, specific growth rate, total amount of fish harvested and yield.

In a nutshell, these studies show that aquaculture in Africa uses various feeding practices aimed at ensuring optimum growth of cultured fish, enhanced feed efficiencies and reduced feed cost for the sustainability of the industry. The effective utilization of feeding practices, such as restricted and re-feeding, could improve growth and production upon re-feeding and save substantial feed costs for sustainable fish production to feed the ever-increasing human population in Africa.

1.3 Feeding Technologies Used in African Aquaculture

Feeding technology is one of the most important aspects for increased growth performance, survival rate and ultimately production of cultured species. The ability to use appropriate feeding technology also determines the profitability of aquaculture due to enhanced utilization of nutrients. The African aquaculture also uses various technologies to improve utilization of plant-based ingredients, which have limited nutritional value in fish. One such approach is to ferment the ingredients used to enhance the nutritional availability. Accordingly, the fermentation process has been used for sunflower by using *Saccharomyces cerevisiae* or *Bacillus subtilis* (Hassaan et al. 2018), palm seed meal fermented with *Aspergillus oryzae* (Dawood et al. 2020d) and poultry by-product meal by using yeast (Dawood et al. 2020i) in Nile tilapia and Common carp (*Cyprinus carpio*) (Dawood et al. 2020h).

Moreover, rice bran fermented by using *Bacillus subtilis* was used in white leg shrimp (*Litopenaeus vannamei*) reared at different salinities (Abdel-Tawwab et al. 2020a). In these studies, fermentation greatly increased the nutritional quality and value of plant by-products in practical diets (Hassaan et al. 2018), improved growth, digestion activity and immune response (Dawood et al. 2020d, h) and enhanced growth performance and health condition (Dawood et al. 2020i) of the cultured fish. In crustaceans, fermentation enhanced growth performance, antioxidant systems and innate immunity (Abdel-Tawwab et al. 2020a).

Apart from fermentation process, various technologies have also been used in African aquaculture for improving growth and health. These include dietary supplementation with lactic acid bacteria-produced nanoselenium spheres (Dawood et al. 2020m) and xylanase (Hassaan et al. 2019b) in Nile tilapia and heat-killed *Lactobacillus plantarum* (HK L-137) in genetically improved farmed tilapia (GIFT) (Dawood et al. 2019). Expectedly, lactic acid supplementation improved growth, oxidative status and immune-related gene expression (Dawood et al. 2020m), enhanced growth, protein digestibility and digestive enzymes activities (Hassaan et al. 2019b) and heat-killed *L. plantarum* promoted growth performance, feed utilization, digestive enzyme activity, fish health and modulated nutrients metabolism (Dawood et al. 2019).

It is clear from these studies that fermentation as a feeding technology holds potential application in African aquaculture for improved growth, nutrients digestion and health of cultured fish and crustaceans. This might be one of the strategies for improving utilization of plant-based ingredients for sustainable African aquaculture. Moreover, supplementation of different treated bacteria, such as heat killed, is an effective strategy to enhance growth, nutrients utilization and health for sustainable fish production in Africa.

1.4 Fishmeal and Soybean Replacement in African Aquaculture

Historically, fishmeal has been used as an important high-quality animal protein ingredient for aquaculture feeds production for most commercially farmed fish species (Luthada-Raswiswi et al. 2021; Limbu et al. 2022). However, fishmeal as a source of protein for aquafeed industry is expensive and has limited supply. The high prices and limited supply have tempted research in African aquaculture for alternatives to replace fishmeal (Dawood and Koshio 2020). Indeed, several studies have been conducted on fishmeal replacement in African aquaculture (Table 1.2). Most studies on fishmeal replacement were conducted in Egypt on *O. niloticus* with a few on European sea bass, *Dicentrarchus labrax* (Sallam et al. 2022), Grey mullet, *Mugil cephalus* (Abo-Taleb et al. 2021a, b; Ashour et al. 2021a), Common sole*, Solea solea* (Saleh et al. 2021) (Table 1.2). This is not surprising because Egypt is the leading country in African aquaculture production (FAO 2020, 2022) and it is the third producer of *O. niloticus* in the world (Dawood et al. 2020c). Moreover, a few studies on fishmeal replacement have also been conducted in other countries, such as Kenya (Kirimi et al. 2017; Ogello et al. 2017), Nigeria (Solomon et al. 2010; Olude and Badmus 2015), Zambia (Yossa et al. 2021) and Tanzania (Limbu et al. 2022). Results from these studies indicated total fishmeal replacement without adverse effect on *O. niloticus* fingerlings performance by using soybean meal (El-Saidy and Gaber 2002), shrimp meal, meat and bone meal, bone meal and poultry by-products meal (El-Sayed 1998) and plant protein mixture in *O. niloticus* juveniles in Egypt (El-Saidy and Gaber 2003). Moreover, complete replacement of fishmeal was reported in Grey mullet, *Mugil cephalus,* fry by using zooplankton biomass meal in Egypt (Abo-Taleb et al. 2021b) and a single cell protein feedstuff for *O. niloticus* fingerlings in Zambia (Yossa et al. 2021). The findings from these studies pinpoint at the possibility of replacing total fishmeal for sustainable African aquaculture industry.

Notwithstanding the above findings, several other ingredients partially replaced fishmeal in the diets for various fish species in African aquaculture, such as earthworm, *Eisenia fetida*, bedding meal in *O. niloticus* fingerlings in Kenya (Musyoka et al. 2020), *Daphnia magna* meal up to 75 to 100% for *M. cephalus* larvae in Egypt (Abo-Taleb et al. 2021a), black soldier fry larvae diet up to 75 to 84% for *O. niloticus* fry in Tanzania (Limbu et al. 2022) and methylated soy protein isolates at 66% in *O. niloticus* fingerlings in Egypt (Amer et al. 2020). Furthermore, partial fishmeal replacement of up to 50% has been reported by using amphipod meal, *Gammarus pulex* for *M. cephalus* fry (Ashour et al. 2021a) and broad bean meal for *O. niloticus* fry both in Egypt (Gaber 2006) and blood meal in *O. niloticus* juveniles in Kenya (Kirimi et al. 2017). Moreover, further lower partial fishmeal replacement has been reported by using whey protein of up to 45% in *D. labrax* juveniles (Sallam et al. 2022), soybean protein concentrate of up to 35% in Common sole, *Solea solea* post-larvae (Saleh et al. 2021) and whey protein concentrate up to 27.7% in *O. niloticus* fingerlings in Egypt (Amer et al. 2019), a mixture of moringa (*Moringa oleifera*) leaf

Table 1.2 The ingredients used for fishmeal and soybean replacement in African aquaculture

Ingredient used; country	Species and growth stage; study time	Effects	References
Fishmeal replacement			
Soybean meal; Egypt	*Oreochromis niloticus* fingerlings; 10 weeks	• Improved growth performance, feed utilization, nutrients digestibility and food intake	El-Saidy and Gaber (2002)
Shrimp meal, blood meal, meat and bone meal, their mixture and poultry by-product meal; Egypt	*Oreochromis niloticus* fingerlings; 21 weeks	• No difference on growth and body composition • Reduced feed utilization • Higher ash contents • Economically superior to fishmeal	El-Sayed (1998)
A plant protein mixture; Egypt	*Oreochromis niloticus* juveniles; 16 weeks	• No difference on growth and body composition • Reduced apparent protein digestibility for 100% fishmeal replacement • Economically superior to fishmeal	El-Saidy and Gaber (2003)
Three plant protein sources extruded soybean meal, extruded full-fat soybean and corn gluten meal; Egypt	*Oreochromis niloticus* and tilapia galilae *Sarotherodon galilaeus* fingerlings; 17 weeks	• Reduced growth performance and feed intake for Nile tilapia fed on plant protein • Increased growth performance for *Tilapia galilae* fed on soybean meal diet • Better feed conversion ratio for Nile tilapia and *Tilapia galilae* fed on soybean meal diet	Goda et al. (2007)
Methylated soy protein isolates; Egypt	*Oreochromis niloticus* fingerlings; 10 weeks	• Increased growth performance, phagocytic index, immunoglobulin M level and lysozyme activity post-bacterial challenge • Increased liver and intestine histomorphological structures with an increased level of replacement • Increased the total return, net profit, and performance index % for methylated soy protein	Amer et al. (2020)

(continued)

Table 1.2 (continued)

Ingredient used; country	Species and growth stage; study time	Effects	References
Whey protein concentrate; Egypt	*Oreochromis niloticus* fingerlings; 10 weeks	• Increased immunity parameters as whey concentrate replacement increased • Increased liver damage as whey concentrate replacement increased • Total return increased with whey protein replacement increased • Increased cysteine-aspartic acid protease 3 activity	Amer et al. (2019)
Whey protein; Egypt	European sea bass, *Dicentrarchus labrax* juveniles; 10 weeks	• No difference on growth, feed utilization and survival up to 45% fishmeal replacement • Total immunoglobulin and complement 3 increased up to 15% and 30% replacement of FM by whey protein • Increased liver and kidney function enzymes with increasing whey protein incorporation levels • Enhanced histopathological signs at high fishmeal substitution by whey protein	Sallam et al. (2022)
Zooplankton biomass meal; Egypt	Grey mullet, *Mugil cephalus* fry; 8 weeks	• Increased growth performance and feed utilization for fish fed on 100% zooplankton biomass meal • Improved intestinal villus length, crypts depth and muscle thickness with zooplankton biomass meal inclusion • No histopathological changes on fish fed on zooplankton biomass meal • Reduced diet cost formulation by 18% and the price per kg weight gain by about 40%	Abo-Taleb et al. (2021b)
Daphnia magna meal; Egypt	Grey mullet, *Mugil cephalus* larvae; 8 weeks	• Higher growth, and feed utilization parameters for fish fed on 75%	Abo-Taleb et al. (2021a)

(continued)

Table 1.2 (continued)

Ingredient used; country	Species and growth stage; study time	Effects	References
		Daphnia magna • Improved intestinal histomorphometric indices and goblet cell number with increasing *Daphnia magna* inclusion levels. • Reduced feed cost and incidence cost, and the increased profit index and economic efficiency ratio for fish fed on 100 *Daphnia magna*	
Amphipod meal, *Gammarus pulex*; Egypt	Grey mullet, *Mugil cephalus* fry; 8 weeks	• Increased growth performance and survival rate of fish fed on 50% amphipod meal • Enhanced feed utilization of diets for fish fed on 50% amphipod meal • Increased number of goblet cells and intestinal villi for fish fed on 50% amphipod meal • Better economic conversion ratio for fish fed on 50% amphipod meal	Ashour et al. (2021a)
Cotton seed meal; Egypt	*Oreochromis niloticus* juveniles; 10 weeks	• Improved growth performance, feed utilization efficiency and digestibility for fish fed on 2:1 and 1.1 fishmeal: cotton seed meal	Hassaan et al. (2019a)
Soybean protein concentrate; Egypt	Common sole*, Solea solea* post-larvae; 6 weeks	• No difference in growth and survival up to 50% replacement • Increased aspartate and alanine aminotransferases activities • Increased oxidative stress biomarkers • Increased hepatocyte infiltration and massive lipid accumulations in fish fed with 75% and 100% soybean protein diets	Saleh et al. (2021)
Poultry offal silage; Egypt	*Oreochromis niloticus* fingerlings; 16 weeks	• No differences on growth performance • Increased feed	Eissa et al. (2022)

(continued)

Table 1.2 (continued)

Ingredient used; country	Species and growth stage; study time	Effects	References
		efficiency on fish fed on poultry offal silage and fishmeal with betaine supplementation	
Sunflower cake and corn oil; Kenya	*Oreochromis niloticus* fingerlings; 10 weeks	• Higher linoleic acid on fish fed on sunflower cake	Maina et al. (2003)
Earthworm, *Eisenia fetida*, bedding meal; Kenya	*Oreochromis niloticus* fingerlings; 16 weeks	• No differences in mortalities, growth and feed efficiency • Superior amino acid profile, low fibre content and fish carcass crude protein • Higher mean weight gain and biomass for fish fed on 30% earthworm and fishmeal, respectively • Higher crude lipids content, economic returns and profit index for fish fed on 100% earthworm	Musyoka et al. (2020)
Broad bean meal; Egypt	*Oreochromis niloticus* fry; 16 weeks	• Comparable growth performance between fish fed on 50% broad meal and fishmeal • Decreased protein, energy and lipid digestibility of fish fed on broad bean meal above 50%	Gaber (2006)
Soybean meal; Egypt	*Oreochromis niloticus* fingerlings; 10 weeks	• Improved growth rate, feed utilization and food intake for fish fed on 55% soybean meal • Enhanced protein content of fish fed on 55% soybean meal	El-Saidy and Gaber (2002)
Sunflower seed meal; Kenya	*Oreochromis niloticus* juveniles; 14 weeks	• Similar growth for sunflower up to 25% • Similar nutrient utilization parameters in all diets except for sunflower 100%	Ogello et al. (2017)
Blood meal; Kenya	*Oreochromis niloticus* juveniles; 14 weeks	• Reduced essential amino acid levels	Kirimi et al. (2017)
A mixture of moringa (*Moringa oleifera*) leaf and kernel meal; Nigeria	*Clarias gariepinus* juveniles; 8 weeks	• Increased weight gain and specific growth rate of fish reared on control and	Olude and Badmus (2015)

(continued)

Table 1.2 (continued)

Ingredient used; country	Species and growth stage; study time	Effects	References
		20% moringa leaf and kernel meal • Better protein efficiency ratio for fish fed on control and 20% moringa leaf and kernel meal	
Silkworm caterpillar (*Anaphe infracta*) meal; Nigeria	*Heterobranchus bidorsalis* fingerlings; 8 weeks	• Better weight gain, specific growth rate, food conversion ratio and protein efficiency ratio for fish fed on 50% silkworm caterpillar meal	Solomon et al. (2010)
Duckweed, *Lemna minor* meal; Nigeria	*Oreochromis niloticus* fry; 10 weeks	• Comparable growth performance between fish fed on fishmeal and 15% duckweed diet meal	Ofojekwu et al. (2010)
A single cell protein feedstuff; Zambia	*Oreochromis niloticus* fingerlings; 12 weeks	• No effect on weight gain or gut length and weight for fish fed on 2 to 100% single cell protein • Improved feed and nutrient utilization for fish fed on 2 to 100% single cell protein • No gastrointestinal tract histopathology	Yossa et al. (2021)
Black soldier fry larvae meal; Tanzania	*Oreochromis niloticus* fry; 12 weeks	• Increased specific growth rate, total weight gain, Zihler's index of fry and nitrate in the culture water for fish fed on 75% black soldier fry larvae meal • Reduced feed conversion ratio of diet and total suspended solids in the culture water for fish fed on 75% black soldier fry larvae meal • Reduced incidence cost by 32% and 29% and increased profit index by 4% and 3%, respectively, for fry fed on 75% and 100% black soldier fry larvae meal	Limbu et al. (2022)

(continued)

Table 1.2 (continued)

Ingredient used; country	Species and growth stage; study time	Effects	References
Soybean meal replacement			
Cottonseed meal; Egypt	*Oreochromis niloticus* fingerlings; 14 weeks	• No difference on growth up to 75% replacement of soy bean meal with cottonseed meal • Reduced feed utilization efficiency at higher cottonseed meal levels • No difference on moisture, lipid and ash content in whole body and muscle	El-Saidy and Saad (2011)
Leaf protein concentrate from Sugar beet, *Beta vulgaris* and carrot, *Daucus carota*; Egypt	*Oreochromis niloticus* fingerlings; 12 weeks	• No differences in the growth, feed intake and feed conversion ratio indices • No differences on blood biochemical and haematological parameters • Increased condition factor for fish fed on carrot and sugar beet meal • Depleted crude lipid in fish fed on 50% sugar concentrate • Lower feeding cost and best profit margin for fish fed on 100% carrot protein	Ayyat et al. (2021)
Cassia fistula seed meal; Nigeria	*Oreochromis niloticus* fingerlings; 10 weeks	• Reduced growth, diet utilization efficiency, survival rate, digestibility, protein content in fish fed *Cassia fistula* seed meal at varying inclusion levels • Similar feed conversion ratio, specific growth rate and protein efficiency ratio of fish fed on 170 g kg^{-1} to the control diet • Fish fed on 170 g kg^{-1} had efficient cost per unit weight gain	Adebayo et al. (2004)
Shrimp by-products; Egypt	African catfish, *Clarias lazera* fingerlings; 12 weeks	• Increased growth and nutrient utilization parameters, plasma proteins and immunity in fish fed on 50% shrimp by-products • Increased body dry	Abu-Alya et al. (2021)

(continued)

Table 1.2 (continued)

Ingredient used; country	Species and growth stage; study time	Effects	References
		matter and crude protein for fish fed on shrimp by-products • Decreased diet costs and diet costs per 1 kg of weight gain	
Black soldier fry larvae meal; Kenya	*Oreochromis niloticus* juveniles; 12 weeks	• Increased final body weight, body weight gain, specific growth rate, feed conversion ratio, survival rate and condition factor • Increased phenylalanine, threonine, isoleucine, lysine, proline and glutamic acid amino acids • Reduced cost of production	Shati et al. (2022)

and kernel meal (1:1) of up to 20% in *C. gariepinus* juveniles (Olude and Badmus 2015) and 15% dietary duckweed meal in *O. niloticus* fry (Ofojekwu et al. 2010) in Nigeria. These studies suggest partial fishmeal replacement is possible by using various plant-based ingredients. To achieve complete fishmeal replacement, feeding techniques are required to increase plant-based proteins utilization in African aquaculture.

Various approaches have been used to improve the utilization of plant-based protein sources to replace fishmeal. Accordingly, 55% soybean meal supplemented with 0.5% L-lysine totally replaced fishmeal in *O. niloticus* fingerlings (El-Saidy and Gaber 2002). Furthermore, both extruded soybean meal and extruded full-fat soybean supplemented with DL-methionine and L-lysine completely replaced dietary fishmeal in *Sarotherodon galilaeus* fingerlings in Egypt (Goda et al. 2007). Moreover, poultry offal silage supplemented with 0.7% betaine replaced fishmeal in *O. niloticus* fingerlings in Egypt (Eissa et al. 2022), while an exogenous protease enzyme improved growth, nutrient assimilation and haematology of *O. niloticus* juveniles fed on cotton seed meal (Hassaan et al. 2019a). These studies suggest that the nutritional quality of plant-based protein contained in various ingredients for fishmeal replacement can be improved by various techniques. Fully utilization of these techniques at farm level holds the potential for increased aquaculture production in Africa.

Interesting, most ingredients used to replace fishmeal in African aquaculture resulted in reduced feed costs and thus increased economic returns (Table 1.2). Such studies were evident in *O. niloticus* when fishmeal was replaced by shrimp meal, blood meal, meat and bone meal, their mixture and poultry by-product meal

(El-Sayed 1998), a plant protein mixture (El-Saidy and Gaber 2003), methylated soy protein isolates (Amer et al. 2020), whey protein concentrate (Amer et al. 2019) and black soldier fry larvae diet (Limbu et al. 2022). Moreover, reduced diet cost was reported after fishmeal was replaced by zooplankton biomass meal (Abo-Taleb et al. 2021b), amphipod meal (Ashour et al. 2021a) and *Daphnia magna* meal (Abo-Taleb et al. 2021a) in *Mugil cephalus*. These studies highlight that feeding cost can be reduced in aquafeed industry by using various ingredients in African aquaculture to ensure sustainable production.

Despite the existence of studies using soybean meal to replace fishmeal, the former is also expensive and requires replacement. Therefore, several studies have been conducted in African aquaculture to replace soybean meal in various species without any adverse effects on growth and feed utilization efficiency. Indeed, carrot leaf protein concentrate replaced 100% of soybean meal in *O. niloticus* fingerlings without any negative effects on growth and blood constituents in Egypt (Ayyat et al. 2021), while black soldier fly meal replaced soybean meal up to 100% without negative effect on growth and carcass body composition (Shati et al. 2022). Moreover, up to 41.25% cotton seed mean replaced 75% of soybean protein in Nile tilapia fingerlings without any adverse effects on the growth performance, feed utilization, body composition and haematological indices (El-Saidy and Saad 2011). Furthermore, sugar beet leaf concentrate replaced 50% of soybean in *O. niloticus* fingerlings without any negative effects on growth and blood constituents (Ayyat et al. 2021). In addition, 25% duckweed replaced soybean meal protein obtaining the best growth performance and feed utilization in *O. niloticus* fingerlings (Ibrahim et al. 2017). Despite growth performance and feed utilization efficiency, various ingredients replaced soybean meal in African aquaculture to reduce feed cost and improve economic performance. Accordingly, 50% acid-treated shrimp by-products positively influenced productive and economic performances of African catfish, *Clarias lazera* fingerlings in Egypt (Abu-Alya et al. 2021) and 17% *Cassia fistula* seed meal was the most efficient diet in terms of cost per unit weight gain of *O. niloticus* fingerlings in Nigeria (Adebayo et al. 2004). Moreover, 50 and 100% black soldier fly reduced production cost in *O. niloticus* juveniles in Kenya (Shati et al. 2022). These findings indicate that soybean meal can be replaced by various ingredients in African aquaculture without adverse effects on growth performance and nutrients utilization at a lower cost for sustainability of the industry.

In general, fishmeal is limited and its price is prohibitively expensive in most African countries. Therefore, many African countries are investigating ingredients for complete and/or partial replacement of fishmeal by using low-cost and locally available plant by-products for use in fish grow-out facilities (Obirikorang et al. 2015). Moreover, although soybean holds the qualities as a potential plant-based ingredient for fishmeal replacement, it is also expensive and sources are limited. Accordingly, several studies have been conducted in African aquaculture for replacing soybean. Fishmeal and soybean are both expensive feedstuff in the aquafeed, which limit aquaculture development. The future of African aquaculture development should be directed towards overcoming the dependency on fishmeal and soybean by using other ingredients while ensuring environmental sustainability

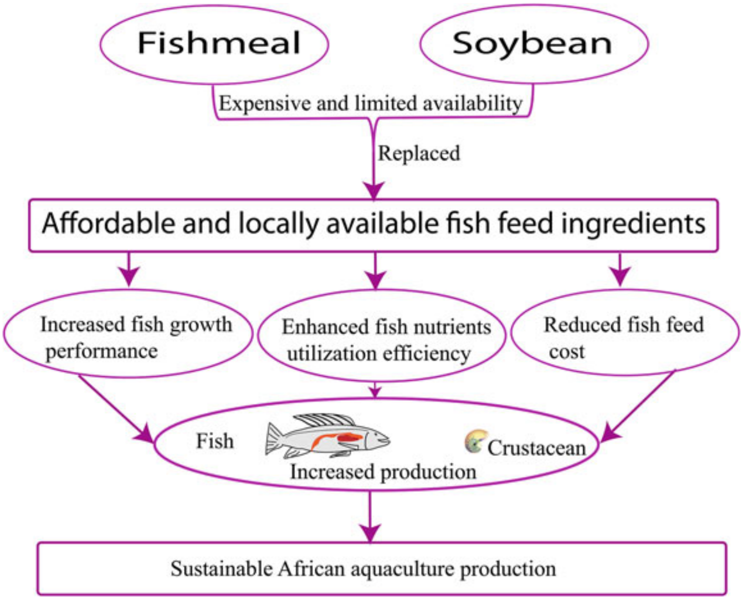

Fig. 1.1 Hypothetical consequences of replacing expensive and limited availability fishmeal and soybean by using cheap and locally available feed ingredients in African aquaculture

to provide enough protein for the increasing human population in the continent (Fig. 1.1). African aquaculture nutritionists should explore various ingredients, including edible crickets, which lacks information on its potential utilization as an ingredient in the aquaculture industry (Magara et al. 2021).

1.5 Feed Additives Used in African Aquaculture

The use of additives as growth enhancers, immunostimulants, disease-controlling agents and anaesthetics in African aquaculture is a common practice (Ashry et al. 2022; Gabriel et al. 2022). Most studies on feed additives were conducted in Egypt by using *O. niloticus* similar to fishmeal and soybean replacement above due to the reasons given before in this chapter. Additives are used for various purposes in African aquaculture production as discussed in the following sections (Table 1.3).

Table 1.3 The various feed additives used in African aquaculture for numerous functions

Feed additive and country	Species, growth stage and time	Purpose	Effect	References
Triticale; Egypt	*Oreochromis niloticus* juveniles; 8 weeks	Dietary feed additive as protein and carbohydrate source	• No effect on growth performance indices up to 20% • Increased lipid content for fish fed on 20% • Decreased amylase, lipase and protease for fish fed on 20% • No effect on haematological and biochemical blood parameters • Increased superoxide dismutase and glutathione peroxidase	Dawood et al. (2020c)
Inorganic, organic, and elemental nanoselenium; Egypt	*Oreochromis niloticus* fingerlings; 9 weeks	Selenium nanoparticles	• Enhanced growth performance • Increased haematological and immunity parameters • Reduced lipid peroxidation	Ghaniem et al. (2022)
Oregano essential oil; Egypt	Common carp, *Cyprinus carpio* fingerlings; 8 weeks	Dietary feed additive as a phytobiotic growth promoter	• Improved growth parameters and feed intake • No effects on body composition and haematological parameters • No histological damages on kidney and intestine	Abdel-Latif et al. (2020)
Curcumin; Egypt	*Oreochromis niloticus* juveniles; 8 weeks	Alleviate negative effects of melamine toxicity	• Alleviated the negative effect on growth performance and lipid composition • Enhanced haematological reduced by melamine • Improved antioxidant capacity • Increased survival rate of fish after bacteria challenge	Abd El-Hakim et al. (2020)

Turmeric powder alone or plus black pepper powder; Egypt	*Clarias gariepinus* juveniles; 4 weeks	Alleviate negative effects of cadmium toxicity	• Alleviated adverse effects on growth rate for fish fed on turmeric and pepper powders • Reduced kidney and liver toxicity on fish fed on turmeric and pepper powders • Improved antioxidant capacity and reduced lipid peroxidation for fish fed on turmeric and pepper powders • Restored depleted ATP for fish fed on turmeric and pepper powders • Normal hepatic histomorphological structures for fish fed on turmeric and pepper powders	El-Houseiny et al. (2019)
Curcumin; Egypt	*Oreochromis niloticus* fingerlings; 12 weeks	Dietary feed additive for growth performance and general fish health	• Inhibited *Aeromonas hydrophila* and *A. sobria* • Increased growth performance and survival rate indices • Better feed conversion and protein efficiency ratios • Increased catalase and reduced glutathione content • Decreased malondialdehyde level	Mahmoud et al. (2017)
Cucurbita mixta seed meal	*Oreochromis mossambicus* juveniles; 4 weeks	Immunostimulant	• Enhanced survival rate, weight gain, protein efficiency ratio, specific growth rate, feed conversion ratio and feed efficiency • Enhanced complement activity, phagocytic activity, respiratory burst activity and lysosome activity	Musthafa et al. (2017)

(continued)

Table 1.3 (continued)

Feed additive and country	Species, growth stage and time	Purpose	Effect	References
Curcumin; Egypt	*Oreochromis niloticus* fingerlings; 10 weeks	Immunostimulant	• Enhanced feed conversion ratio, fish body protein and ash contents but decreased body fat content • Increased villus height and width and upregulated tumor necrosis factor alpha and cysteine-aspartic acid protease 3 • Increased serum catalase activity and reduced glutathione level • Boosted serum superoxide dismutase activity and reduced the malondialdehyde level • Increased lysosome, complement 3, interleukin 10 and immunoglobulin M levels • Increased fish survival rate challenged with *Aeromonas hydrophila*	Amer et al. (2022)
Glycyrrhiza glabra extract and protexin concentrate; Egypt	*Oreochromis niloticus* fingerlings; 12 weeks	High stocking density stressor attenuator	• Increased growth, antioxidant, immunity and bacterial disease resistance of fish	Mahmoud et al. (2021)
Moringa oleifera seeds and leaves; Egypt	*Oreochromis niloticus* juveniles; 4 weeks	Ameliorative of chlorpyrifos health disturbances	• Counteracted the chlorpyrifos-induced adverse impacts on growth performance and health	Ibrahim et al. (2019)
Natural clay, coumarin, curcumin, vitamin C, probiotics and prebiotics; Egypt	*Oreochromis niloticus* fingerlings; 14 weeks	Safe feed additives for alleviating aflatoxin B_1 toxicity	• Higher growth rate for fish fed on vitamin C and aflatoxin • Better feed conversion ratio for fish fed on bentonite and Bio-Mos® • Increased haemoglobin, total erythrocyte, total protein, albumin	Ayyat et al. (2018)

			and globulin in fish fed on feed additives	
Lemongrass (*Cymbopogon citratus*) and geranium (*Pelargonium graveolens*) essential oils; Egypt	*Oreochromis niloticus* fry; 12 weeks	Immunostimulant	• Improved growth indices and feed utilization • Increased protein content of the whole body • Increased catalase activity and reduced glutathione and malondialdehyde levels • Increased lysozyme activity and total immunoglobulin M levels • Increased survival rate after *Aeromonas hydrophila* challenge	Al-Sagheer et al. (2018)
Moringa oleifera aqueous extract; Egypt	*Oreochromis niloticus* fingerlings; 12 weeks	Growth and immunity stimulator	• Enhanced final weight, weight gain, specific growth rate, red blood cells, haemoglobin, packed cell volume, white blood cells and total serum protein in fish fed 200 mg moringa/kg diet • Severe histological degenerative changes in the gills and liver of fish fed 400 mg moringa/kg diet • Positive cysteine-aspartic acid protease 3 cells in fish fed 400 mg moringa/kg diet	Emam et al. (2021)
Oregano essential oil; Egypt	*Oreochromis niloticus* juveniles; 8 weeks	Ameliorative of long-term acute heat stress	• Enhanced final weight, weight gain and specific growth rate • Increased villi length and width • Reduced aspartate aminotransferase and alanine aminotransferase • Increased total protein, albumin and globulin levels	Magouz et al. (2022)

(continued)

Table 1.3 (continued)

Feed additive and country	Species, growth stage and time	Purpose	Effect	References
			• Increased superoxide dismutase, catalase, phagocytic index and lysozyme activity • Decreased malondialdehyde content and relative expression of heat shock protein 70	
Mannan oligosaccharides and β-glucans; Egypt	*Oreochromis niloticus* juveniles; 8 weeks	Ameliorate lead reproductive toxicity	• Increased body weight, gonadal somatic index, estradiol, testosterone, gonadal antioxidant enzymes • Reduced cortisol, glucose and gonadal malondialdehyde	El-Fahla et al. (2022)
Aspergillus oryzae; Egypt	*Oreochromis niloticus* juveniles; 12 weeks	Alleviating salinity stress	• Decreased glucose, cortisol, alanine transaminase, aspartate transaminase and malondialdehyde • Increased albumin, globulin, total protein, lysozyme activity, phagocytic activity, phagocytic index, glutathione peroxidase, catalase and superoxide dismutase • Downregulated mRNA expression values of heat shock protein 70 and interferon-gamma genes, and upregulated interleukin 1 beta and interleukin 8 genes	Shukry et al. (2021)
Zinc sulphate; Egypt	*Oreochromis niloticus* juveniles; 3 weeks	Ameliorate nonylphenol toxicity	• Reduced haemolytic anaemia, leukocytosis, hyperbilirubinaemia, hyponatraemia, hyperkalaemia, azotemia, hyperproteinaemia, hypoalbuminaemia, hyper alpha1-	Mohamed et al. (2019)

			globulinaemia, hyper alpha2- and beta-globulinaemia, and hypogammaglobulinaemia • Reduced aspartate aminotransferase and alanine aminotransferase • Reduced lactate dehydrogenase, ammonia, cholesterol, creatinine, malondialdehyde, myeloperoxidase and tumor necrosis-alpha • Increased alkaline phosphatase, immunoglobulin M, complement 3, lysozyme activity and nitric oxide • Reduced hepatic and renal structural damages	
Silybum marianum and/or coenzyme Q10; Egypt	*Clarias gariepinus* adults; 8 weeks	Alleviate fluoride negative effects	• Increased weight gain and specific growth rate and reduced hepatosomtic index • Reduced leukopaenic and anaemic condition • Decreased serum, hepatic enzymes and kidney damage • Enhanced non-enzymatic and enzymatic antioxidants and reduced lipid peroxidation product • Enhanced lysozyme activity, complement 3, nitric oxide, total proteins, albumin and γ globulin contents in the serum • Reduced pathological alterations in the liver, kidney, and spleen • Increased survival rate	El-Houseiny et al. (2022)

(continued)

Table 1.3 (continued)

Feed additive and country	Species, growth stage and time	Purpose	Effect	References
			percentage after 14 days of *Aeromonas sobria* challenge	
Coenzyme Q10 and vitamin C; Egypt	*Oreochromis niloticus* juveniles; 8 weeks	Feed additive to improve growth performance and health	• Increased feed intake, amylase, lipase and protease activities • Decreased glucose, cortisol, total cholesterol, triglycerides and increased total protein • Increased superoxide dismutase and catalase activities and genes expression • Increased percentage survival rate of fish after *Streptococcus agalactiae* challenge	El Basuini et al. (2021)
Yucca extract; Egypt	*Cyprinus carpio* juveniles; 4 weeks	Ammonia absorbent	• Increased growth performance, survival rate, total protein, albumin and globulin • Reduced feed conversion ratio, uric acid, urea, creatinine, aspartate aminotransferase, alkaline phosphatase and alanine aminotransferase • Downregulated mRNA expression of heat shock protein, interleukin 8, tumor necrosis factor alpha, interferon gamma and interleukin 1 beta	Dawood et al. (2021b)
Sodium butyrate; Egypt	*Oreochromis niloticus* juveniles; 8 weeks	Nanoparticles dietary feed additives	• Increased final body weight, weight gain percentage, specific growth rate, feed intake, serum amylase, lipase and protease	Abdel-Tawwab et al. (2021c)

			activities • Increased villi length/width, crypt depth, surface absorption area and goblet cells	
Ziziphus mauritiana leaf powder; Egypt	*Oreochromis niloticus* fingerlings; 12 weeks	Dietary feed additive for growth and general health	• Increased body weight, weight gain percentage, feed intake, feed efficiency ratio, protein efficiency ratio and apparent protein utilization • Increased serum ion Na+ and Ca ++ • Upregulated insulin-like growth factor and ghrelin genes expression • Increased intestinal mucosal folds, heights, widths, area and perimeter of the villi and thickness of muscular layers	Amin et al. (2019)
Phosphorus supplemented with phytase enzyme; Egypt	*Oreochromis niloticus* juveniles; 8 weeks	Mineral supplement with digestive enhancer	• Increased final body weight, total body gain, average daily gain and weight gain for fish fed on 50% phosphorus and 500 or 1000 phytase units/kg • Improved immune response parameters • Reduced pathological lesions in the liver, spleen, stomach and intestine	Abo Norag et al. (2018)
Lycopene and/or resveratrol; Egypt	*Oreochromis niloticus* juveniles; 4 weeks	Ameliorate nanozinc oxide toxicity	• Reduced aspartate aminotransferase, alanine aminotransferase, alkaline phosphatase, cholesterol, urea and creatinine • Increased total proteins and albumin serum levels	Abdel-Daim et al. (2019)

(continued)

Table 1.3 (continued)

Feed additive and country	Species, growth stage and time	Purpose	Effect	References
			• Decreased malondialdehyde and increased reduced glutathione levels and superoxide dismutase and catalase activities	
Aspergillus oryzae and β-glucan; Egypt	*Oreochromis niloticus* fingerlings; 8 weeks	Synbiotic functional feed additive	• Increased growth performance and feed efficiency • Enhanced blood haematocrit, haemoglobin, red and white blood cells, total protein and digestive enzymes • Decreased blood triglyceride • Enhanced glutathione peroxidase and reduced malondialdehyde • Enhanced nitro blue tetrazolium, immunoglobulin M, lysozyme, bactericidal and phagocytosis	Dawood et al. (2020f)
Pyrazole derivatives; Egypt	*Clarias gariepinus* adult; 4 weeks	Ameliorate lead nitrate toxicity	• Reversed alterations in biochemical parameters, antioxidant biomarkers, lipid peroxidation, hepatic DNA damage and histopathological changes in liver	Soliman et al. (2019)
Green tea (*Camellia sinensis*) extract; Egypt	*Clarias gariepinus* adults; 2 weeks	Protective against 4-nonylphenol toxicity	• Increased serum glucose, aspartate aminotransferase, alanine aminotransferase, total protein, total lipids, cholesterol, glucose-6-phosphate dehydrogenase and cortisol • Increased serum acetylcholinesterase, alkaline phosphatase and lactate dehydrogenase	Sayed and Soliman (2018)

			• Increased superoxide dismutase, catalase, glutathione S-transferase and total antioxidant capacity • Reduced hepatic lipid peroxidation, DNA fragmentation and apoptosis • Reduced liver histopathological effects	
Anise (*Pimpinella anisum*); Egypt	*Dicentrarchus labrax* juveniles; 17 weeks	Dietary feed additive for fish growth and health	• Enhanced growth performance and reduced feed conversion ratio • Increased haematocrit, red blood cell, haemoglobin and white blood cells	Ashry et al. (2022)
Spirulina platensis; Egypt	*Clarias gariepinus* fingerlings; 2 weeks	Protection against hydroxychloroquine toxicity	• Normal haematological and biochemical indexes as well as antioxidant levels and the histological architecture	Sayed et al. (2021)
Spirulina platensis; Egypt	*Clarias gariepinus* adults; 4 weeks	Protection against lead nitrate toxicity	• Dietary inclusion of *Spirulina platensis* ameliorated cytotoxic and genetic changes in a time and dose dependent	Hamed et al. (2019)
Spirulina platensis; Egypt	*Clarias gariepinus* adults; 2 weeks	Protection against sodium dodecyl sulphate toxicity	• Dietary *Spirulina platensis* restored hepatic and renal dysfunction, electrolytes imbalance, as well as enzymatic and non-enzymatic antioxidants disruption, and micronuclei and apoptosis percentages in erythrocytes close to control treatment	Sayed and Authman (2018)
Spirulina platensis; Egypt	*Oreochromis niloticus* fry; 2 weeks	Bioremediation agent against ethidium bromide	• Increase total antioxidant capacity and decreased superoxide	El-Din et al. (2021)

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Table 1.3 (continued)

Feed additive and country	Species, growth stage and time	Purpose	Effect	References
			dismutase and catalase activities • Reduced DNA fragmentation	
Spirulina platensis; Egypt	*Oreochromis niloticus* juveniles; 8 weeks	Protection against gibberellic acid toxicity	• *Spirulina platensis* supplementation restored biochemical, antioxidants and histological changes near to control levels	Sayed et al. (2020)
Single- and multi- strain *Bacillus* species; Egypt	*Oreochromis niloticus* fry; 8 weeks	Probiotics additive	• Increased growth performance • Improved intestinal villi length and goblet cell number • Enhanced haemoglobin, haematocrit percentage and monocyte and leukocyte, lymphocyte and neutrophil contents • Better phagocytic activity, phagocytic index and lysozyme activity	Ghalwash et al. (2022)
Seaweeds mixture extract; Egypt	Striped catfish (*Pangasianodon hypophthalmus*) fry; 8 weeks	Antibacterial agents	• Increased growth performance • Enhanced haematological parameters and serum protein profile • Decreased serum alanine and aspartate aminotransferases and hepatic malondialdehyde and serum nitrous acid levels • Increased hepatic superoxide dismutase, catalase and glutathione peroxidase levels and serum lysozyme, total immunoglobulin and complement C3 activities	Abdelhamid et al. (2021)

			• Higher survival rate of fish after *Aeromonas hydrophila* infection	
Quillaja saponaria and linseed oil; Egypt	*Oreochromis niloticus* fingerlings; 8 weeks	Synergetic feed additives	• Improved growth performance and feed utilization efficiency, water quality and welfare indices • Increased serum total protein and globulin and reduced the cholesterol and triglycerides, increased catalase, superoxide dismutase and reduced malondialdehyde values • Improved lipase and amylase activities and expression of insulin growth factor I, superoxide dismutase and tumor necrosis factor-alpha	Elkaradawy et al. (2022)
Quillaja saponaria and *Yucca schidigera*; Egypt	*Oreochromis niloticus* adults; 8 weeks	Synergetic feed additives	• Improved water quality parameters • Increased growth performance and reduced feed conversion ratio • Improved gill health, increased intestinal villi length and goblet cell number • Increased lymphocytes, total protein, globulin and lysozyme activity and reduced cholesterol, triglycerides, glucose and creatinine • Increased lipase, amylase, superoxide dismutase, catalase activities and reduced malondialdehyde content	Abozeid et al. (2021)
Quillaja saponaria and Vitamin E; Egypt	*Oreochromis niloticus* fingerlings; 8 weeks	Synergetic feed additives	• Decreased total ammonia nitrogen and unionized ammonia	Elkaradawy et al. (2021)

(continued)

Table 1.3 (continued)

Feed additive and country	Species, growth stage and time	Purpose	Effect	References
			• Improved growth and feed utilization indices • Increased total protein, albumin, globulin, A/G ratio, cholesterol and triglycerides • Increased lipase, amylase and oxidative parameters superoxide dismutase and catalase activities • Improved villi length, villi surface area and goblet cells count	
Rice straw and zeolite; Egypt	*Oreochromis niloticus* juveniles; 4 weeks	Bioadsorbents for the removal of pollutants	• Better blood biochemistry, biochemical and histologic architecture	El Saidy et al. (2020)
Dunaliella algae; Egypt	*Oreochromis niloticus* juveniles; 8 weeks	Protection against lead acetate toxicity	• Increased growth performance parameters, serum antioxidant enzyme activities, fish body crude protein and liver antioxidant enzymes gene expression • Decreased degeneration and necrosis of hepatocytes	Fadl et al. (2021)
Spirulina platensis; Egypt	*Oreochromis niloticus* juveniles; 10 weeks	Dietary feed additive for growth performance and general health	• Increased final body weight, average daily weight gain, total weight gain and specific growth rate • Enhanced intestinal morphometric measures with increased hepatopancreatic acinar secretory activities • Increased serum catalase and superoxide dismutase activity and reduced glutathione and malondialdehyde levels	El-Araby et al. (2022)

			• Improved interleukin 10, lysozyme activity, complement 3 and immunoglobulin M serum levels	
Vitamin E and chitosan vitamin E nanocomposite; Egypt	*Oreochromis niloticus* fingerlings; 10 weeks	Nanoparticles to alleviate stress induced by high stocking density	• Improved final body weight, total weight gain, feed intake, specific growth rate and average daily weight gain • Decreased aspartate aminotransferase and alanine aminotransferase • Improved lysozyme activity, nitric oxide, phagocytic index and interleukin 10 • Improved serum and hepatic antioxidant enzymes and decreased lipid peroxidation • Increased survival rates of fish after *Aeromonas sobria* challenge	Ahmed et al. (2021)
Chitosan-vitamin C nanocomposite; Egypt	*Oreochromis niloticus* fingerlings; 10 weeks	Nanoparticle feed additive	• Increased final body weight, body weight gain, feed conversion efficiency, protein efficiency ratio, specific growth rate and daily weight gain • Increased serum and hepatic superoxide dismutase and glutathione, and decreased serum malondialdehyde • Increased serum lysozyme, nitric oxide, survival rate and phagocytic activity • Increased villus height, goblet cell count and lymphocytes	Ibrahim et al. (2021b)

(continued)

Table 1.3 (continued)

Feed additive and country	Species, growth stage and time	Purpose	Effect	References
Vitamin C; Egypt	*Oreochromis niloticus*; fingerlings; 10 weeks	Dietary feed additive for growth performance and general health	• Increased final body weight, total weight gain, specific growth rate and daily weight gain • Enhanced serum and hepatic antioxidant activities, lysozyme, nitric oxide and interleukin 10, phagocytic and survival rate of fish against *Aeromonas sobria* • Increased intestinal villus height and width	Ibrahim et al. (2020)
Seaweed liquid extract; Egypt	*Oreochromis niloticus* fingerlings; 10 weeks	Natural agent to rearing water	• Increased growth performance, feed intake and feed utilization • Improved total protein, albumin, globulin levels and lysozyme activity and antioxidant enzyme activities • Improved survival rate of fish after *Aeromonas hydrophila* challenge • Improved zooplankton community, diversity and abundance	Ashour et al. (2021b)
Potassium diformate and *Lactobacillus acidophilus*; Egypt	*Oreochromis niloticus* fingerlings; 12 weeks	Synergistic effects of probiotic and potassium diformate	• Improved growth and feed efficiency • Improved haemoglobin, red blood cells and white blood cells count • Decreased serum alanine and aspartate aminotransferase • Improved serum total protein, albumin, phosphorus and calcium content	Hassaan et al. (2021a)

			• Increased superoxide dismutase, total antioxidant capacity and catalase • Increased villi length width and goblet cells	
Arthrospira platensis; Egypt	Pacific white shrimp, *Litopenaeus vannamei* postlarvae; 13 weeks	Nanoparticle feed additive	• Improved all growth indices, survival and feed utilization parameters • Upregulated insulin growth-like factor I and II mRNA expression	Sharawy et al. (2022)
Arthrospira platensis; Egypt	*Oreochromis niloticus* fingerlings; 10 weeks	Nanoparticle feed additive	• Improved final weight, weight gain and feed conversion ratio • Enhanced total protein, albumin, globulin, lowered serum glucose and aspartate aminotransferase and alanine aminotransferase • Improved catalase, superoxide dismutase and glutathione peroxidase, lysozyme and respiratory burst activities alleviated inflammation induced by *Aeromonas hydrophila* challenge	Mabrouk et al. (2022)
Spirulina platensis; Egypt	*Oreochromis niloticus* juveniles; 8 weeks	Alleviate sodium sulphate toxicity	• Increased glutathione peroxidase, catalase, superoxide dismutase and total antioxidant capacity	Awed et al. (2020)
β-glucan; Egypt	*Oreochromis niloticus* juveniles; 4 weeks	Alleviate chlorpyrifos toxicity	• Increased final body weight, weight gain, specific growth rate, survival rate and feed intake • Decreased alkaline phosphatase, aspartate aminotransferase, alanine aminotransferase and cortisol levels	Dawood et al. (2020a)

(continued)

Table 1.3 (continued)

Feed additive and country	Species, growth stage and time	Purpose	Effect	References
			• Increased lysozyme levels and phagocytic activity and phagocytic index	
Copper nanoparticles; Egypt	Common carp, *Cyprinus carpio* fry; 8 weeks	Nanoparticle feed additive	• Increased growth performance and reduced feed conversion ratio • Increased carcass protein, lipid and ash contents • Increased haemoglobin, red blood cells, total protein, albumin and globulin levels • Increased Immunoglobulin M level, phagocytic, lysozyme, superoxide dismutase, catalase and glutathione peroxidase activities and decreased malondialdehyde content	Dawood et al. (2020e)
β-glucan and heat-killed *Lactobacillus plantarum*; Egypt	*Oreochromis niloticus* juveniles; 4 weeks	Synbiotics to alleviate deltamethrin toxicity and low water temperature	• Downregulated mRNA expression of heat shock protein 70 and cysteine–aspartic acid protease-3 genes • Reduced expression of interleukin 1 beta and interleukin 8 • Regular, normal and protected histopathological damages on gills, intestine, spleen and liver tissues	Gewaily et al. (2021a)
Lactobacillus plantarum; Egypt	*Oreochromis niloticus* juveniles; 4 weeks	Probiotic to alleviate deltamethrin and *Aeromonas hydrophila* effects	• Improved survive rate of fish after *Aeromonas hydrophila* infection • Elevated serum total protein,	Gewaily et al. (2021b)

			albumin, globulin, phagocytic index, phagocytic, and lysozyme activities, but reduced urea, uric acid bilirubin, creatinine, glucose, aspartate aminotransferase, alkaline phosphatase and alanine aminotransferase activities • Upregulated levels of superoxide dismutase, catalase and glutathione peroxidase genes • Relieved the inflammatory features in liver, spleen, gills and intestine	
Isatis; Egypt	*Oreochromis niloticus* juveniles; 4 weeks	Alleviate atrazine toxicity	• Enhanced final body weight, weight gain and specific growth rate • Improved feed conversion ratio • Increased survival rate of fish • Enhanced branching of the intestinal villi • Reduced uric acid, urea, creatinine, aspartate and alanine aminotransferase, and increased total protein, globulin and albumin • Increased superoxide dismutase, catalase, and glutathione peroxidase activities and decreased malondialdehyde content	Ali et al. (2022)
Propolis nanoparticles; Egypt	*Oreochromis niloticus* fingerlings; 4 weeks	Alleviate glyphosate toxicity	• Decreased malondialdehyde in the liver and gill and acetylcholinesterase activity • Increased glutathione concentration and white blood cell and red blood cell counts	Abdelmagid et al. (2022b)

(continued)

Table 1.3 (continued)

Feed additive and country	Species, growth stage and time	Purpose	Effect	References
Foeniculum vulgare; Egypt	*Oreochromis niloticus* fingerlings; 4 weeks	Alleviate glyphosate toxicity	• Decreased alanine aminotransferase, aspartate aminotransferase and alkaline phosphatase activities • Decreased malondialdehyde and DNA fragmentation and increased antioxidant enzyme activities • Downregulated mRNA expression tumor necrosis factor-alpha and interleukin-1 beta	Abdelmagid et al. (2021)
Ziziphus mauritiana leaf powder; Egypt	*Oreochromis niloticus* fingerlings; 6 weeks	Control *Aeromonas hydrophila* infection	• Upregulated lysozyme, interleukin 1 beta and superoxide dismutase genes expression • Improved serum lysozyme and liver antioxidant enzymes activities • Increased survival rate of fish after *Aeromonas hydrophila* infection • Reduced histopathological alterations in the liver, spleen, kidney and muscle of the fish	El Asely et al. (2020)
A mixture of taurine and medium-chain fatty acids; Egypt	*Oreochromis niloticus* fingerlings; 13 weeks	Digestive enhancer dietary feed additive	• Increased growth performance, feed intake, lipase, amylase and protease activities and reduced feed conversion ratio • Increased villus length, width and goblet cells • Improved phagocytic and lysozyme activities	Magouz et al. (2020a)
Azolla meal; Egypt		Dietary feed additive as an ingredient for fish	• Decreased final body weight, weight gain and specific growth rate	Magouz et al. (2020b)

	Genetically-improved farmed tilapia, *Oreochromis niloticus* fingerlings; 13 weeks		and increased feed conversion ratio • Increased villus length in mid and hind gut • Increased goblet cells in foregut and hindgut	
Lactobacillus plantarum and β-glucan; Egypt	Genetically-improved farmed tilapia *Oreochromis niloticus* fingerlings; 12 weeks	Synergetic effects of probiotics	• Increased final body weight and weight gain • Enhanced specific growth rate and feed efficiency ratio • Increased mucosal and villi lengths and muscle thickness • Improved lipase and protease enzymes activities • Upregulated insulin-like growth factor 1 and glucose-6-phosphate dehydrogenase genes expression • Increased haematocrit, haemoglobin and white blood cells and decreased triglyceride and glucose levels	Dawood et al. (2020j)
Lactobacillus plantaruml-137; Egypt	*Oreochromis niloticus* fingerlings; 4 weeks	Probiotic to alleviate deltamethrin toxicity	• Decreased blood creatinine, urea and bilirubin and increased hepatic enzymes aspartate aminotransferase, alkaline phosphatase and alanine aminotransferase • Increased blood total protein, globulin, albumin, white blood cells red blood cells, haemoglobin, phagocytic index, phagocytic and lysozyme activities • Upregulated immunity and downregulated stress genes	Dawood et al. (2020l)

(continued)

Table 1.3 (continued)

Feed additive and country	Species, growth stage and time	Purpose	Effect	References
			• Increased catalase and glutathione peroxidase	
Fenugreek; Egypt	*Oreochromis niloticus* fingerlings; 8 weeks	Alleviate *Aeromonas hydrophila* toxicity	• Increased growth performance parameters and decreased feed conversion ratio • Improved lysozyme, immunoglobulin and respiratory burst activity and superoxide dismutase and glutathione peroxidase and malondialdehyde • Upregulated immune-related genes expression in liver and kidney, interleukin 1 beta and tumor necrosis factor alpha • Reduced blood aspartate aminotransferase and alanine aminotransferase • Alleviated intestine, hepatopancreas, spleen and kidney damage • Increased survival rate of fish after *Aeromonas hydrophila* challenge	Moustafa et al. (2020)
Clenbuterol; Egypt	*Oreochromis niloticus* adults; 4 weeks	Dietary supplement	• Increased body weight, decreased liver, spleen and abdominal fat weights, and decreased total circulatory cholesterol and triacylglycerol levels • Downregulated fatty acid synthase gene expression and enhanced lipolysis	Mohamed et al. (2020)

Menthol essential oil; Egypt	*Oreochromis niloticus* fingerlings; 8 weeks	Alleviate ammonia toxicity	• Enhanced final body weight, weight gain, and feed conversion ratio • Enhanced protease activity • Increased lysozyme, phagocytic activities, phagocytic index, superoxide dismutase, catalase and glutathione peroxidase • Decreased cortisol, glucose and malondialdehyde • Reduced interleukin 8, tumor necrosis factor alpha and interleukin 1 beta • Reduced heat shock protein 70	Magouz et al. (2021b)
A mixture of *Bacillus amyloliquefaciens*, sodium butyrate, zinc methionine and digestive enzymes; Egypt	Common carp, *Cyprinus carpio* fry; 8 weeks	Multi-stimulants blend	• Enhanced fish growth and feed intake • Increased intestinal amylase, lipase and protease • Increased superoxide dismutase, catalase and glutathione peroxidase activities • Decreased malondialdehyde • Increased fish survival rate after ammonia exposure	Abdel-Tawwab et al. (2020c)
β-glucan; Egypt	*Oreochromis niloticus* fingerlings; 8 weeks	Alleviate high stocking density stress	• Increased growth for fish reared in low and medium stocking density • Reduced feed conversion ratio of fish reared in low and medium stocking density • Increased villus length, villus width and goblet cell count in fish reared on medium and high stocking	Dawood et al. (2020k)

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Table 1.3 (continued)

Feed additive and country	Species, growth stage and time	Purpose	Effect	References
			density • Increased haemoglobin levels and red blood cells counts • Reduced cortisol and glucose levels in fish reared in low and medium stocking density • Increased lysozyme activity, phagocytic activity and phagocytic index • Upregulated interferon-gamma, tumor necrosis factor alpha and interleukin 1 beta and downregulated heat shock protein 70 transcription levels	
Mannan oligosaccharide; Egypt	Thinlip grey mullet, *Liza ramada* juveniles; 8 weeks	Dietary feed additive for growth and general health	• Increased final body weight, protein gain and protein retention • Increased blood total protein, albumin globulin, lysozyme, phagocytic activity and phagocytic index • Increased superoxide dismutase, glutathione peroxidase and, catalase activities and decreased malondialdehyde concentration	Magouz et al. (2021a)
Zinc oxide, zinc methionine and zinc oxide nanoparticles; Egypt	Marbled spinefoot rabbitfish, *Siganus rivulatus* fry; 8 weeks	Zinc nanoparticles for alleviating ammonia toxicity	• Improved growth performance and protein utilization for fish fed on zinc methionine, and zinc oxide nanoparticles • Increased catalase, superoxide dismutase and glutathione peroxidase and decreased in	Sallam et al. (2020)

			malondialdehyde content • Improved lysozyme and phenoloxidase activities • Increased survival rate of fish after ammonia challenge	
Cinnamaldehyde and thymol; Egypt	*Oreochromis niloticus* fingerlings; 10 weeks	Dietary essential oils feed additives	• Increased growth performance for fish fed on thymol • Reduced malondialdehyde formation • Increased glutathione reductase in the muscle, lysozyme activity, immunoglobulin M, immunoglobulin G levels and catalase activity	Amer et al. (2018)
Doum palm, *Hyphaene thebaica*; Egypt	African catfish, *Clarias gariepinus* adults; 10 weeks	Feed additive for alleviating *Aeromonas hydrophila* infection	• Improved final body weight, body weight gain, specific growth rate, feed conversion ratio and protein efficiency ratio • Increased intestinal villi height, goblet cells and intraepithelial lymphocytes • Decreased glucose, cholesterol and triglyceride levels in serum • Increased catalase, superoxide dismutase and reduced glutathione content • Increased phagocytic percent and index, lysozyme activity, nitric oxide production and reduced myeloperoxidase • Increased survival rate of fish after *Aeromonas hydrophila* infection	Al-Khalaifah et al. (2020)

(continued)

Table 1.3 (continued)

Feed additive and country	Species, growth stage and time	Purpose	Effect	References
Taurine; Nigeria	African catfish, *Clarias gariepinus* fingerlings; 12 weeks	Feed additive for growth and general health as a plant protein source	• Improved growth performance • Increased serum glucose, cholesterol, total protein, albumin, globulin, aspartate aminotransferase, alanine aminotransferase, alkaline phosphatase, urea and creatinine • Increased lysozyme and respiratory burst activities and superoxide dismutase and catalase activities	Adeshina and Abdel-Tawwab (2020)
Chlorella vulgaris; Egypt	*Oreochromis niloticus* fingerlings; 10 weeks	Dietary feed additive as protein source for growth and general health	• Increased feed intake, specific growth rate and weight gain • Increased serum protease, amylase, lipase enzyme, total proteins, total lipids and globulin levels • Increased glutathione peroxidase, superoxide dismutase and catalase activities and serum lysozyme and respiratory burst activities, and total immunoglobulin M levels and reduced malondialdehyde levels • Upregulated hepatic growth hormone, insulin-like growth factor 1, interleukin 1 beta and tumor necrosis factor alpha genes	Abdel-Tawwab et al. (2022b)
Spirulina platensis, *Tetraselmis chuii* and decapsulated artemia cysts; Egypt	Common sole, *Solea solea* larvae; 4 weeks	Dietary novel feed additives for growth and survival rate	• Increased growth rate • Increased body protein contents • Increased survival rate	Shawky et al. (2021)
Tetraselmis suecica; Egypt	Pacific white shrimp, *Litopenaeus vannamei* post-larvae; 13 weeks	Dietary feed additive	• Increased survival rate of shrimps • Increased weight gain, and	Sharawy et al. (2020)

			specific growth rate and reduced feed conversion ratio • Increased protein, lipid and ash contents • Increased superoxide dismutase and glutathione peroxidase	
Miswak, *Salvadora persica*; Egypt	*Oreochromis niloticus* juveniles; 8 weeks	Nutraceutical immunostimulant dietary feed additive	• Increased immune and biochemical parameters such as white blood cell counts • Decreased malondialdehyde content • Increased antioxidant enzyme activities • Increased survival rate of fish	El-latif et al. (2021)
Pomegranate, *Punica granatum* peel; Egypt	*Oreochromis niloticus* fingerlings; 6 weeks	Alleviate silver nanoparticles toxicity	• Reduced fish performance for pomegranate alone but enhanced antioxidant and immunological activities • Attenuated hepato-renal damage, oxidative stress and immunity parameters	Hamed and Abdel-Tawwab (2021)
Yucca schidigera and/or *Saccharomyces cerevisiae*; Egypt	*Oreochromis niloticus* juveniles; 8 weeks	Water additive probiotic synergetic effects	• Reduced pH and NH_3 levels • Improved growth performance • Decreased aspartate aminotransferase, uric acid and creatinine • Increased superoxide dismutase, catalase, and glutathione peroxidase and reduced malondialdehyde values	Abdel-Tawwab et al. (2021b)
Chamomile, *Matricaria chamomilla* oil; Egypt	Indian shrimp, *Penaeus indicus* juveniles; 8 weeks	Immunostimulant feed additive	• Improved final weight, weight gain, specific growth rate and feed	

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Table 1.3 (continued)

Feed additive and country	Species, growth stage and time	Purpose	Effect	References
			intake • Improved total protein, albumin, and globulin, antioxidant and immunity variables • Reduced aspartate and alanine aminotransferase, creatinine, urea, malondialdehyde and nitric oxide • Improved survival rates after *Vibrio parahaemolyticus* infection	Abdel-Tawwab et al. (2022a)
Basil, *Ocimum basilicum* oil; Egypt	Indian shrimp, *Penaeus indicus* juveniles; 13 weeks	Dietary feed additive for growth and general health	• Increased final weight, weight gain, specific growth rate and feed intake • Increased total protein, albumin and globulin values • Decreased aspartate, alanine aminotransferases creatinine and urea levels • Increased superoxide dismutase, catalase, glutathione peroxidase, lysozyme and phenol oxide activities • Decreased malondialdehyde and nitrous oxide levels • Improved survival rates after *Vibrio parahaemolyticus* infection	Abdel-Tawwab et al. (2021a)
Tridax procumbens leaves extract; Nigeria	*Oreochromis niloticus*, juvenile; 8 weeks	Chemotherapy to kill *Dactylogyrus vastator* parasites	• Increased growth and feed consumption • Enhanced villi length/width and absorption area • Elevated antioxidant and immunity responses	Adeshina et al. (2021)

			• Increased survival rate of fish after *Dactylogyrus vastator* infestation	
β-carotene and phycocyanin extracted from *Spirulina platensis*; Egypt	*Oreochromis niloticus* fry; 10 weeks	Immunostimulant feed additive	• Increased weight gain, specific growth rate and survival rate and reduced feed conversion ratio • Increased chymotrypsin, trypsin, lipase and amylase • Improved haematology parameters • Increased phagocytic, lysozyme, immunoglobulin M, superoxide dismutase, catalase, glutathione peroxidase and total antioxidant capacity activities • Upregulated interferon gamma and interleukin 1 beta genes • Downregulated heat shock protein 70 gene	Hassaan et al. (2021b)
Zinc oxide nanoparticles using *Ulva fasciata*; Egypt	*Oreochromis niloticus* fingerlings; 8 weeks	Zinc oxide nanoparticles as anti-fungal agent against *Candida albicans*	• Improved growth performance, survival rate and lysozyme, phagocytic, phagocytic index and respiratory burst activities • Improved interleukin 1 beta, tumor growth, transforming growth factor beta, tumor necrosis factor alpha, digestive enzyme activity and histopathological	Diab et al. (2022)
Bulk zinc oxide or zinc oxide nanoparticles; Egypt	*Oreochromis niloticus* fingerlings; 12 weeks	Dietary zinc nanoparticles	• Increased growth and digestive enzyme activity • Improved intestinal topography • Enhanced haematological indices	Ibrahim et al. (2022)

(continued)

Table 1.3 (continued)

Feed additive and country	Species, growth stage and time	Purpose	Effect	References
			• Reduced alanine and aspartate aminotransferase • Increased total serum protein, albumin and globulin contents	
Natural clay nanozeolite; Egypt	*Oreochromis niloticus* fingerlings; 12 weeks	Alleviate aflatoxin B_1 toxicity	• Increased growth performance and feed utilization • Increased amylase and chymotrypsin activities • Enhanced haemoglobin, haematocrit, red blood cells and white blood cells count • Decreased alanine and aspartate aminotransferase, alkaline phosphatase, total protein, albumin and globulin • Increased superoxide dismutase, catalase, lysozyme activities and DNA fragmentation, and reduced malondialdehyde content	Hassaan et al. (2020b)
Bulk selenium or selenium nanoparticles; Egypt	*Oreochromis niloticus* fingerlings; 12 weeks	Nanoparticle feed additive	• Improved growth performance and amylase and lipase enzymes activities • Increased villi height and width and goblet cells • Increased mucosal-to-serosal amplification ratio and villous absorption area • Increased haemoglobin, haematocrit, red blood cells and white blood cell count	Ibrahim et al. (2021a)

			• Reduced alanine and aspartate aminotransferases, while increased total serum protein, albumin and globulin contents • Increased superoxide dismutase, catalase, glutathione peroxidase, glutathione, glutathione-S-transferase and glutathione reductase activity accompanied with the lower malondialdehyde content	
Selenium nanoparticles; Egypt	European sea bass, *Dicentrarchus labrax* fingerlings; 13 days	Nanoparticle feed additive	• Increased final body weight, weight gain and specific growth rate • Haemoglobin, haematocrit, red blood cell counts and white blood cells • Increased protein and globulin contents • Enhanced phagocytic index, phagocytic and lysozyme activities • Increased superoxide dismutase and catalase activities • Reduced malondialdehyde content • Upregulated growth hormone, insulin-like growth factor 1, interleukin 8, and interleukin 1 beta • Downregulated heat shock protein 70	Abd El-Kader et al. (2021)
Selenium nanoparticles and *Spirulina platensis*; Egypt	*Oreochromis niloticus* juveniles; 8 weeks	Selenium nanoparticles and *Spirulina platensis* synergistic effects	• Improved weight gain, specific growth rate and decreased feed conversion ratio • Increased total protein and	Al-Deriny et al. (2020)

(continued)

Table 1.3 (continued)

Feed additive and country	Species, growth stage and time	Purpose	Effect	References
			immunoglobulin M • Upregulated superoxide dismutase and tumor necrosis factor alpha genes • Downregulated heat shock protein 70	
Fucoidan; Egypt	*Oreochromis niloticus* juveniles; 4 weeks	Alleviate aflatoxin B_1 toxicity	• Decreased alanine and aspartate aminotransferases, alkaline phosphatase, cholesterol, urea and creatinine • Increased blood protein, glutathione, glutathione peroxidase, superoxide dismutase and catalase activities	Abdel-Daim et al. (2020)
Zinc oxide; Egypt	*Oreochromis niloticus* adults; 4 weeks	Mineral feed additive	• Increased hepatosomatic index and gonadosomatic index • Increased total absolute relative fecundity and fry survival • Increased pH, motility and sperm concentration • Enhanced triglyceride cholesterol and high density lipoprotein • Increased catalase, glutathione peroxidase and superoxide dismutase enzymes	Soaudy et al. (2021)
Silicate clay; Egypt	*Oreochromis niloticus* fingerlings; 10 weeks	Mineral feed additive	• Improved final body weight, weight gain, specific growth rate and feed conversion ratio and protein efficiency ratio	Hassaan et al. (2020a)

			• Increase alkaline phosphatase, amylase, trypsin, chymotrypsin and lipase enzymes • Improved white blood cells, monocytes and lymphocytes • Increased total protein and immunoglobulin M	
Citrus limon peels; Egypt	*Oreochromis niloticus* and *Clarias gariepinus*; 6 weeks	Chemotherapeutics	• Decreased glucose but increased nitric oxide • Enhanced catalase, glutathione, lysozymes, myeloperoxidase in both fish • Enhanced superoxide dismutase in *Clarias gariepinus* • Increased survival rate after *Aeromonas hydrophila* challenge	Abdel Rahman et al. (2019)
Mannan oligosaccharide; Egypt	Red sea bream, *Pagrus major* juveniles; 8 weeks	Prebiotic feed additive to alleviate low salinity stress	• Increased final body weight, weight gain, and specific growth rate with decreased feed conversion ratio • Enhanced haematocrit level and total serum protein • Decreased glutamic pyruvic transaminase • Increased biological antioxidant potential and reactive oxygen metabolites, lysozyme, bactericidal, peroxidase, blood nitro blue tetrazolium assay and alternative complement pathway • Enhanced tolerance against low salinity stress	Dawood et al. (2020g)

(continued)

Table 1.3 (continued)

Feed additive and country	Species, growth stage and time	Purpose	Effect	References
Ginger nanoparticles; Egypt	*Oreochromis niloticus* juveniles; 4 weeks	Alleviate glyphosate toxicity	• Reduced alanine and aspartate aminotransferases activities, glucose and cortisol levels, and malondialdehyde levels • Reduced urea and creatinine levels and higher total protein, albumin and globulin • Increased reduced glutathione, lysozyme activity and immunoglobulin levels	Abdelmagid et al. (2022a)

1.5.1 The Use of Feed Additives for Growth Performance and General Fish Health

The primary goal of commercial aquaculture production is to produce bigger fish in the shortest possible period. Therefore, growth performance is the main target for fish farmers in Africa. Indeed, various additives are used in African aquaculture as dietary feed for growth enhancement and general health management for various development stages of cultured species. Feed additives used in African aquaculture on *O. niloticus* fingerlings include curcumin (*Curcuma longa*) (Mahmoud et al. 2017), *Ziziphus mauritiana* leaf powder (Amin et al. 2019), vitamin C (Ibrahim et al. 2020), a mixture of taurine and medium-chain fatty acids (Magouz et al. 2020a), Azolla meal (Magouz et al. 2020b) and *Chlorella vulgaris* (Abdel-Tawwab et al. 2022b). Moreover, triticale (Dawood et al. 2020c) and *Spirulina platensis* (El-Araby et al. 2022) have been used as feed additives for growth and general body health in *O. niloticus* juveniles, whereas only clenbuterol was used in *O. niloticus* adults (Mohamed et al. 2020). In other cultured fish species, taurine was used in *C. gariepinus* fingerlings (Adeshina and Abdel-Tawwab 2020), oregano essential oil in *C. carpio* fingerlings (Abdel-Latif et al. 2020) and Anise (*Pimpinella anisum*) in *D. labrax* juveniles (Ashry et al. 2022).

Results from these studies indicated that appropriate feed additive doses improved growth performance (Mahmoud et al. 2017; Amin et al. 2019; Abdel-Latif et al. 2020; Ibrahim et al. 2020; Magouz et al. 2020b; Mohamed et al. 2020; Abdel-Tawwab et al. 2022b; Ashry et al. 2022), feed utilization efficiency (Mahmoud et al. 2017), antioxidant capacity (Mahmoud et al. 2017; Abdel-Tawwab et al. 2022b; El-Araby et al. 2022), immune responses (Mahmoud et al. 2017; Ibrahim et al. 2020; Magouz et al. 2020b; Abdel-Tawwab et al. 2022b; El-Araby et al. 2022) and disease resistance against *A. hydrophila* (Mahmoud et al. 2017; Abdel-Tawwab et al. 2022b; El-Araby et al. 2022), *A. sobria* (Ibrahim et al. 2020) and *Pseudomonas fluorescens* and *Vibrio anguillarum* (Abdel-Tawwab et al. 2022b). Moreover, feed additives improved intestinal health (Amin et al. 2019; Abdel-Latif et al. 2020; Magouz et al. 2020b), hepatic and intestinal structures (Ibrahim et al. 2020), enhanced well-being (Ashry et al. 2022) and improved general fish health (El-Araby et al. 2022). Some additives, such as Azolla meal, was beneficial on the digestive enzymes (Magouz et al. 2020b), while clenbuterol reduced fat deposition rates (Mohamed et al. 2020). These studies indicate that additives are a feeding strategy for sustainable African aquaculture production (Dawood et al. 2020c). However, research must be taken to ensure appropriate doses are used because higher inclusion levels of dietary taurine limited growth, immunity, and antioxidant responses of *C. gariepinus* (Adeshina and Abdel-Tawwab 2020).

In addition to the use of single additives, multiple blends of feed additives are also used in African aquaculture due to their synergetic effects. Accordingly, more than one feed additives have been used in *O. niloticus* fingerlings by using *Quillaja saponaria* and vitamin E (Elkaradawy et al. 2021) and *Quillaja saponaria* and linseed oil (Elkaradawy et al. 2022). Moreover, coenzyme Q10 and vitamin C were used in *O. niloticus* juveniles (El Basuini et al. 2021), while *Quillaja saponaria* and *Yucca schidigera* were used in *O. niloticus* adults (Abozeid et al. 2021). For other species than *O. niloticus*, *S. platensis*, *Tetraselmis chuii* and decapsulated artemia cysts were used in *S. solea* larvae (Shawky et al. 2021). Expectedly, the feed additives interacted to improve growth performance (Abozeid et al. 2021; El Basuini et al. 2021; Elkaradawy et al. 2021, 2022), feed efficiency (El Basuini et al. 2021), digestive enzymes activities (Abozeid et al. 2021; El Basuini et al. 2021), biochemical blood indices (El Basuini et al. 2021), immune response (Abozeid et al. 2021; El Basuini et al. 2021; Elkaradawy et al. 2022) and antioxidant capacity (Abozeid et al. 2021; El Basuini et al. 2021; Elkaradawy et al. 2022). Moreover, feed additives interacted synergistically to improve water quality (Abozeid et al. 2021; Elkaradawy et al. 2021, 2022), gills and intestine health (Abozeid et al. 2021; Elkaradawy et al. 2021) and general health welfare profile of fish (Elkaradawy et al. 2021, 2022). They also interacted to increase resistance against *Streptococcus agalactiae* infection (El Basuini et al. 2021). A mixture of dietary additives has also been reported as an effective diet in the weaning of post-larvae stages in *S. solea*) (Shawky et al. 2021). Moreover, a mixture of taurine and medium-chain fatty acids was effective for *O. niloticus* reared at suboptimal temperatures to maintain normal growth rates without a decrease in the physiological and immunological status (Magouz et al. 2020a).

Interestingly, feed additives for growth and general health are also used in crustacean African aquaculture, although to a limited level. Accordingly, *T. suecica* were used in Pacific white shrimp, *Litopenaeus vannamei* post-larvae (Sharawy et al. 2020), while Basil, *Ocimum basilicum,* oil was used in Indian shrimp, *Penaeus indicus* juveniles (Abdel-Tawwab et al. 2021a). In these studies, the highest inclusion level of dried *T. suecica* improved growth and nutrient utilization (Sharawy et al. 2020), whereas appropriate dietary Basil oil enhanced growth performance, antioxidant capacity and innate immunity (Abdel-Tawwab et al. 2021a). Moreover, Basil oil also increased resistance of *P. indicus* against *Vibrio parahaemolyticus* infection (Abdel-Tawwab et al. 2021a).

In general, feed additives whether used singly or in combination provide valuable resources for improving growth performance, immunity and general health of fish and crustaceans. The diversity of feed additives resources for feeding fish and crustacean to improve growth performance and general health makes the African aquaculture viable for sustainable production. Discovering novel feed additives and improving the technology for higher inclusions are further required to ensure a sustainable African aquaculture for enhanced blue economy development.

1.5.2 Use of Feed Additives to Alleviate Toxicity of Various Xenobiotics and Stressful Conditions

The importance of feed additives in African aquaculture has led to their use in alleviating various xenobiotics effects during fish farming in the continent. Metal contamination is a common phenomenon in aquatic environment. Several feed additives are used in African aquaculture to alleviate the toxicity caused by metal contamination. They include pyrazole derivatives (Soliman et al. 2019) and *S. platensis* (Hamed et al. 2019), which were used in *C. gariepinus* adults to ameliorate lead nitrate toxicity. Moreover, Pomegranate, *Punica granatum,* peel and *Dunaliella* algae have been used in *O. niloticus* fingerlings and juveniles to alleviate silver nanoparticles toxicity (Hamed and Abdel-Tawwab 2021) and lead acetate toxicity (Fadl et al. 2021), respectively. The use of such feed additives minimized the effects of lead toxicity (Hamed et al. 2019; Soliman et al. 2019; Fadl et al. 2021; Hamed and Abdel-Tawwab 2021) on various pathological changes in organs (Fadl et al. 2021), cytotoxic and genotoxic effects (Hamed et al. 2019) and oxidative stress and immune suppression (Hamed and Abdel-Tawwab 2021). Moreover, various feed additives, including fennel extract, *Foeniculum vulgare,* and Isatis, have been used to alleviate herbicides toxicity caused by glyphosate and atrazine in *O. niloticus* fingerlings (Abdelmagid et al. 2021) and juveniles (Ali et al. 2022), respectively. Furthermore, zinc sulphate and green tea (*Camellia sinensis*) extract were used in *O. niloticus* juveniles (Mohamed et al. 2019) and *C. gariepinus* adults (Sayed and Soliman 2018) to ameliorate nonylphenol toxicity as an environmental endocrine disruptor. In addition, *M. oleifera* seeds and leaves (Ibrahim et al. 2019) and β-glucan (Dawood et al. 2020a) were used to ameliorate chlorpyrifos insecticide toxicity, while curcumin was used to alleviate melamine toxicity as a nitrogenous industrial material (Abd El-Hakim et al. 2020), all in *O. niloticus* juvenile.

In these studies, feed additives alleviated the toxicity of xenobiotics on growth retardation (Ibrahim et al. 2019; Ali et al. 2022), antioxidant capacity (Sayed and Soliman 2018; Ibrahim et al. 2019; Abd El-Hakim et al. 2020; Abdelmagid et al. 2021; Ali et al. 2022), nephrotoxicity (Mohamed et al. 2019; Ali et al. 2022), hepatotoxicity (Ibrahim et al. 2019; Mohamed et al. 2019; Dawood et al. 2020a; Abdelmagid et al. 2021), immunity (Ibrahim et al. 2019; Mohamed et al. 2019; Abd El-Hakim et al. 2020; Dawood et al. 2020a; Abdelmagid et al. 2021), haematotoxicity (Ibrahim et al. 2019; Mohamed et al. 2019; Abd El-Hakim et al. 2020), lipotoxicity (Ibrahim et al. 2019), spleen toxicity (Abd El-Hakim et al. 2020), gills and intestinal toxicity (Dawood et al. 2020a) and genotoxicity (Sayed and Soliman 2018; Ibrahim et al. 2019; Abdelmagid et al. 2021). The results from these studies suggest the great potential of feed additives as innovative approach for improving growth and general health for enhanced production and economic benefit for sustainable African aquaculture industry.

Feed additives are also used in African aquaculture to alleviate stress caused by various conditions. The available literature indicates studies conducted on

O. niloticus at various developmental stages. These include β-glucan for alleviating high stocking density stress (Dawood et al. 2020k), menthol essential oil for protecting against ammonia toxicity (Magouz et al. 2021b) in *O. niloticus* fingerlings, *A. oryzae* for alleviating salinity stress (Shukry et al. 2021) and oregano essential oil for ameliorating long-term acute heat stress (Magouz et al. 2022) in *O. niloticus* juveniles. The feed additives used alleviated the various stress factors by improving growth performance (Dawood et al. 2020k; Magouz et al. 2021b, 2022), digestive enzyme activity (Magouz et al. 2021b), intestinal morphometry (Dawood et al. 2020k), haemato-biochemical parameters (Shukry et al. 2021; Magouz et al. 2022), antioxidant responses (Magouz et al. 2021b, 2022; Shukry et al. 2021) and immunity (Dawood et al. 2020k; Magouz et al. 2021b, 2022; Shukry et al. 2021). These studies suggest that feed additives used in African aquaculture counteract the potential negative stressful conditions during production for sustainable aquaculture.

Bacteria diseases are a common challenge in intensively cultured fish production, which is the future for the industry to tackle shortage of food due to increasing population. Luckily, several feed additives are used in African aquaculture to alleviate toxicity of bacteria and other pathogenic organisms. Such studies have been conducted by using fenugreek for alleviating *A. hydrophila* toxicity (Moustafa et al. 2020), fucoidan for alleviating aflatoxin B_1 toxicity (Abdel-Daim et al. 2020) in *O. niloticus* fingerlings and juveniles, respectively. Moreover, Doum palm, *Hyphaene thebaica,* was used in African catfish, *C. gariepinus* adults for alleviating *A. hydrophila* infection (Al-Khalaifah et al. 2020). In these studies, the feed additives used were protective against the pathogenic organisms by enhancing growth performance (Al-Khalaifah et al. 2020; Moustafa et al. 2020), feed efficiency (Moustafa et al. 2020), biochemical parameters (Abdel-Daim et al. 2020), intestinal histomorphology (Al-Khalaifah et al. 2020; Moustafa et al. 2020), hepatic, hepatopancreas, spleen and kidney health (Moustafa et al. 2020), antioxidant capacity (Abdel-Daim et al. 2020; Al-Khalaifah et al. 2020), immune response (Al-Khalaifah et al. 2020) and disease resistance against *A. hydrophila* challenge (Al-Khalaifah et al. 2020; Moustafa et al. 2020). These studies indicate that the feed additives used in African aquaculture are beneficial as natural alternatives for alleviating toxicity caused by pathogenic organisms. Extending the available studies to species other than *O. niloticus* and *C. gariepinus* and selecting effective feed additives in alleviating toxicity caused by disease-causing organisms in African aquaculture could provide the extent of their use. In fact, the feed additives differ in their efficiency when used in African aquaculture. For instance, dietary β-carotene had a superior impact on growth performance, haemato-biochemical and immune-oxidative stress biomarkers (Taalab et al. 2022), phycocyanin was more effective for improving antioxidant capacity and immunity compared to β-carotene (Hassaan et al. 2021b) and thymol stimulated more growth and immune responses than cinnamaldehyde as essential oils in Nile tilapia nutrition (Amer et al. 2018) in *O. niloticus*. Therefore, further studies are required to designate effective additives, which can be used for multiple purposes in African aquaculture.

Indeed, a few feed additives, such as *Spirulina platensis,* has been used in African aquaculture to alleviate toxicity caused by multiple xenobiotics in various fish species. *Spirulina platensis* has been used as a feed additive to protect against fluorescent tag ethidium bromide (El-Din et al. 2021), gibberellic acid, a fungus metabolic by-product (Sayed et al. 2020) and sodium sulphate used in home detergents (Awed et al. 2020) in *O. niloticus* fry and juveniles. Moreover, *Spirulina platensis* has been used to protect against toxicity caused by an antibiotic hydroxychloroquine (Sayed et al. 2021) and sodium dodecyl sulphate, a surfactant used in houses (Sayed and Authman 2018) in *C. gariepinus* fingerlings and adults. *Spirulina platensis* alleviated toxicity induced by the xenobiotics by scavenging reactive oxygen species (ROS) (Sayed and Authman 2018), sustaining the antioxidant status (Sayed and Authman 2018; Awed et al. 2020; Sayed et al. 2020, 2021; El-Din et al. 2021), rendering haematological and biochemical indices (Sayed et al. 2021), reducing hepatotoxicity (Sayed et al. 2020, 2021), nephrotoxicity (Sayed et al. 2020) and genotoxicity (Sayed and Authman 2018; El-Din et al. 2021). These results offer a promising role of using certain well-studied feed additives in African aquaculture industry to protect fish against multiple xenobiotics and stressors.

Another potential use of feed additives in African aquaculture is a combination of more than one additive in order to benefit from their synergistic effects in alleviating toxicity and stressful conditions in captivity. Evidently, *Glycyrrhiza glabra* extract and protexin concentrate (Mahmoud et al. 2021) and natural clay, coumarin, curcumin, vitamin C, probiotics and prebiotics (Ayyat et al. 2018) were used in *O. niloticus* fingerlings for alleviating high stocking density stress and aflatoxin B_1 toxicity, respectively. Moreover, mannan oligosaccharides and β-glucans (El-Fahla et al. 2022) and lycopene and/or resveratrol (Abdel-Daim et al. 2019) were used to ameliorate lead reproductive and nanozinc oxide toxicity in *O. niloticus* juvenile, respectively. Furthermore, turmeric powder alone or plus black pepper powder (El-Houseiny et al. 2019) and *Silybum marianum* and/or coenzyme Q10 (El-Houseiny et al. 2022) were used in *C. gariepinus* juveniles and adults for alleviating negative effects of cadmium and fluoride toxicity, respectively. Clear synergetic effects were reported in alleviating toxicity and stress by enhancing growth performance (Ayyat et al. 2018; El-Houseiny et al. 2019, 2022; Mahmoud et al. 2021) and reducing hepatotoxicity (Ayyat et al. 2018; El-Houseiny et al. 2019, 2022), nephrotoxicity (El-Houseiny et al. 2019, 2022), haematotoxicity (Ayyat et al. 2018; El-Houseiny et al. 2022) and reprotoxicity effects (El-Houseiny et al. 2019; El-Fahla et al. 2022), improving antioxidant capacity (Abdel-Daim et al. 2019; Mahmoud et al. 2021; El-Fahla et al. 2022; El-Houseiny et al. 2022), immunity (Mahmoud et al. 2021; El-Houseiny et al. 2022) and bacterial disease resistance of fish (Mahmoud et al. 2021). In a nutshell, the use of feed additives in combination in African aquaculture is beneficial for alleviating toxicity of multiple xenobiotics and stressful factors for enhanced fish growth and immunity, resulting in increased production. Such an approach offers a means to ensure sustainable African aquaculture production required during this blue economy era.

1.5.3 The Use of Feed Additives as Prebiotics, Probiotics and Synbiotics

Probiotics, prebiotics and synbiotics use in African aquaculture production are considered a viable, safe and environmentally friendly alternative for enhancing growth performance, feed utilization, immunity, disease resistance and fish survival against pathogens and environmental stress (Dawood et al. 2020b; Mugwanya et al. 2022). Probiotics, prebiotics and synbiotics are used in African aquaculture as alternative to antibiotics (Dawood et al. 2020b), which have been shown to affect fish health globally (Limbu et al. 2021) and African aquaculture (Limbu 2020a).

Prebiotics are non-digestible food ingredients, which enhance proliferation of beneficial microbiota in the intestines. The existing limited information in African aquaculture indicates the use of mannan oligosaccharide prebiotic in Thinlip grey mullet, *Liza ramada* juveniles (Magouz et al. 2021a), and Red sea bream, *Pagrus major* juveniles, to alleviate low salinity stress (Dawood et al. 2020g). Expectedly, mannan oligosaccharide enhanced growth rate (Dawood et al. 2020g; Magouz et al. 2021a), feed efficiency, digestive enzyme activity and blood chemistry (Magouz et al. 2021a), antioxidant capacity (Dawood et al. 2020g; Magouz et al. 2021a) and immunity (Dawood et al. 2020g; Magouz et al. 2021a). Contrary to prebiotics, several probiotics as live beneficial microbiota are widely used in African aquaculture as single or multi-strains for their useful qualities, including alleviating toxicity effects. They promote good health by enhancing the internal microbiota balance (El-Saadony et al. 2021). Accordingly, single- and multi-strain *Bacillus* species were used in *O. niloticus* fry as feed additive for improving growth and immunological parameters (Ghalwash et al. 2022). *Lactobacillus plantarum* were used to alleviate deltamethrin toxicity in *O. niloticus* fingerlings (Dawood et al. 2020l) and juveniles (Gewaily et al. 2021b) and for reducing *A. hydrophila* adverse effects in *O. niloticus* juveniles (Gewaily et al. 2021b). Results showed that *L. plantarum* relieved toxicity and adverse effects by improving antioxidant capacity (Dawood et al. 2020l; Gewaily et al. 2021b), biochemical responses (Dawood et al. 2020l), immunity (Dawood et al. 2020l; Gewaily et al. 2021b), reducing inflammation (Gewaily et al. 2021b) and histopathological effects (Dawood et al. 2020l). These studies highlight the importance of prebiotics and probiotics in improving growth and immunity of cultured fish in African aquaculture.

Some probiotics are either used in African aquaculture in combination with other additives or multiple species in order to benefit their interactive effects. Evidently, potassium diformate and *Lactobacillus acidophilus* were used in *O. niloticus* fingerlings (Hassaan et al. 2021a); *Yucca schidigera* and/or *Saccharomyces cerevisiae* were used in *O. niloticus* juveniles as water additive (Abdel-Tawwab et al. 2021b). Conceivably, additives worked synergistically to improve growth performance (Abdel-Tawwab et al. 2021b; Hassaan et al. 2021a), intestine morphology (Hassaan et al. 2021a) and antioxidant capacity (Abdel-Tawwab et al. 2021b; Hassaan et al. 2021a). To further optimize the benefits of prebiotics and probiotics, African aquaculture practitioners mix them in the form of synbiotics. Evidently, *L. plantarum* and β-glucan (Dawood et al. 2020j) and *A. oryzae* and β-glucan (Dawood et al. 2020f) were used together as synbiotics functional feed additives in *O. niloticus* fingerlings. This form of mixture has been used to ameliorate toxicity of xenobiotics in a few studies. Accordingly, natural clay, coumarin, curcumin, vitamin C, prebiotics and probiotics were used in *O. niloticus* fingerlings for alleviating aflatoxin B_1 (Ayyat et al. 2018), whereas β-glucan and heat-killed *L. plantarum* were used in *O. niloticus* juveniles to alleviate deltamethrin toxicity and low water temperature (Gewaily et al. 2021a). Results from these studies showed clear that the synbiotics improved growth performance (Dawood et al. 2020f, j), condition factor (Ayyat et al. 2018), feed efficiency, digestive capacity, nutrients metabolism (Dawood et al. 2020j), antioxidant status (Dawood et al. 2020f; Gewaily et al. 2021a), haematological parameters (Dawood et al. 2020j), immunity (Dawood et al. 2020f; Gewaily et al. 2021a), ameliorated histopathological damages (Dawood et al. 2020j; Gewaily et al. 2021a) and inflammation (Gewaily et al. 2021a).

In general, prebiotics, probiotics and synbiotics application in African aquaculture improve growth performance through increased nutrients metabolism, enhancing antioxidant capacity and immunity for improved health of cultured fish. They offer beneficial effects for the industry either singly or in combination or added to other feed additives for alleviating toxicity of various xenobiotics. Therefore, prebiotics, probiotics and synbiotics provide potential solution as functional feed additives for improving African aquaculture industry to ensure its sustainability for protecting fish against stressful conditions.

1.5.4 The Use of Nanoparticles as Feed Additives in African Aquaculture

Nanoparticles are increasingly used in different animal nutrition systems for enhancing physical and chemical properties of feeds. The African aquaculture industry also uses them for improving growth and health of cultured fish, especially *O. niloticus* at various development stages. Accordingly, chitosan-vitamin C nanocomposite (Ibrahim et al. 2021b), *Arthrospira platensis* nanoparticles (Mabrouk et al. 2022), nanozinc oxide particles (Ibrahim et al. 2022), and nanoselenium particles (Ibrahim et al. 2021a; Ghaniem et al. 2022) were used in *O. niloticus* fingerlings, while sodium butyrate nanoparticles (Abdel-Tawwab et al. 2021c) were used in *O. niloticus* juveniles as dietary feed additives. Limited studies are available on other species, including *C. carpio* fry (Dawood et al. 2020e) and *D. labrax* fingerlings (Abd El-Kader et al. 2021), in which copper and selenium nanoparticles were used, respectively. The nanomaterials used enhanced growth performance (Dawood et al. 2020e; Abd El-Kader et al. 2021; Abdel-Tawwab et al. 2021c; Ibrahim et al. 2021a, b, 2022; Ghaniem et al. 2022; Mabrouk et al. 2022), feed efficiency (Dawood et al. 2020e; Abdel-Tawwab et al. 2021c; Ibrahim et al. 2021a, 2022), digestive enzymes (Abdel-Tawwab et al. 2021c; Ibrahim et al. 2021a, 2022), nutrients body composition (Dawood et al. 2020e), intestinal histomorphology (Abdel-Tawwab et al. 2021c; Ibrahim et al. 2021a, b, 2022), haemato-biochemical parameters (Abd El-Kader et al. 2021; Ibrahim et al. 2021a, 2022; Ghaniem et al. 2022; Mabrouk et al. 2022), antioxidant capacity (Dawood et al. 2020e; Abd El-Kader et al. 2021; Ibrahim et al. 2021a, b, 2022; Ghaniem et al. 2022; Mabrouk et al. 2022), liver, kidney, and spleen health (Mabrouk et al. 2022), immunity response (Dawood et al. 2020e; Abd El-Kader et al. 2021; Ibrahim et al. 2021b; Ghaniem et al. 2022) and disease resistance (Ibrahim et al. 2021b). These studies indicate that nanoparticles are beneficial in African aquaculture for enhancing growth, immunity and general health of cultured fish species.

Limited studies have explored the synergetic effects of nanoparticles in African aquaculture. The available literature point to a study conducted by Al-Deriny et al. (2020) on selenium nanoparticles and *S. platensis* in *O. niloticus* juveniles (Al-Deriny et al. 2020). In this study, the mixture of selenium nanoparticles and *S. platensis* interacted to improve growth performance, feed efficiency, haemato-biochemical parameters, immunity, antioxidant capacity and reduced stress (Al-Deriny et al. 2020). Interestingly, several nanoparticles have been used in African aquaculture to alleviate xenobiotics toxicity in fish. Most studies have been used in *O. niloticus* fingerlings by using chitosan vitamin E nanocomposite to alleviate stress induced by high stocking density (Ahmed et al. 2021), natural clay nanozeolite to alleviate aflatoxin B_1 toxicity (Hassaan et al. 2020b), propolis nanoparticles to alleviate glyphosate toxicity (Abdelmagid et al. 2022b), zinc oxide nanoparticles using *Ulva fasciata* as anti-fungal agent against *Candida albicans* (Diab et al. 2022) and *A. platensis* nanoparticles to protect against *A. hydrophila* (Mabrouk et al. 2022). Moreover, ginger nanoparticles were used in *O. niloticus* juveniles to alleviate glyphosate toxicity (Abdelmagid et al. 2022a) and zinc oxide nanoparticles were utilized in Marbled spinefoot rabbitfish, *Siganus rivulatus* fry to alleviate ammonia toxicity (Sallam et al. 2020).

The nanoparticles used ameliorated toxicity and stress to promote growth performance (Hassaan et al. 2020b; Sallam et al. 2020; Ahmed et al. 2021; Diab et al. 2022), feed utilization (Hassaan et al. 2020b), survival rate (Diab et al. 2022), digestive enzymes activities (Hassaan et al. 2020b; Diab et al. 2022), antioxidant status (Hassaan et al. 2020b; Sallam et al. 2020; Ahmed et al. 2021; Abdelmagid et al. 2022b) and immune response (Sallam et al. 2020; Ahmed et al. 2021; Abdelmagid et al. 2022b; Diab et al. 2022). The nanoparticles also reduced genotoxicity (Hassaan et al. 2020b), enhanced fish resistance to *A. sobria* infection (Ahmed et al. 2021) and *C. albicans* (Diab et al. 2022) and alleviated the inflammation induced by *A. hydrophila* (Mabrouk et al. 2022). Limited studies have been conducted in crustaceans on nanoparticles in African aquaculture. The available study was conducted on *L. vannamei* post-larvae by using *A. platensis* nanoparticle feed additive (Sharawy et al. 2022). In this study, *A. platensis* nanoparticle improved growth, survival rate and feed utilization (Sharawy et al. 2022). Taken together, the utilization of nanoparticle in African aquaculture as feed additives improve production, and general health of fish and crustaceans. The nanoparticles used are beneficial for eliminating toxicity and stress induced by xenobiotics. Studies exploring the production of nanoparticles by using technologies accessible to small-scale farmers could further ensure the sustainability of the industry.

1.5.5 The Use of Feed Additives as Immunostimulants in African Aquaculture

Several feed additives are used in African aquaculture due to their immunostimulant effects on fish health because of the presence of various bioactive compounds. They act as natural immunostimulants and antioxidants, thereby improving growth performance and general health of cultured fish (El Basuini et al. 2021). The immunostimulators applied in African aquaculture include curcumin (Amer et al. 2022) and *M. oleifera* aqueous extract (Emam et al. 2021) used in *O. niloticus* fingerlings. Moreover, miswak, *Salvadora persica* as nutraceutical immunostimulant was used in *O. niloticus* juveniles (El-latif et al. 2021), while *Cucurbita mixta* seed meal was applied in *O. mossambicus* juveniles (Musthafa et al. 2017). Evidently, appropriate doses of the immunostimulants used improved growth performance (Musthafa et al. 2017; Emam et al. 2021; Amer et al. 2022), antioxidant capacity (El-latif et al. 2021; Amer et al. 2022), immunity (Musthafa et al. 2017; El-latif et al. 2021; Amer et al. 2022), intestinal histology (Amer et al. 2022), liver and kidney functions (Emam et al. 2021), haematological parameters (El-latif et al. 2021; Emam et al. 2021) and disease resistance against *A. hydrophilla* (Musthafa et al. 2017; El-latif et al. 2021). Clearly, these studies indicate the stimulation of immune system of cultured fish upon application of immunostimulants in African aquaculture. However, the application of immunostimulants as feed additives in African aquaculture should be guided by specific research because high doses (Emam et al. 2021; Amer et al. 2022) used for longer periods affect fish health (Amer et al. 2022).

Some of the bioactive compounds contained in immunostimulants function synergistically to influence growth and health of cultured fish (Dawood et al. 2021a). To this end, several immunostimulants have been used in African aquaculture to benefit from their synergistic actions. These include lemongrass (*Cymbopogon citratus*) and geranium (*Pelargonium graveolens*) as essential oils (Al-Sagheer et al. 2018), β-carotene and phycocyanin extracted from *Spirulina platensis* (Hassaan et al. 2021b) applied in *O. niloticus* fry and cinnamaldehyde and thymol also as essential oils used in *O. niloticus* fingerlings (Amer et al. 2018). A mixture of *Bacillus amyloliquefaciens*, sodium butyrate, zinc methionine and digestive enzymes as multi-stimulants blend was also used in *C. carpio* fry (Abdel-Tawwab et al. 2020b). The results obtained clearly indicated the synergetic effects of immunostimulants on improving growth performance (Al-Sagheer et al. 2018; Abdel-Tawwab et al. 2020b), feed utilization (Al-Sagheer et al. 2018; Abdel-Tawwab et al. 2020b), digestive enzymes (Abdel-Tawwab et al. 2020b; Hassaan et al. 2021b), antioxidant capacity (Al-Sagheer et al. 2018; Amer et al. 2018; Abdel-Tawwab et al. 2020b; Hassaan et al. 2021b), haematology parameters (Hassaan et al. 2021b), immune responses (Al-Sagheer et al. 2018; Amer et al. 2018; Hassaan et al. 2021b), disease resistance (Al-Sagheer et al. 2018) and survival against ammonia stress (Abdel-Tawwab et al. 2020b). In crustaceans, limited studies have been conducted in African aquaculture with only one report on the use of Chamomile, *Matricaria chamomilla* oil in *P. indicus* juveniles (Abdel-Tawwab et al. 2022a). The results also indicated improved growth performance, antioxidant capacity, immunity and resistance to *V. parahaemolyticus* infection (Abdel-Tawwab et al. 2022a).

In summary, immunostimulators are useful resources for improving growth performance, antioxidant capacity and immunity, which are all important for enhanced general health and control of infectious diseases in African aquaculture. Immunostimulators offer an alternative to antibiotics for controlling bacterial pathogens in the African aquaculture industry for the expected intensive production systems in the near future. Such an approach promises the sustainable future of the industry considering that antibiotics affect severely fish health (Limbu et al. 2018, 2019, 2020, 2021; Zhou et al. 2018; Limbu 2020a) and are currently threatening global human health (Zhang et al. 2022). Therefore, concerted efforts are required to explore immunostimulants uses in African aquaculture for several species cultured, particularly to control pathogenic organisms.

1.5.6 The Use of Feed Additives for Controlling Pathogenic Organisms

Diseases are known as one of the challenges for sustainable aquaculture globally. The African aquaculture is also threatened by diseases in cultured fish. Interestingly, several feed additives have been used for controlling pathogenic organisms in African aquaculture. These include *Z. mauritiana* leaf powder to control *A. hydrophila* infection in *O. niloticus* fingerlings (El Asely et al. 2020), *Tridax procumbens* leaves extract as chemotherapy to kill *Dactylogyrus vastator* parasites in *O. niloticus* juveniles (Adeshina et al. 2021), *Citrus limon* peels in *O. niloticus* and *C. gariepinus* chemotherapeutic against *A. hydrophila* (Abdel Rahman et al. 2019) and seaweeds mixture extract as antibacterial agents in Striped catfish (*Pangasianodon hypophthalmus*) fry (Abdelhamid et al. 2021). Expectedly, the feed additives used controlled pathogenic organisms by enhancing antioxidant capacity (Abdel Rahman et al. 2019; El Asely et al. 2020; Abdelhamid et al. 2021; Adeshina et al. 2021) and immunity (Abdel Rahman et al. 2019; El Asely et al. 2020; Abdelhamid et al. 2021; Adeshina et al. 2021), resulting in improved well-being of fish. The results from these studies highlight the importance of using feed additives to control pathogenic organisms, which cause significant economic loss in African aquaculture. Feed additives are potential functional supplements that could be successfully used as cheap curative agents in aquaculture to enhance disease resistance and avoid economic losses for sustainable African aquaculture industry.

1.5.7 The Use of Minerals as Feed Additives in African Aquaculture

Most minerals used in aquaculture are currently applied as nanoparticles as indicated above in this chapter. However, a few minerals are also used as feed additives in African aquaculture for *O. niloticus* at various development stages. These include silicate clay used in *O. niloticus* fingerlings (Hassaan et al. 2020a), phosphorus supplemented with phytase enzyme as digestive enhancer in *O. niloticus* juveniles (Abo Norag et al. 2018) and zinc oxide in *O. niloticus* adults (Soaudy et al. 2021). The use of the minerals as feed additives enhanced growth rate (Abo Norag et al. 2018; Hassaan et al. 2020a), reproduction performance (Soaudy et al. 2021), immunity (Abo Norag et al. 2018; Hassaan et al. 2020a), feed utilization and digestive enzymes activities (Hassaan et al. 2020a), antioxidant capacity (Soaudy et al. 2021), modulated lipid metabolism (Abo Norag et al. 2018; Soaudy et al. 2021) and gut microbiota of *O. niloticus* (Hassaan et al. 2020a). In short, minerals used as feed additives in aquaculture improve growth performance and health status of cultured fish for protein production required by the growing African population.

1.5.8 Feed Additives as Water Quality Cleaning Agents

The growth and general health in aquaculture are also affected by water quality parameters in the culture systems. Water quality parameters influence feeding, immunity and disease risk due to stress. Accordingly, several feed additives are used in African aquaculture to improve water quality parameters. Indeed, seaweed liquid extract (Ashour et al. 2021b), and *Y. schidigera* and/or *S. cerevisiae* (Abdel-Tawwab et al. 2021b) were used as natural agents to rearing water in *O. niloticus* fingerlings and juveniles, respectively. Moreover, rice straw and zeolite were used water for rearing *O. niloticus* juveniles as bioadsorbents for removing pollutants (El Saidy et al. 2020), while yucca extract was used as water additive for *C. carpio* juveniles as ammonia absorbent (Dawood et al. 2021b). The feed additives used were effective to removal most pollutants in water, thereby improved growth performance (Abdel-Tawwab et al. 2021b; Ashour et al. 2021b; Dawood et al. 2021b), nutrients metabolism (Abdel-Tawwab et al. 2021b), biochemical parameters (El Saidy et al. 2020; Dawood et al. 2021b), histologic architecture (El Saidy et al. 2020; Dawood et al. 2021b), antioxidant capacity (Dawood et al. 2021b), health status (El Saidy et al. 2020; Ashour et al. 2021b), immunity (Dawood et al. 2021b), and resistance of fish against pathogenic bacteria challenge and modulated natural microbiota in the

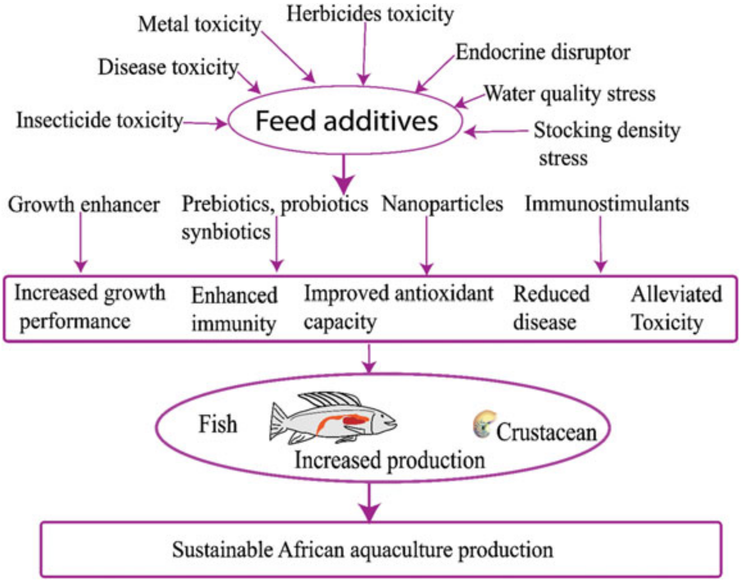

Fig. 1.2 The types and roles of feed additives used in African aquaculture

water (Ashour et al. 2021b). Overall, feed additives provide a solution for water contamination in aquaculture for improved fish growth, immunity and general health for enhanced production and sustainability of the African aquaculture industry.

Taken together, the African aquaculture uses several feed additives as growth promoters, prebiotics, probiotics and synbiotics, nanoparticles and immunostimulants to alleviate toxicity of various xenobiotics and stressful conditions, control pathogenic organisms and water cleaning purposes (Fig. 1.2). Ultimately, feed additives used improve production, and general health of fish and crustaceans for sustainable African aquaculture industry.

1.6 Conclusion

The African aquaculture industry feeds fish by using mixed protein levels, restriction and re-feeding, on-farm feeds and supplemental feeds with fertilization. The industry utilizes and array of technologies, including fermentation, supplementing with various nutrients modulators to ensure optimum growth of cultured fish, enhanced feed efficiencies and reduced feed cost for sustainability of the industry. Fish nutritionists in Africa are working tirelessly to replace the limited and expensive ingredients, such as fishmeal and soybean through various feed additives, whether singly or in combination for improving growth performance, immunity, and general health of fish and crustaceans. Feed additives are used for various purposes, including alleviating toxicity of multiple xenobiotics and stressful factors, functional feed, nanoparticles, immunostimulators, mineral sources and for cleaning water used in aquaculture for improved fish growth performance, immunity and general health for enhanced production and sustainability of the African aquaculture industry. The African aquaculture holds potential for supplying aquatic products for the blue economy.

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Chapter 2
Feed Restriction as a Feed Management Strategy in Tilapia and Catfish Culture: An African Perspective

**Ndakalimwe Naftal Gabriel, Kenneth Prudence Abasubong,
and Benjamin U. Akpoilih**

Abstract Aquaculture is recognised throughout Africa as an option with the ability to contribute significantly to food security, job development, wealth generation, and community empowerment, just as elsewhere in the world. However, the high feed cost and the limited availability of feed components prevent this industry from reaching its full potential. Diverse feed management strategies have been investigated and developed in various aquaculture systems to reduce feed costs without sacrificing fish production performance by reducing feed ration. This chapter reviewed feeding rate (% body weight per day), feeding frequency, and cyclic feeding (feed deprivation and refeeding cycles) as feed management strategies in tilapia and catfish species, focusing on their applicability in African aquaculture. The optimal feeding rates and frequency at various stages and temperatures have been determined for tilapia and catfish species; these feeding strategies reduce feed ration, enhance feed utilisation, and promote fish growth. Cyclic feeding appears to be a relatively novel concept, yet it has the potential to save feed without impacting fish production in the studied species, mainly when the feeding regime is not severe (feeding days are more than starvation days). These feed management solutions are suitable for African farmers since they do not necessitate additional financial resources or technologically advanced equipment beyond competent labour. However, information on the influence of these feeding strategies on fish physiological

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responses, water quality, and economic parameters in various aquaculture systems worldwide is still needed for better optimisation.

Keywords Aquaculture · Cyclic feeding · Cichlid · Catfish · Feeding rate · Feeding frequency

2.1 Introduction

Aquaculture is one of the world's fastest-growing food-producing industries. It is recognised as one of the options in Africa and elsewhere in the world that can significantly contribute to food security, poverty alleviation, job development, and community empowerment, among other things. Between 1995 and 2018, Africa's aquaculture production climbed from 110,200 to 2,196,000 tonnes, representing a compound annual growth rate of 15.5% (FAO 2020). Although small compared to other parts of the world, Africa's extraordinary production performance is due to several factors, including capacity growth in key aquaculture sectors, good governance, private sector involvement, and intensification of production aquaculture systems (Satia 2017). Nonetheless, more work needs to be done for aquaculture to be sustainable, as difficulties, such as high reliance on formulated feed, poor water quality, increased disease susceptibility, high energy demand, and chemical use, among others, make intensification both a blessing and a curse.

Aquaculture's long-term viability depends on cost-effective production strategies with little environmental impact. Feeding is one of the activities in aquaculture that needs to be optimised because overfeeding can result in more significant production costs and water pollution, whilst underfeeding can result in poor growth performance and economic loss (Yogev et al. 2020). Feed costs often account for 40–60% of overall aquaculture production costs, making it challenging to translate the benefits of higher productivity associated with commercial feeds into economic gains when fed fish are fed according to conventional procedures. To improve aquaculture earnings, fish farmers have devised numerous feeding management systems that reduce feed inputs, water quality problems, and labour costs. Mixed feeding, such as commercial pellets mixed with farm-made feed (Akinwole and Faturoti 2007), and restricted feedings, such as feeding rate, feeding frequency, and cyclic feeding, are some strategies (Ali et al. 2003) (Fig. 2.1).

Feed restriction is a generally practised feed management approach in aquaculture (Maciel et al. 2018; Assis et al. 2020). This strategy is based on evidence that, in nature, fish may go without food for a long time and survive by utilising stored energy and can compensate for growth when feeding is resumed (de Souza e Silva et al. 2019; Assis et al. 2020). Feeding after starvation can result in overcompensation growth (higher growth than typically fed fish) (Hayward et al. 1997), complete/total compensation (same growth as typically fed fish) (Jobling and Johansen 1999), or partial compensation (lower growth than typically fed fish) (Hayward et al. 1997; Paul et al. 1995). Feed restriction is a feed management method because in addition to boosting fish growth, it also improves fish health (de Souza e Silva et al. 2019),

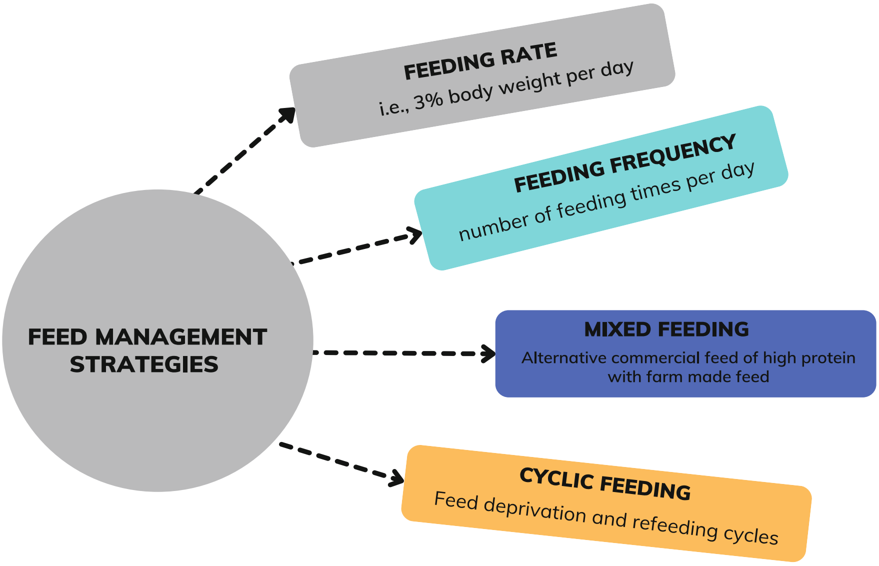

Fig. 2.1 A schematic representation of some feed management strategies in fish farming

water quality (Turano et al. 2008), and economic benefits (Turano et al. 2008; Khan et al. 2009). Moreover, this feed management strategy has been widely reported in a range of fish species, including tambaqui, *Colossoma macropomum* (Assis et al. 2020), actinopteri, *Brycon amazonicus* (Urbinati et al. 2014), marine shrimp (Maciel et al. 2018), common carp, *Cyprinus carpio* (Tiogué et al. 2017), and tilapia species (Abdel-Tawwab et al. 2006; Bolivar et al. 2006; Tiogué et al. 2017; Gabriel et al. 2018).

Therefore, this chapter covers several feed management strategies, such as feeding rate, feeding frequency, and cyclic feeding, as feed management measures in aquaculture, with particular focus on tilapia and catfish species; these are Africa's most popular aquaculture fish species (Adeleke et al. 2020). The chapter also discusses their present advancements and perspectives on their application in African aquaculture.

2.2 Feed Restriction in Aquaculture

Several feed restriction strategies are part of the critical knowledge necessary to improve productivity when adopting a fish in aquaculture. Feeding strategies are influenced by various parameters, including fish species, size, health, culture environment, feed, and the type of culture system (Schram et al. 2009). Fish fed until they are satiated or at a high feeding rate have been demonstrated to develop poorly due to low feed utilisation efficiency (Yakupitage 2013) (Fig. 2.2). As a result, the

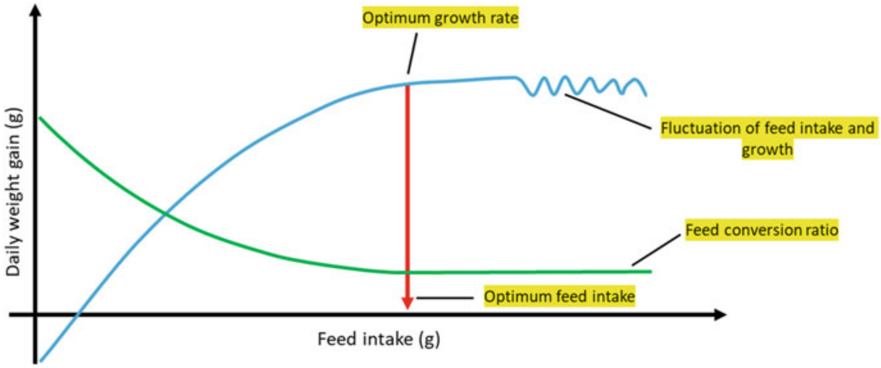

Fig. 2.2 A schematic illustration of fish growth and feed intake for a specific size (Yakupitage 2013)

feeding rate, feeding efficiency, and various cyclic feeding regimes in various fish species have been extensively studied, with some of them being used in aquaculture to maximise growth and profit.

2.2.1 Feeding Rate and Feeding Frequency

The feeding rate estimates how much feed should be delivered depending on the animal's body weight, total fish biomass in the culture pond, and water temperature (Goddard 1996). For example, if a fish farmer stocks a pond with 100 kg of fish biomass, the quantity of daily feed that can be supplied if they must be fed at 4% of their body weight may be calculated as follows (Wurts 2015):

$$\begin{aligned}\text{Daily feed ration} &= \text{biomass}(\text{kg}) \times \text{feeding rate}(\%)\\ &= 100\,\text{kg} \times 4\%\\ &= 4\,\text{kg of feed}.\end{aligned} \tag{2.1}$$

Additionally, the feeding rate should consider the relationship between the specific growth rate and the ration for that size at a given temperature (De Silva and Anderson 1994). In general, the feeding rate of most fish species studied decreases as the fish grows larger (Halver and Hardy 2003). Feeding frequency, on the other hand, refers to how many times per day a feed is supplied (Davis and Hardy 2022). Most fish are fed many times, and the frequency of feeding also decreases as the fish develops; feeding is mainly controlled by the stomach's ability to hold feeds, as well as the fish's nutritional demand, growth, and other physiological processes (Craig et al. 2017). The feeding frequency may also be impacted by the quality of the water, the feeding technique, the expectation of increased production, and the size uniformity of the fish (Davis and Hardy 2022). Nonetheless, understanding when and how much to feed promotes good fish growth, feed efficiency, a reduced feed conversion ratio, and the preservation of culture water quality.

2.2.1.1 Feeding Rate and Frequency in Some Tilapia Species

The feeding regime of genetically improved farmed Nile tilapia, *Oreochromis niloticus,* has been established in non-circulating and non-biofiltered systems. Huang et al. (2015) studied the effects of different feeding frequencies (two and three meals per day) and feeding rates (2, 4, 6, 8, 10%) on the growth and physiological response of GIFT fry fed a 34% crude protein (CP) diet at 28.2 °C water temperature for over 70 days. According to this research, a 6% feeding rate at two and three meals per day resulted in a more significant weight gain rate, specific growth rate, and better physiological performance (Huang et al. 2015). Hisano et al. (2021) reported that when Nile tilapia fingerlings (5.36–1.45 g) were fed a 32% (CP) diet at 5–3% of their body weight in the biofloc system in a water temperature range of 22.20–22.47 °C, they exhibited more significant weight gain and protein efficiency ratio, with no impact on general health. Chowdhury (2011) reported in a comprehensive study on Nile tilapia that the optimal daily feeding rate of juveniles (1.1 g) was 10–8% in the first week and 8–6% in the second week, and 3% for fish between 80 and 115 g and 1.2% for fish larger than 260 g when fed a 34.2% CP diet at 25–26 °C and subjected to mixed feeding frequencies. This is in accordance with the published guides for feeding tilapia species at different stages, such as fingerlings (Table 2.1) and grow-out (Table 2.2) by Min (2015). Furthermore, recommended

Table 2.1 Feeding rations (g/10000 fish) for tilapia fingerlings of various sizes at various temperatures (Min 2015)

Water temp (°C)	Fingerlings size (cm)					
	<2	2–4	4–6	6–8	8–10	>10
20–22	5–15	10–50	100–250	200–1000	500–1200	1500–3000
23–24	10–28	40–120	150–400	400–1500	800–1500	2000–4500
25–26	18–50	60–180	300–800	800–2000	1800–3000	3500–6000
27–28	22–65	100–300	450–1000	1500–3000	2500–5000	5000–7000
29–30	40–100	200–600	550–1500	40,000–7000	6000–8000	12,000–16,000

Table 2.2 Tilapia feeding rations (percentage of body weight/100 kg fish) in the grow-out culture stage (Min 2015)

Water temp (°C)	Fish size (g)			
	<50	50–200	200–500	>500
16–18	1–2	1–2	0.5–1	0.1–0.5
18–20	2–4	2–3	1–2	0.5–1
20–25	4–6	3–4	2–3	1–1.5
25–30	6–8	4–6	3–4	1.5–2
Above 30	4–6	3–4	2–3	1–1.5

tilapia feeding practices should be carried out with common sense, for example, (1) the feeding rate should be adjusted depending on the weather condition, water temperature, and water quality. For instance, the feed amount should be reduced when the water temperature is above 30 °C, as failure to do so will result in the decomposition of uneaten feed, which degrades water quality; (2) feeding should also be reduced when the water temperature is below 20 °C, due to the fish's poor appetite; (3) improved fish performance may be gained by feeding fish twice a day between 8:00 a.m. and 10:00 a.m., and 2:00 p.m. and 4:00 p.m.; and (4) fries and fingerlings should be fed in shallow water near the pond dike (Min 2015).

2.2.1.2 Feeding Rate and Frequency in Catfish Production

Similar to other fish species, the feeding regime required for optimising feed efficiency and growth performance in catfish is influenced by the interaction of several factors, including feed composition (Li et al. 2004; Marimuthu et al. 2011), ratio size (Dada et al. 1998), fish species (Li et al. 2005; Akomoda et al. 2019), size (Robinson and Li 2007), and environmental factors (e.g. temperature and dissolved oxygen) and experimental conditions (e.g. photoperiod) (Almazán-Rueda et al. 2004). If feeding level and frequency are not optimised, they impact fish nutrient utilisation (Nwanna et al. 2012; Elesho et al. 2021) and, ultimately, growth performance (Li et al. 2005). For example, Okomoda et al. (2019) investigated the effect of different feeding frequencies on the growth and nutrient utilisation of African catfish (*Clarias gariepinus*) fry and fingerlings by feeding the fry ad libitum with decapsulated *Artemia* cysts 1, 2, 3, 4, 5, or 6 times per day. The fingerlings were fed an equal daily ration (15% body weight per day) of a commercial diet administered in one, two, three, or four meals per day. This study discovered that fry fed five or six rations per day and fingerlings fed three or four meals of the same ration per day grew faster than those fed less frequently (Okomoda et al. 2019). Similarly, feeding African catfish (44 g) a methionine adequate diet once daily for 32 days resulted in lower feed intake and nutrient digestibility than providing two or six meals per day (Elesho et al. 2021). *Heterobranchus bidorsalis* (Clariidae family) fry (30 mg) can be fed as many as 40 meals per day (Dada et al. 1998), and *H. bidorsalis* fingerlings (about 10 g) had the best growth performance when provided 4–6 meals per day (Dada 2012). Ndome et al. (2011) reported that when fed a compounded diet (42% CP) two–three times daily, fingerling (4.12 g) of hybrid catfish (*C. gariepinus* × *H. longifilis*) showed the lowest feed conversion ratio (FCR) and the highest feed efficiency when compared to other feeding frequencies (one, four, or five meals a day). *Clarias gariepinus* and *H. bidorsalis* feeding frequency could reflect variability in culture conditions, diet composition, and fish species (Dada and Olarenwaju 2002; Marimuthu et al. 2011).

Studies concluded that catfish post-fry (0.10–1.3 g) could be fed two to three times per day at an 8% body weight rate (Asiwaju et al. 2014), whereas advanced fingerling reared in grow-out ponds can be fed compounded feed (40–42% CP) at a 5–10% body weight/day rate in three equal meals per day (Aderolu et al. 2010; Ajani

Table 2.3 African catfish, *Clarias gariepinus,* feeding rate (% body weight/ day) at different temperatures (Hecht 2013)

	Fish size (g)					
Water temp (°C)	1–10	10–25	25–50	50–100	100–300	300–800
16–18	1.0–3.0	0.6–1.6	0.4–1.0	0.3–0.8	0.2–0.6	0.2–0.5
18–20	3.0–5.0	1.6–3.0	1.0–2.0	0.8–1.5	0.6–1.2	0.5–1.0
20–22	5.0–6.8	3.0–4.5	2.0–3.0	1.5–2.4	1.2–2.0	1.0–1.7
24–26	6.8–8.1	4.5–6.0	3.0–4.0	2.4–3.0	2.0–2.5	1.7–2.2
26–28	8.1–9.5	6.0–6.6	4.0–5.1	3.0–3.6	2.5–3.2	2.2–2.8
28–30	9.5–10.0	6.6–7.0	5.1–5.5	3.6–4.0	3.2–3.5	2.8–3.1
30–32	9.5–9.8	6.5–6.8	5.0–5.3	3.5–3.7	3.0–3.2	2.8–2.9

et al. 2011; Lawan et al. 2017; Akomoda et al. 2019; Abanikannda et al. 2019; Marimuthu et al. 2011) (Table 2.3). But, depending on the experimental rearing conditions, limiting feed intake (>5% of body weight) may make fish eat more often per day because they are not getting as many nutrients (Akomoda et al. 2019), especially for smaller fish (0.88–0.98 g) (Arshad Hossain et al. 2010). Interestingly, fish that are fed at night do better than fish that are fed during the day because they swim more (Arshad Hossain et al. 2010). Larger catfish can optimise feed intake and growth with two meals per day as opposed to three to four meals per day (Pantazis and Neofitou 2003; Ayisi et al. 2021).

2.3 Feeding Deprivation and Refeeding Cycles in Aquaculture

As briefly mentioned above, many aquatic animals in the wild go hungry for short periods due to seasonal changes, reproduction, and spawning migration (McCue 2010; Li et al. 2018). To deal with this type of short-term starvation, aquatic animals have evolved compensatory mechanisms. The activation of acute-phase protein production, which protects the fish from oxidative stress, is one of these (Sakyi et al. 2020). Fish growth in captivity has increased with feed deprivation and refeeding programs (Mohanta et al. 2017). This is because fish have increased hyperphagia (high feed appetite) after starvation and during the refeeding period, which could help aquatic animals achieve higher growth efficiency by increasing food intake, improving digestion and absorption, and decreasing total feed consumption (Abdel-Tawwab et al. 2006; Mohanta et al. 2017; Shao et al. 2020; Py et al. 2022). Depending on the species, compensatory growth may be partial, complete, overcompensation, or absent entirely (Jobling and Johansen 1999; Mohanta et al. 2017). Feed restrictions can occur for various reasons, including low fish prices, economic pressure from high commercial feed prices, or farm disease outbreaks (Bosworth and Wolters 2005).

2.3.1 Feeding Deprivation and Refeeding Cycles in Tilapia Species

In a study by Gabriel et al. (2017), *O. mossambicus* (5.53 g) was subjected to a variety of short-term feeding, starvation, and refeeding cycles, including 2 days of starvation followed by 2 days of refeeding, 2 days of starvation followed by 3 days of refeeding, 2 days of starvation followed by 4 days of refeeding, and daily feeding (control) for 60 days. According to this study, the growth of fish that went without food for 2 days and then ate again for 4 days did not differ much from the growth of fish that ate every day (complete compensation). At the end of the trial, however, the starved fish had eaten a lot less feed than the other fish. This means that feed can be saved without hurting the performance of the fish being raised. Gabriel et al. (2018) found the same results when they fed hybrid tilapia (*O. mossambicus* × *O. niloticus*) on the exact schedules.

Similarly, Nile tilapia, *O. niloticus* juveniles that were starved for one week and then fed for another 13 weeks were found to have fully compensated for their starvation (Abdel-Tawwab et al. 2006; Gao and Lee 2012). It is interesting to note that overcompensation was observed in Nile tilapia following 2–4 days of feed deprivation and long-term feeding (80 and 185 days) (Gao et al. 2015). Feed deprivation was also successfully used to induce total compensatory growth in Nile tilapia raised in a biofloc system (6 days of feeding/one day of deprivation; 5 days of feeding/2 days of deprivation; 4 days of feeding, 3 days of deprivation) (Correa et al. 2020).

Moreover, some studies showed that feeding a combination of low- and high-protein feed for a set period causes compensatory growth in fish. For example, Liu et al. (2020) investigated whether feeding a low-protein diet (25%) once a day for 10 days or 20 days and then refeeding a high-protein diet (35%) thrice daily for 30 days or 20 days, respectively, would elicit compensatory growth in genetically improved farmed tilapia (GIFT), *O. niloticus* (11.02 0.05 g), compared to those fed 35% (control). Fish fed low-protein feed for 10 days and high-protein feed for 30 days grew similarly to controls, but the weight of those fed low-protein feed for 20 days and high-protein feed for 20 days was lower at day 20. Nonetheless, this significant difference vanished at the end of the experiment.

On the other hand, starving fish can harm their growth and other health-related factors. However, only those that have not experienced a prolonged period of severe feed deprivation can recover after refeeding (Abdel-Tawwab et al. 2006; Gao et al. 2015). Based on the evidence, it can be said that feed deprivation and refeeding regimens (such as 6 days of feeding followed by a starvation cycle lasting 1–2 days or one week of starvation followed by a long period of refeeding) can be effective for tilapia species, but caution should be used when selecting these regimens.

2.3.2 Feeding Deprivation and Refeeding Cycles in Catfish Production

Studies of feed deprivation and refeeding cycles in catfish species have also been reported, and the effects on fish vary depending on the species and length of feed deprivation, as was seen in tilapia species. Neotropical catfish (0.9 g) fed in a recirculating system for 45 days showed complete growth in fish starved for 1 or 2 days a week (de Souza e Silva et al. 2019). Li and Robinson (2005) found that fingerling channel catfish (*Ictalurus punctatus*) (14.4 g) raised in a flow-through system and fed once daily to satiation gained significantly more weight than groups that were starved for one, two, or three consecutive days per week, or one day per 5-day period, or three consecutive days per 10-day period, and fed to satiation for 82 days. Gaylord and Gatlin III (2001) found that starving channel catfish for three days and then refeeding them for 11 days to satiation for three cycles resulted in weight gain comparable to that of those fed daily to satiation. Chatakondi and Yant (2001) also found that channel catfish fingerlings (2.5 g) fed a floating diet (36% CP) for 1–3 days and then re-fed for 10 weeks to satiation gained the same weight as fish fed daily. Reigh et al. (2006) compared the production performance of channel catfish (22 g) raised in tanks and exposed to three cycles of 5 days of fasting and refeeding (57 days of feeding and 15 days of fasting) or 10 days of fasting and refeeding (42 days of feeding and 30 days of fasting) to the group that was fully fed for 72 days. They found that weight gain was 25% and 41% lower, respectively, than the body weight of fully fed fish (Reigh et al. 2006).

Similarly, Ali and Jauncey (2004) found that 13.05 g of *C. gariepinus* fed a 35% CP diet that included repeated cycles of feed restriction and feeding until satiation (14, 7, 3, and 2 days) showed some compensatory growth. Reduced growth in the starved group could be attributed to lower levels of lipid and protein in the liver and muscle, indicating decreased liver metabolism and nutrient deposition in the flesh (Luo et al. 2009). Similar to tilapia species, it is evident that feed deprivation and refeeding regimes could also work in catfish species, and a longer duration of refeeding could maximise growth and reduce feeding costs, as demonstrated by Ofor and Ukpabi (2013).

2.4 Conclusion and Perspectives

The importance of feed management in aquaculture cannot be emphasised, especially in an era of scarce resources. Different feed management strategies, such as restricted feeding levels, feeding frequency, and feeding deprivation/refeeding cycles, are being investigated in numerous fish species, including tilapia and catfish. Most of the research indicate that certain levels of feeding rate, feeding frequency, and feeding deprivation and refeeding cycles tend to lower the amount of feed, enhance feed utilisation, and, ultimately, increase fish growth performance. African fish farmers at all levels may be able to implement these tactics for improved feed management, given that they do not necessitate additional financial resources other than skilled staff. However, there is still much work before feed management systems can be broadly implemented. For example, the economic question (i.e. feed cost savings and profit) and water quality are not well addressed for various restricted feeding management strategies in various aquaculture production systems. As the response can be species-specific (Schram et al. 2009), the feeding management strategies highlighted in this chapter should be applied to a broader range of tilapia and catfish species cultivated in Africa. For better optimisation, future research should further elaborate on the impact of restricted feeding as a feed management approach on the physiological parameters of fish in various culture systems.

Overall, regulated feeding is a crucial aspect of feed management that contributes to the sustainability of the aquaculture industry.

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Chapter 3
Black Soldier Fly (*Hermetia illucens*) Larvae Meal as a Sustainable Protein Source for Fish Feed Production in Kenya

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Abstract Aquaculture has been ranked as one of the fastest-growing food sub-sectors, providing quality protein to better the livelihoods of rural communities alongside curbing malnutrition and food security globally. Nonetheless, the industry's sustainability has been threatened by the high cost of fish feeds, which account for approximately 60–70% of the total operational costs. Fish meal (FM) has been extensively utilised as the main source of protein in the diets of farmed finfishes. However, due to declining capture fisheries and competing uses from other animal feed producers, the ingredient has become a scarce resource with limited availability and high prices. Black soldier fly larvae (BSFL) have been identified as a promising alternative protein source in fish feeds. BSFL are documented to have high nutritional content: crude protein (of up to 64% dry matter), essential amino acids, fatty acids, and other micro-nutrients which are vital for the growth of fish. BSFL meal has the potential success of replacing FM in the diets of various fish species. This chapter focuses on analysing recent research work in BSFL proximate and chemical composition, its current utilisation in fish feeds and gaps to be filled in its complete utilisation as an ingredient in commercial feed production. This information is expected to help both cottage and commercial fish feed producers utilise BSFL in feed production in Kenya and further will promote the sustainability of the aquaculture industry.

Keywords Aquaculture · Black soldier fly larvae · Fish feeds · *Oreochromis niloticus*

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3.1 Introduction

The aquaculture industry is faced with the challenge of the high cost of feeds which represents up to 60–70% of operational costs in fish production (Holeh et al. 2020). Fishmeal and fish oil have been the main source of protein and essential fats in the aquatic feed production (Betancor et al. 2016). This is due to the high nutritional value of fishmeal, balanced essential amino acids profile, high essential fatty acids, and phospholipids near to requirement levels of most cultivated aquatic organisms (Tacon 2018). However, high global demand and competition for fish meal (FM) from other animal feed manufacturers have increased the prices of the products, and the global supplies are on the decline (Montoya-Camacho et al. 2019; FAO 2020). These economic and sustainability concerns have led to the search for non-conventional ingredients from both plant and animal sources to replace fishmeal in fish diets (El-Sayed and Tacon 1997; El-Sayed 1998; Hasan and Chakrabarti 2009; Katya et al. 2017; Khalifa et al. 2018; Alfaro et al. 2019).

Research on insects focuses on various species of Coleoptera and Diptera, including the Black soldier fly (*Hermetia illucens*) (Burtle et al. 2012), common houseflies (*Musca domestica)* (Awoniyi 2007) and beetles (*Tenebrio molitor*) (Khosravi et al. 2018) as a potential replacement of fishmeal in aquaculture nutrition have gained attention in the recent years. This is attributed to the fact that they contain high protein levels with high availabilities since they can be reared on low-grade bio-wastes to effectively convert organic wastes into high-quality proteins (Veldkamp et al. 2012; Shumo et al. 2019a, b). Black soldier fly larvae (BSFL) appear to be superior among other insects as a potential source of animal protein for use in fish feed formulations (Henry et al. 2015). BSFL contains up to 50% crude protein (CP) and up to 35% lipids and has an amino acid profile that is similar to that of the FM (Elwert et al. 2010; Henry et al. 2015; Katya et al. 2017; Shumo et al. 2019a, b). Its sustainability is due to ease in production using organic wastes (Barragan-Fonseca et al. 2017; Ewald et al. 2020). Moreover, the Black soldier fly (BSF) is neither a non-vector nor a pest, and it is known to reduce the presence of harmful bacteria, especially *Escherichia coli* and *Salmonella enterica,* from food substrates (Liu et al. 2017; Shumo et al. 2019a, b). In most studies, dietary inclusion of BSFL in fish diets has improved fish growth, yields and reduced production cost, thus promoting profitability and resource utilisation (Kroeckel et al. 2012; Li et al. 2017; Fawole et al. 2020; Wachira et al. 2021).

3.2 Basic Culture Method of Black Soldier Fly

3.2.1 Life History and Culture Conditions

The BSF occurs in the tropical and sub-tropical regions of the world and possesses holometabolous metamorphosis (Nairuti et al. 2022). Their life cycle starts from an

Table 3.1 Abiotic factors requirements for rearing black soldier fly larvae (Barragan-Fonseca et al. 2017)

Parameter	Minimum	Optimal	Maximum
Temperature (°C)	12	26–27	36
Relative humidity (%)	25	60–70	99
Substrate moisture (%)	40	52–70	70
Light intensity/m^2/s	60	135–200	–

egg, which marks the end of the previous life stage, i.e. the female dies after laying eggs (Shumo et al. 2019a, b). A female fly lays 400–800 eggs in tiny, dry and well-sheltered cavities and close to a food source, preferably decomposing organic matter. After hatching, the cream-like larvae take up large amounts of decomposing organic matter and increase from a few millimetres to approximately 2.5 cm in length and 0.5 cm in width (Dortmans et al. 2017). Larval development takes 14–16 days under optimal conditions (Shumo et al. 2019a, b) (Table 3.1).

The pupae stage is symbolised by replacing the larval mouthparts with a hook-shaped structure and changing colour from cream to dark brown-charcoal grey. The pupation stage takes 2–3 weeks and is marked by the transformation of the pupa into a fly. The emergent fly does not feed and is only dependent on water for development along the life cycle (Dortmans et al. 2017; Zurbrügg et al. 2018). During this phase, the adult searches for a partner and copulates and the female lays eggs. The flies have been found to prefer copulating during the morning light, and females lay their eggs in well-shaded areas near substrates. Light intensity affects mating and egg fertilisation of BSF (Zurbrügg et al. 2018). The insects have higher mating activities in shaded areas, with the females ovipositing eggs in dark crevices (Shumo et al. 2019a, b).

3.2.2 Culture Substrates for BSF Larvae

The growth, production and maturation of *H. illucens* are highly dependent on the quantity and nutritional quality of the culture substrate. Adult BSF does not take up any food (Tomberlin et al. 2002) but instead survives on the food reserves built up during the larval stage and water (Diener et al. 2011; Nguyen et al. 2015). The larvae of the BSF require food that is obtained from suitable substrates. Previous studies indicate that substrates rich in protein and carbohydrates result in good larval growth and translate to larvae with high Crude protein and fat content (Dortmans et al. 2017). However, culture substrates with high oily amounts produce larvae with high lipid levels, which subsequently translates to lower protein content, because of the inverse relation of proteins and lipids in animal tissues (Mohanta et al. 2016).

Naturally, the BSF is found in faecal waste piles of livestock, poultry, swine and humans (Dortmans et al. 2017). Further, they are found colonizing domestic and wastes from industrial by-products, including kitchen vegetable and fruit wastes, decaying coffee pulp wastes and municipal organic wastes (Barragan-Fonseca et al. 2017). The presence of bacterial and fungal communities in these wastes acts as

Table 3.2 Nutritional composition of BSFL cultured in the different substrates in Kenya (Shumo et al. 2019a, b)

Parameters (% dry matter)	Chicken manure	Kitchen waste	Spent grain
Dry matter	80.7	87.7	83.1
Ash	9.3	9.6	11.6
Crude protein	41.1	33	41.3
Neutral detergent fibre	21.9	20.4	28.6
Acid detergent fibre	12.6	13.2	15
Ether extract	30.1	34.3	31

decomposition aids to further breakdown of organic matter making it easier for the larvae to access the nutrients (Dortmans et al. 2017). For the culture of BSF, the larvae can be fed on a wide range of organic food substrates rich in nitrogen and calcium (Ca) (Dortmans et al. 2017) and has a moisture content between 52 and 70% (Sophie et al. 2007; Shumo et al. 2019a, b). However, the wastes used as substrates should be free from potential pathogens, which can be harmful to human beings. They should not have food safety hazards as per the EU regulation of 2017 and must contain "products of non-animal origin" with those substrates made of flesh and manure (human food waste) explicitly excluded (EU Commission Regulation of 2017). In the United States of America, the Food and Drug Administration (FDA) also approved dried larvae of *Hermetia illucens* cultured in substrates comprising exclusively of feed grade materials containing not less than 34% CP and 32% fat for use in feeding salmonid fishes. These restrictions were implemented to fulfil the safety conditions for insect production for farmed fish and animal feed (Wang and Shelomi 2017). However, in Kenya, no regulations have been implemented to regulate the substrate used for BSFL production. The nutritional composition of cultured BSFL differs depending on the culture substrate. Substrates documented for use for BSFL culture include chicken manure, kitchen waste and spent grains (Table 3.2).

3.3 Biochemical Composition of BSF Larvae as a Feed Ingredient

3.3.1 Crude Protein and Fat Content

The protein and fat content of BSFL depends highly on the quality and quantity of the substrate used for the culture of the larvae (Nguyen et al. 2015; Barragan-Fonseca et al. 2017; Shumo et al. 2019a, b; Ewald et al. 2020). A study by Spranghers et al. 2017 reported significantly higher CP levels in larvae reared in restaurant waste (43.1%) compared to chicken feed and vegetable waste. Nguyen et al. (2015) also recorded higher protein and low fat in larvae fed on kitchen waste than those fed chicken feed. Previous studies have also reported higher fat content in

Table 3.3 Content of crude protein and crude fat (CF) of BSF larvae reared on different substrates. (Modified from Barragan-Fonseca et al. (2017)

Substrate	% Crude protein[a]	% Crude fat
Cattle manure	42.1	34.8
Chicken manure	40.1; 41.1	27.9
Swine manure	43.6; 43.2	26.4
Palm kernel meal	42.1; 45.8	27.5
Restaurant waste	43.1	39.2
Chicken feed	47.9	14.6
Liver	62.7	25.1
Fruits and vegetables	38.5; 30.84	26.63; 33.10
Fish	57.9	34.6

[a] All values are expressed on a dry matter basis

larvae reared on cattle manure (34.8%) in comparison to chicken (27.9%) and swine manure (26.4%) (Table 3.3).

3.3.2 Amino Acid Content

Essential amino acids (AA) are important in fish feeds and should be considered when selecting a fish feed ingredient. The AA content in BSFL is mainly influenced by the processing efficiency of the larvae. Defatting, which involves the mechanical or chemical removal of fat from the larvae, has been found to help increase the amino acid content of dried BSFL meal (Renna et al. 2017). Most studies have shown that the amino acid contents of the BSFL do not differ much based on the culture substrate (Table 3.4). However, some AA, like methionine, have been reported to be relatively low in BSFL meal compared to FM. Generally, BSFL meal has a good protein quality compared to FM and has higher contents of arginine, isoleucine, alanine, valine histidine and tryptophan (Barragan-Fonseca et al. 2017).

3.3.3 Fatty Acids Content of BSF Larvae

The BSF larvae meal is rich in monounsaturated fats but has lower polyunsaturated fatty acid percentages compared to other insects, such as housefly maggots, mealworms and adult crickets used in animal feed (Ghosh et al. 2017). BSFL contain between 58 and 72% saturated fatty acids and 19 and 40% mono- and polyunsaturated fatty acids (Table 3.5) (Larouche 2019). The quality and quantity of fatty acid content in the BSFL are highly influenced by the type of substrate used. They tend to accumulate more lipids when the larvae are fed on a lipid-rich animal diet (Wang and Shelomi 2017). Larvae fed on fish by-products and fish wastes have increased levels of n-3 polyunsaturated fatty acids (n-3 PUFA), a-linolenic acid (ALA), eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) in their tissues

Table 3.4 Amino acid profile of the BSF larvae. (Source: Spranghers et al. (2017)

Parameter (g/kg dry matter)	Chicken feed	Digestate	Vegetable waste	Restaurant waste
Essential amino acids				
Isoleucine	17.2	18.4	17.3	19.1
Leucine	28.6	29.5	28	30.6
Lysine	23.4	25.7	22.6	23
Arginine	20.3	20.3	20	19.9
Methionine	7.6	8.7	7.6	7.1
Histidine	13.6	13.5	12.4	3.8
Phenylalanine	17	18.7	16.3	16.4
Threonine	16.4	16.8	15.4	16.2
Non-essential amino acids				
Alanine	25.2	24.3	24.2	27.8
Cystine	2.5	2.4	2.1	2.2
Glutamic acid	41.9	39.8	41.3	45.8
Glycine	22.6	22.6	22.2	25.2
Proline	22.5	22.1	21.4	25.1
Serine	16.6	15.5	15	15.9
Aspartate	37.8	33.6	35.9	36.9
Tryptophan	6.7	6.2	5.8	5.4
Valine	24.1	24.9	24.8	28.2

Table 3.5 Fatty acid profile of the black soldier fly larvae. (Data adapted and modified from (Larouche 2019))

Parameter (% lipid)	Content in BSF larvae (Oonincx et al. 2015; Liu et al. 2017)
Lauric (C12:0)	29–61
Myristic (C14:0)	7–10
Palmitic (C16:0)	8–17
Palmitoleic (C16:1n-7)	3–7
Stearic (C18:0)	1–3
Oleic (C18:1n-9)	8–18
Linoleic (C18:2n-6)	4–17
Alpha-linolenic (C18:3n-3)	0–2
Unsaturated fatty acid	18–37
Saturated fatty acid	58–80

(Sophie et al. 2007; Renna et al. 2017). This indicates that BSFL provide the necessary fatty acids requirements to meet the different nutritional requirements of different fish species, which is 0.5–1% (Andersen et al. 2016).

3.3.4 Mineral Content of BSF Larvae

The mineral content of the BSFL larvae is profoundly influenced by the type of substrate used for feeding the larvae and the stage of development (Table 3.6). For instance, a study by Shumo et al. (2019a, b) reported higher phosphorus levels in BSFL reared on spent grain compared to kitchen waste and cattle manure. High Ca has been reported in larvae fed on digestate compared to chicken feed, vegetable and restaurant waste. The high Ca concentration and ash contents (9 and 28% dry matter, respectively) reported in the larvae were attributed to the secretion of calcium carbonate ($CaCO_3$) by the epidermis (Finke 2013). On the other hand, the low Ca content (0.03%) in the newly emerged adults has been attributed to the fact that the pupal cuticle that is concentrated with Ca is shed off to give rise to the adult fly, indicating that the Ca levels are affected by the larvae stage of development (Finke 2013; Spranghers et al. 2017).

3.4 Utilisation of BSF Larvae in Fish Feed Formulation

Earlier studies have documented the utilisation of BSFL in fish feed formulation (Henry et al. 2015; Barragan-Fonseca et al. 2017; Katya et al. 2017; Dietz and Liebert 2018; Fawole et al. 2020; Wachira et al. 2021). BSFL have attracted enormous attention due to their higher reproductive capacity, short life cycle, ability to convert organic matter into high-quality protein and their capacity to thrive in a wide array of environments (Barragan-Fonseca et al. 2017). Additionally, the high protein content, digestibility, and amino acid profiles of the BSFL have been the selling point for this meal in fish diets. The BSFL meal has successfully replaced conventional protein sources in the diets of salmon (*Salmo salar*) (Weththasinghe et al. 2021), African catfish (*Clarias gariepinus*) (Fawole et al. 2020), European sea bass (*Dicentrarchus labrax*) (Moutinho et al. 2021), Nile tilapia (*Oreochromis*

Table 3.6 Mineral composition of BSF larvae reared on three different rearing substrates. (Data adapted and modified from Tschirner and Simon (2015) and Shumo et al. (2019a, b))

Mineral composition g/kg DM)	Cattle manure	Kitchen waste	Spent grain	Sugar beet pulp	Requirements by fish (National Research Council (NRC) 2011)
Phosphorus	3.9	4.1	4.6	1.3	7 g
Potassium	4.9	5.7	4.4	1.9	1–3 g
Calcium	3.2	2.0	1.7	6.2	5 g
Magnesium	4.0	3.3	3.5	0.5	500 mg
Iron	0.6	2.2	0.3	0.02	50–100 mg
Copper	0.4	0.2	0.5	1.2	1–4 g
Manganese	1.4	0.9	1.1	0.05	20–50 mg
Zinc	0.3	0.3	0.3	0.01	30–100 mg

niloticus) (Nairuti et al. 2021; Wachira et al. 2021), rainbow trout (*Oncorhynchus mykiss*) (Sophie et al. 2007) and turbot (*Psetta maxima*) (Kroeckel et al. 2012).

3.5 BSF Larvae Meal Effect on Fish Growth Performance

The inclusion of BSFL meals in the diets of *O. niloticus* do not lead to any negative effect on the body weight gain (BWG) and specific growth rate (SGR) of the fish (Devic et al. 2018; Toriz-Roldan et al. 2019). Similarly, a partial or total dietary replacement of FM with BSFL meal did not lead to differences in the BWG and SGR of juvenile Japanese bass (*Lateolabrax japonicus)* and rainbow trout (*Oncorhynchus mykiss*), respectively (Wang and Shelomi 2017). A study carried out by Fawole et al. (2020) recorded better final weight and BWG when 50% FM was replaced by BSFL meal in the diets of *C. gariepinus*. Similarly, Muin et al. (2017) reported the highest weight gain and SGR values when BSFL meal was used to replace 50% FM in the diets of Nile tilapia (Table 3.7). Additionally, BSFL meal has been demonstrated to be a promising FM replacement in the diets of the pacific white shrimp (*Litopenaeus vannamei*) at a 25% inclusions level (Cummins et al. 2017).

3.6 Cost Reduction of Fish Feeds Using Black Soldier Fly Larvae Meal

Reducing feed costs is critical to the profitability and sustainability of aquaculture production since fish feeds account for more than half of the operating cost (Holeh et al. 2020). BSF larvae have lower prices than other animal-based products, like fish and soybean meals in Kenya. The cost of dry BSFL ranges from 0.5 to 0.7 USD, while the FM is from 0.9 to 1.2 USD and soybean meal is from 1.5 to 1.7 USD in Kenya (Nairuti et al. 2022). These low costs of BSFL could be because they are produced and fed on low-value organic wastes, which are readily available (Shumo et al. 2019a, b). Previous studies have reported a reduction in the cost of feed when BSF meal was used to replace primary conventional sources of proteins, especially soybean meal and FM (Onsongo et al. 2018; Wachira et al. 2021). Abdel-Tawwab et al. (2020) reported decreased diet costs at increasing levels of BSFL meal in European sea bass diets from 0.71 to 0.60 USD kg^{-1}. Similarly, Wachira et al. (2021) recorded 14.4% cost reduction in feed production when the FM was replaced by a BSFL meal at 100% for Nile tilapia diets and a cost–benefit ratio of 2.172 when 33% of FM was replaced with BSFL meal. This indicates that the utilisation of BSFL reduces the cost of feeds used in fish production.

Table 3.7 Growth performance of different species of fish fed diets with different BSFL meal levels. (Adapted and modified from Nairuti et al. (2022))

Fish species	Attribute/element tested	Replacement levels (%)
Jian carp (*Cyprinus carpio*) (Li et al. 2017)	Substitution of 100% FM by defatted BSFL meal in diets for Jian carp had a negative effect on growth performance and feed utilisation efficiencies	0, 25, 50, 75, **100**
Meagre (*Argyrosomus regius*) juveniles (Guerreiro et al. 2020)	10% of *Hermetia illucens* can be included in Meagre diets without major adverse effects on growth, feed utilisation, whole-body composition and fatty acid profile; further increase in the substitution rates leads to negative effects on the growth performance parameters	**10,** 20, 30
Nile tilapia (*Oreochromis niloticus*) (Dietz and Liebert 2018)	Replacement of soy protein concentrate by partly defatted BSFL meal up to a level of 50% had no negative effect on growth performance and improved the dietary protein quality of tilapia feeds under study	25, **50,** 100
Siberian sturgeon *(Acipenser baerii*) (Caimi et al. 2020)	Overall, this study showed that it is possible to replace up to 25% of FM with BSFL meal in the diet of Siberian sturgeons (equal to 18.5% HIM inclusion level) without affecting the growth performance	**25**, 50, 100
Rainbow trout (*Oncorhynchus mykiss*) (Dumas et al. 2018) Nile tilapia (*Oreochromis niloticus*) (Muin et al. 2017)	The maximum inclusion of BSFL meal recommended in rainbow trout diets is 13%; further increase in the substitution leads to a decrease in the growth parameters The study suggests that substitution of FM with BSFL up to 100% is possible without any negative effects on the growth performance, feed utilisation efficiency, body composition	0, 6.6, **13.2**, 26.4 0, 25, 50, 75, **100**
European sea bass (*Dicentrarchus labrax*) (Abdel-Tawwab et al. 2020)	With the 3 substitution levels of FM with BSFL meal at (25, 35 and 50%), BSF larvae meal can effectively replace FM up to 50% without any negative effects on the growth performance	25, 35, **50**
Rice field eel (*Monopterus albus*) (Hu et al. 2020)	Lower substitution rates (5.26, 10.52%) of FM by BSFL meal in the diets of Rice field eel exhibited low values of the growth performance parameters as compared to higher substitution rates of FM by BSF larvae meal made at 15.78%	5.26, 10.52, **15.78**
African catfish (*Clarias gariepinus*) (Fawole et al. 2020)	Substitution of FM by BSFL up to 75% leads to no negative effects on the growth performance and nutrient utilisation	0, 25, 50, **75**
Juvenile turbot (*Psetta maxima*) (Kroeckel et al. 2012)	The maximum inclusion of BSFL meal recommended in Juvenile turbot diets is 33%; further increase in the substitution	0, 17, **33,** 49, 64, 76

(continued)

Table 3.7 (continued)

Fish species	Attribute/element tested	Replacement levels (%)
	leads to a decrease in the growth performance parameters and nutrient utilisation	

*Values in bold represent the recommended replacement or inclusion levels

3.7 Conclusion

The BSF larvae have shown very promising results in aquaculture due to their high levels of CP, balanced amino acid profile and fatty acid profile, together with high mineral contents, which makes them suitable as a dietary component in fish feed. Different studies have reported that it can replace FM up to100% in diets of several fish species. However, in some cases, levels above 50% have resulted in a negative effect on growth performance. This is probably due to the high chitin and fat content of the larvae. Therefore, proper culture systems for the BSFL and further processing by defatting and removing the chitin contents can improve the utilisation of BSFL by a wide range of fish species to improve fish growth performance and reduce aquaculture production costs. Further work to promote BSFL rearing and commercialisation in Kenya is needed to achieve the full potential of its use as a protein feed ingredient. BSFL rearing will also provide additional ecosystem services through municipal and organic waste management leading to environmental ecological balance.

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

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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

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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

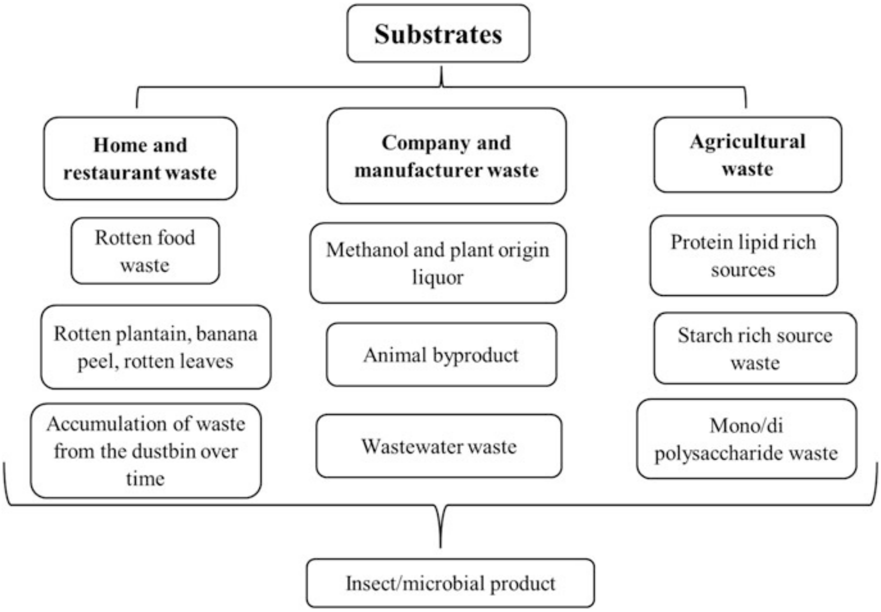

Fig. 4.1 Substrates are used for the culturing of insect and microbial species. (Adopted from Jannathulla et al. (2017))

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

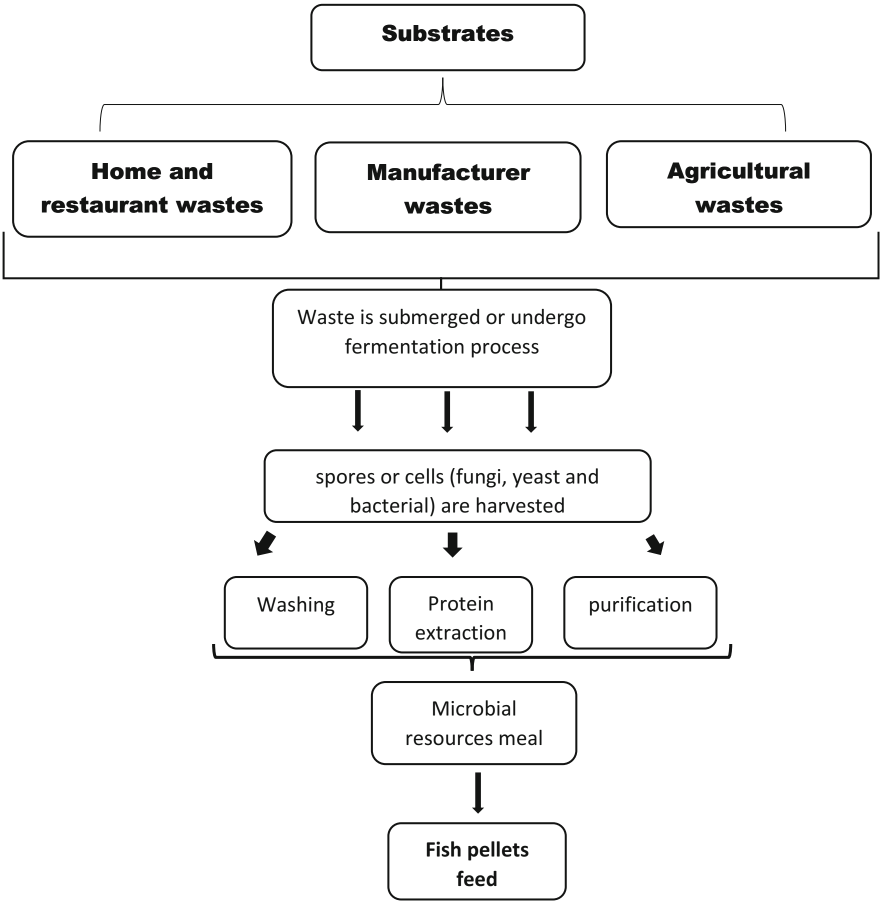

Fig. 4.2 Turning wastes into proteins using the microbial resources (bacterial fungi and yeast) to produce microbial meals to replace FM in aquafeeds for fish culture

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).

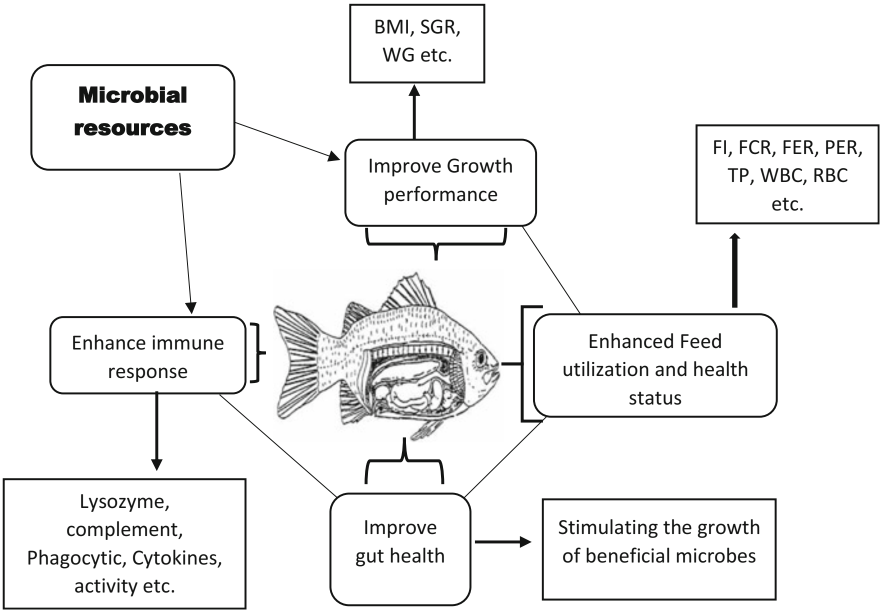

Fig. 4.3 The mode of action of microbial resources comprises of improved growth performance, feed utilization (macro-and micronutrients), health status, and enhanced immune and gut health. *BMI* body mass index, *SGR* specific growth rate, *WG* weight gain, *FI* feed intake, *FCR* feed conversion ratio, *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.

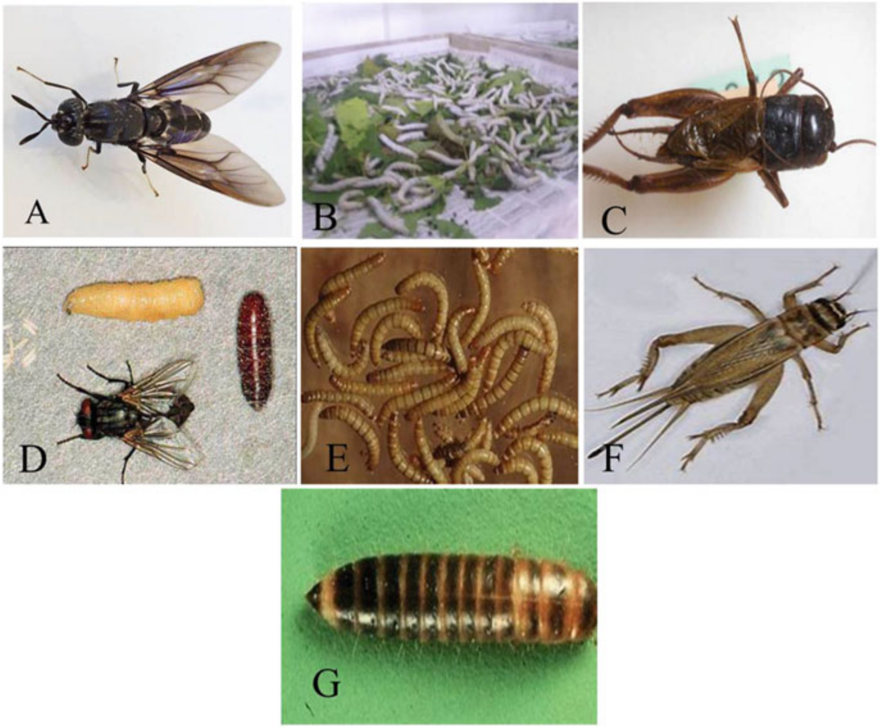

Fig. 4.4 Insect species used in producing meals to replace FM in aquafeeds. (**a**) Black soldier fly (*Hermetia illucens*), (**b**) Silkworms (*Bombyx mori*), (**c**) Jamaican field cricket (*Gryllus assimilis*), (**d**) housefly (Musca domestica) (Malik et al. 2007), (**e**) yellow mealworm (*Tenebrio 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; M^{a}J 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.

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Chapter 5
Prebiotics as Functional Ingredients in Aquafeed: Trends and Prospects in African Aquaculture

Kaulo Salushando and Ahmad Cheikhyoussef

Abstract The aquaculture sector is growing exponentially and has certainly gained popularity in the international economics and development agenda across the world. The challenges in aquaculture intensification can be solved by establishing sustainable technologies that could boost the rapid growth rate while minimizing disease outbreaks. Host physiology is influenced by the microbiome; thus, its modulation can improve human and animal health. This can be achieved through the introduction of beneficial microorganisms (probiotics), a supply of substrates to support the growth of commensal microorganisms (functional additives) and fecal transplants. Functional additives include prebiotics, immunostimulants, and short-chain fatty acids (SCFAs). Prebiotics have been reported to improve growth performance, feed utilization, survival, carcass composition, health status, disease resistance, immune functions, microbiota modulation, and reduced oxidative stress in aquaculture. Prebiotics confer benefits in fish through changes in bacterial communities; they act as energy sources for beneficial bacterial species that ferment prebiotics. The by-products of this fermentation (SCFAs, vitamins, and peptides) are responsible for the beneficial effects of prebiotics in fish. In this chapter, we summarize the effect of prebiotics and their application in aquaculture as functional feed ingredients for fish nutrition and provide perspectives on the potential application of prebiotics in aquaculture in Africa.

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5.1 Introduction

The aquaculture sector is expanding rapidly and has gained prominence in the international economics and development agendas around the world, as well as among small-scale farmers in Sub-Saharan African countries, such as Namibia (Salushando 2022). The oceans are regarded as the world's most significant nutrient reservoirs, with fish and marine organisms well known as rich sources of bioactive compounds and new valuable ingredients for nutraceutical and pharmaceutical formulations (Ngo et al. 2012; Sardari and Nordberg Karlsson 2018). One of the goals of aquaculture is to meet the growing demand for fish as a food source, considering the fact that fish stocks in natural water systems, such as oceans, are depleting.

In developing countries, challenges in aquaculture include lack of quality fish seeds and feeds; high cost of fish feeds; losses due to poor fish health management interventions, sometimes leading to disease outbreaks; food safety and quality of products; and slow growth of some farmed species (Hongskul 1999; Nsonga and Simbotwe 2014). Nevertheless, production can be increased through expansion, intensification, diversification, and improved integration of fish production into current land and water use (Nsonga and Simbotwe 2014; Benedict 2017). Moreover, there is a need to establish sustainable technologies that could boost rapid increase in growth rate, while minimizing disease outbreaks in aquaculture (Bharathi et al. 2019).

The microbiome greatly influences host physiology, and its composition is affected by host, environmental, and diet factors (Romero et al. 2014; Wang et al. 2018). Thus, improving human and animal health via modulation of the microbiome is an evolving strategy that is part of a comprehensive, holistic approach to lifestyle awareness (Gibson et al. 2017). This can be achieved through the introduction of consortia or single beneficial microorganisms (probiotics), supply of substrates to support growth of commensal microorganisms (functional additives) and fecal transplants (Enam and Mansell 2019). Typical examples of functional additives include prebiotics, immunostimulants, and short-chain fatty acids which have been found to improve immunity, feed efficiency, and growth performance of fish through the modulation of the gut microbiota (Ganguly et al. 2013).

Prebiotics are defined as substrates that are selectively utilized by host microorganisms conferring a health benefit (Gibson et al. 2017). Prebiotics can be included in foods, drinks, animal feeds, as well as supplements (Gibson et al. 2010). There are many types of prebiotics, and sources include honey, banana, onion, wheat, human's and cow's milk, barley, tomato, asparagus, garlic, peas, and beans (Davani-Davari et al. 2019). Prebiotics cause shifts in the gut microbiota by supporting the growth of beneficial communities, as well as serving as substrates to produce biologically active metabolites, resulting in positive systemic and specific health outcomes

(Krumbeck et al. 2016). Moreover, they enhance the bioavailability and uptake of minerals, including calcium, magnesium, and possibly iron (Slavin 2013).

In aquaculture, prebiotics have been reported to improve growth performance, feed utilization, survival, carcass composition, health status, disease resistance, immune functions, microbiota modulation, and reduced oxidative stress (Ganguly et al. 2013; Ringø et al. 2014; Akhter et al. 2015; Guerreiro et al. 2018). This chapter aims to review prebiotics and their application in aquaculture as functional feed ingredients for fish nutrition and provide perspectives on the potential application of prebiotics in aquaculture in Africa.

5.2 Prebiotics and Their Functions in Fish

The current aquaculture intensification may lead to water quality deterioration and subsequently to disease outbreaks (Dawood and Koshio 2016). In the past, disease outbreaks were controlled using antibiotics and vaccines, but due to the widespread emergence of antibiotic resistance in fish pathogens, they were banned by the European Union (EU) (Pérez-Sánchez et al. 2018). Prebiotics, together with probiotics, offer a distinct strategy for avoiding disease outbreaks in aquaculture and positive impacts have been reported, such as enhancing growth, survival, intestinal absorption, the well-being of fish and immunomodulation (González-Félix et al. 2018). However, prebiotics present an alternative way of manipulating endogenous microbes to improve host health and as well as overcome issues of biosecurity associated with probiotics (Ringø et al. 2010; Dimitroglou et al. 2011).

Most prebiotics (oligosaccharides) are made up of beta-glycosidic bonds that resist hydrolysis by endogenic enzymes of animals (which only recognize the alpha-glycosidic linkages) and are fermented or hydrolyzed by beneficial microbiota (Lauzon et al. 2014). Common prebiotics in aquaculture include inulin, fructooligosaccharides (FOS), galactooligosaccharides (GOS), xylooligosaccharides (XOS), isomaltooligosaccharides (IMO), short-chain fructooligosaccharides (sc-FOS), oligofructose, mannanoligosaccharides (MOS), trans-galactooligosaccharides (TOS), arabinoxylooligosaccharides (AXOS), and different commercial prebiotic mixtures (Ringø et al. 2014; Zoumpopoulou et al. 2018).

Furthermore, they stimulate selected favorable indigenous microbial populations by altering conditions in favor of beneficial species which potentially enhance fish growth efficiency and reduce disease susceptibility (Ringø et al. 2010; Dimitroglou et al. 2011). Ringø et al. (2010) further hypothesized the potential of prebiotics in increasing efficiency and sustainability of aquaculture production. In fact, several studies (Table 5.1) have documented the benefits of prebiotics in aquaculture (Ortiz et al. 2013; Eshaghzadeh et al. 2015; Tiengtam et al. 2015). However, few studies could be found in the literature from African countries; therefore, further studies are required to elucidate prebiotic's role in aquaculture in Africa and Namibia is not an exception.

Table 5.1 Examples on documented studies on the benefits of prebiotics in aquaculture

Prebiotic	Fish species	Dosage (%)	Size of fish	Duration (weeks)	Results	References
Inulin and Jerusalem artichoke tuber	Nile tilapia (*Oreochromis niloticus*)	0.25, 0.5, and 1	Juveniles (42–47 g)	8	Positive effects on growth performance and health parameters	Tiengtam et al. (2015)
XOS, GOS, FOS, and MOS	Hybrid catfish (*Pangasianodon gigas* × *Pangasianodon hypophthalmus*)	0.6	Fingerlings (5.50 ± 0.04 g)	10	Improved growth performance, gut health, and immune response	Hahor et al. (2019)
Corncob derived XOS	Nile tilapia (*O. niloticus*)	0.5, 1, 2	Fingerlings (20.72 ± 0.02 g)	4 and 8	Improved growth performance and health status	van Doan et al. (2018)
GroBiotic®-A (yeast-based prebiotic)	Totoaba (*Totoaba macdonaldi*)	2	Juvenile (215.6 ± 9.3 g)	16	No effect on growth performance, reduced lysozyme activity, and significant effect on transient intestinal microbiota	González-Félix et al. (2018)
Prebiotic mixtures (inulin and GOS; GOS and D-sorbitol; and inulin, GOS and D-sorbitol)	Juvenile chu's croaker (*Nibea coibor*)	1	Juvenile (13.58 ± 0.07 g)	8	Improved growth performance, increased intestinal microbiota diversity, and improved immune parameters	Li et al. (2019b)
GOS	Caspian roach (*Rutilus rutilus*)	1 and 2	Fry (1.36 ± 0.03 g)	7	Improved growth performance, stress resistance, and modulated intestinal microbiota by increasing lactic acid bacteria	Hoseinifar et al. (2013)
β-glucan; GOS; MOS	Snakehead (*Channa striata*)	0.2, 1, and 0.5	Fingerlings (22.46 ± 0.17 g)	15.5	Improved growth performance, and no effect on hepatosomatic index (HSI)	Munir et al. (2016)
Dietary Fiber Concentrates	Jundiá (*Rhamdia quelen*)	0.5 and 1	Fingerlings (7.16 ± 0.06)	8	Improved growth and intestinal villus height	Goulart et al. (2018)

FOS	Common carp (*Cyprinus carpio*)	1, 2 and 3	Fry (3.23 ± 0.14)	7	No effect on growth performance and hematological parameters, significant increase in total viable heterotrophic aerobic bacteria and lactic acid bacteria, and increased the survival rate and stress resistance	Hoseinifar et al. (2014)
Inulin	Common carp (*C. carpio*)	1	Fry (0.55 ± 0.02 g)	7	No significant effect on the growth performance, increased survival rate and lipid content, and no effects on digestive lipase, protease and amylase activities	Eshaghzadeh et al. (2015)
MOS	Nile tilapia (*O. niloticus*)	0.2, 0.4, and 0.6	Juveniles (49.6 ± 10.8)	8.5	No effect on the growth performance, immune parameters, and intestinal morphology	Yuji-Sado et al. (2015)
sc-FOS	Common carp (*C. carpio*)	0.5 and 1	Larvae (0.55 ± 0.02 g)	7	No significant effect on growth performance and total viable counts of heterotrophic aerobic bacteria (TVC) and lactic acid bacteria, and increased digestive enzyme activities and survival rate	Hoseinifar et al. (2016)

Over the past decades, the definition of what constitutes a prebiotic has evolved; in particular, the prebiotic concept has expanded applications to include not only humans but also other animals and other target sites apart from the gastrointestinal (GI) tract (Gibson et al. 2017). Previously, prebiotics were defined and characterized based on human applications; this has been the case with the criteria to classify an ingredient as a prebiotic. Defining, using, and setting up criteria for prebiotics in aquaculture is complex; Lauzon et al. (2014) suggested criteria for classifying prebiotics in aquaculture (aquatic organisms) as follows:

- Resistance to hydrolysis by the host's enzymes and GI absorption,
- Improvement in intestinal microbial balance, and
- Conferring host benefits (such as improved disease resistance, nonspecific immunity, gut morphology, growth, survival, and/or nutrient digestibility).

The fact that mammals and aquatic organisms significantly vary physiologically justifies the need to define the criteria specific to groups of organisms and consensus on classifying prebiotics is needed to enable correct applications of prebiotics in different animals. Specifically, aquatic organisms lack a well-defined colon, and some fish species have a distinct stomach while some do not (Lauzon et al. 2014). Moreover, pyloric ceca numbers can vary from nil to 1000 for some species, intestinal length ranges from short or up to 20 times the body length, and some species have a hindgut (fermentation) chamber (Lauzon et al. 2014). The criteria by Lauzon et al. (2014) are very similar to the established criteria except they are more applicable to aquatic animals.

5.3 Benefits and Mode of Action of Prebiotics in Aquaculture

Reported benefits of prebiotics in aquaculture are improved growth performance, survival, feed utilization, carcass composition, health status, disease resistance, gut morphology, digestibility, GI enzyme activities, immune functions, glucose and lipid metabolism, microbiota modulation, and reduced oxidative stress (Ganguly et al. 2013; Ringø et al. 2014; Akhter et al. 2015; Guerreiro et al. 2018). Due to the several modes of actions and synergies that often occur, elucidating the mechanisms by which the benefits of prebiotics are conferred is often difficult to explain (Guerreiro et al. 2018). Nevertheless, Merrifield et al. (2010) suggested that the mechanism by which prebiotics confer benefits in fish is through changes in bacterial communities increasing beneficial bacteria that promote the production of inhibitory compounds. What is more, prebiotics act as energy sources for selective (beneficial) bacterial species in the gut that ferment these prebiotics and the end products of this fermentation (short-chain fatty acids (SCFAs), vitamins, and peptides) are responsible for the majority of the beneficial effects of prebiotics in fish (Lauzon et al. 2014; Caipang and Lazado 2015; Guerreiro et al. 2018; Lieke et al. 2020).

Furthermore, mechanisms of action include competition for chemicals, available energy, and adhesion sites; inhibition of virulent gene expression; or disruption of quorum sensing (Merrifield et al. 2010). This chapter will further explain the mechanism of selective stimulation of intestinal microbiota and SCFAs provide and how prebiotics affect health (immunomodulation) and growth performance of fish. Since the major mode of action of prebiotics is through changes in microbiota, it is of outmost importance to elucidate the role of gut microbiota in fish health and growth.

5.3.1 Role of Fish Gut Microbiota

Intestinal microbiota performs a major function in nutrition, development of immunity, disease resistance, health, and well-being of fish similarly to terrestrial animals (Lauzon et al. 2014; Romero et al. 2014; Montalban-Arques et al. 2015). The microbial community of the fish GI tract is made up of viruses, Archae, protozoa, yeast, and bacteria (Guerreiro et al. 2018). However, bacteria are the most abundant in the gut (Guerreiro et al. 2018). Llewellyn et al. (2014) summarized the general lifecycle of a teleost and accessory indigenous microbiota as follows:

1. immediately when the eggs are laid, the interactions and colonization of fish progeny occurs and the diversity of the microbiota that develops reflects the microbial composition of the water;
2. once the egg hatches, environmental microbiota colonizes the larvae;
3. once the larvae begins to feed, early digestive tract colonization occurs with microbial taxa resembling those associated with feed;
4. development of the microbiome occurs, accumulating diversity, and reaching maturity; and finally
5. the adult microbiome is a diverse assemblage of microbial taxa.

Furthermore, gut microbiota of fish is to a greater extent fluidic compared to terrestrial vertebrates on account of the fluctuating environmental conditions, variational factors, high influx of microbe-laden aqueous media and dietary changes (Ringø et al. 2016; Li et al. 2019a). The factors affecting the composition of the gut microbiota can be divided into three categories, namely, host, environmental and diet factors (Romero et al. 2014). Host factors include species, genetics, gender, weight, age, immunity, and different regions of the GI tract (Li et al. 2012; Romero et al. 2014; Ringø et al. 2016). However, environmental factors include seasonal changes, water quality, temperature, salinity, stress, and cultured versus wild (Romero et al. 2014; Ringø et al. 2016; Wang et al. 2018). Diet factors include dietary form, dietary lipid, protein sources, functional glycomic ingredients, nutraceuticals (prebiotics, probiotics, synbiotics, and immunostimulants), antibiotics, dietary iron, and chromium (Li et al. 2012; Romero et al. 2014; Ringø et al. 2016; Wang et al. 2018; Tapia-Paniagua et al. 2019).

Diet is the chief source of energy for microbial growth, making it a significant factor in modulating the GI microbiota composition of fish (Davani-Davari et al. 2019; Enam and Mansell 2019). Among fish gut microbiota *Proteobacteria*, *Bacteroidetes*, *Actinobacteria*, *Firmicutes,* and *Fusobacterium* are the dominant phyla (Wang et al. 2018). Fish gut microbiota potentially has a positive impact in digestive processes of fish. In fact, a broad variety of enzyme-producing microbiota have been isolated and identified in the GI tract of fish (Romero et al. 2014). The enzymes produced by gut microbiota have a significant role in digestion through hydrolysis of feed components and they include amylase, cellulase, lipase, proteases, chitinase, and phytase (Wang et al. 2018; Tapia-Paniagua et al. 2019). In addition, intestinal microbiota participate in epithelial renewal, enhances the stability of β-catenin in intestinal epithelial cells, and promotes cell proliferation in the developing vertebrate intestine (Wang et al. 2018; Tapia-Paniagua et al. 2019). Moreover, the gut microbiota stimulates nutrient uptake of cholesterol and regulates fat storage by stimulating fatty acid uptake in intestinal epithelium leading to the buildup of dietary fatty acids in extraintestinal tissues (Wang et al. 2018).

Furthermore, gut microbes have a vital role in the development, maturation, and modulation of the immune response, which in turn mediate a variety of host immune functions (Wang et al. 2018; Tapia-Paniagua et al. 2019). Gut microbiota and derived products stimulate systemic and mucosal immune response through microbe-associated molecular patterns (MAMPs) interaction with pattern recognition receptors (Tapia-Paniagua et al. 2019). In addition, fish gut-associated lymphoid tissues (GALT) have significant numbers of antigen-presenting cells that participate in the initial stages of the immune response (Tapia-Paniagua et al. 2019). They further modulate the levels of cytokine and immunoglobulin as well as activate cellular response including B and T cells (Tapia-Paniagua et al. 2019). Equally important, the gut microbiota prevents pathogenic microbes from colonizing the GI tract by competitive exclusion or production of toxic secondary metabolites (Llewellyn et al. 2014).

Finally, some species in the phylum *Fusobacteria* are capable of excreting butyrate or synthesizing vitamins which positively affect the health of the fish (Romero et al. 2014). Although there is an increase in research studying the GI microbiota communities of fish Wang et al. (2018), fewer studies have been done on *O. mossambicus* in general and particularly in Namibia. Wang et al. (2018) postulated that the lack of gut microbiota in aquatic organisms could result in damaged physiological functions, for instance, intestinal epithelial cell dysfunction, compromised nutrient absorption, metabolism, and weaker immune responses. Therefore, investigating the role gut microbiota play in metabolism is useful in improving the development of commercial feeds, fish feed efficiency, and overall health and well-being of fish in aquaculture (Li et al. 2014).

5.3.2 Selective Stimulation of Intestinal Microbiota

Gut microbiota plays an important role in host health and immunity as discussed above, and most times can be considered an "extra organ" of the fish due to their significance in development, homeostasis, and protection of the GI tract (Nawaz et al. 2018). Diet plays a significant role in modulating gut microbiota. To sustain beneficial microbe homeostasis, the provision of substrates (prebiotics) that stimulate the proliferation of beneficial microbes, such as bifidobacterial and lactic acid bacteria, is of paramount importance as the basic mechanism of action of prebiotics is via its impact on the gut microbiota (Guerreiro et al. 2018; Nawaz et al. 2018). The key mode of action of prebiotics on the selective modulation of gut microbiota is as a result of the fermentation of prebiotics by advantageous bacteria, such as LAB and Bifidobacteria (Huynh et al. 2017; Guerreiro et al. 2018). These bacteria hydrolyze prebiotics using enzymes into respective sugars and use them as a carbon source to increase biomass of bacteria and therefore become favored compared to less beneficial (pathogenic) bacteria in the gut (Huynh et al. 2017; Guerreiro et al. 2018). Moreover, some species (*Lactobacillus*) have adopted various transport mechanisms and catabolic pathways together with intracellular and extracellular hydrolysis of specific oligosaccharide substrates (Goh and Klaenhammer 2015).

Studies have shown that prebiotics increase lactic acid bacteria, such as Firmicutes (*Lactobacillus* and *Enterococcus*); however, they decrease the abundance of pathogenic bacteria, for instance, Proteobacteria (*Aeromonas* and *Vibrio* spp.) (Boyd et al. 2020). According to Huynh et al. (2017) the mechanism with which prebiotics decrease the abundance of pathogens is through competitive adhesion where prebiotics either bind to receptors on the opportunistic pathogens or bind to the target sites of opportunistic bacteria. Moreover, pathogens have a complex metabolism making them unlikely to take advantage of prebiotics as substrates because they do not possess the necessary enzymes to hydrolyze them (Caipang and Lazado 2015). However, caution needs to be taken because supplying the substrate constantly in the gut could bring about a risk of pathogens acquiring the ability to use either the substrate or its degraded product (Caipang and Lazado 2015). Equally important, because prebiotics are able promote the growth of beneficial microbes, they can be combined with beneficial live microorganisms (probiotics) to facilitate their colonization in the gut to ensure the benefits of the probiotic (Huynh et al. 2017).

5.3.3 SCFAs Production

SCFAs are carboxylic acids made up of aliphatic tails of less than six carbons and are the end products of fermentation of prebiotic carbohydrates that escape digestion in the upper GI tract by anaerobic microbiota (Montalban-Arques et al. 2015; Tran et al. 2020). The most abundant SCFAs in the fish GI tract are acetate, propionate, and butyrate (Lauzon et al. 2014). Among fish and gut regions within a species, differences in the concentration of SCFAs, such as acetate, propionate, and butyrate, are evident (Tran et al. 2020).

The factors that influence the production of SCFAs according to Tran et al. (2020) are as follows: composition of the gut microbiota, environmental conditions (such as pH, hydrogen partial pressure, and available substrates), and species of fish. For instance, freshwater herbivorous fish are reported to have lower SCFAs levels compared to marine herbivorous fish, while carnivorous fish generally have higher concentrations of SCFAs than herbivorous and omnivorous fish (Hao et al. 2017). Other factors include living environments, seasons, intestinal morphology, intestinal regions, gut transit time, and rate of SCFA transport across the gut epithelium; however, in aquatic animals, limited data are available on the biosynthesis of SCFAs (Tran et al. 2020).

Furthermore, SCFAs play a crucial role in maintaining energy homeostasis, metabolism, and gut health (Tran et al. 2020). Nearly all SCFAs produced are absorbed in the hindgut as an energy source and aids in various biosynthetic processes within the vicinity of the gut (Tran et al. 2020). Nonetheless, small proportions of propionate and acetate reaches the liver and is used as substrates for the energy-producing tricarboxylic acid cycle and gluconeogenesis (Tran et al. 2020). Moreover, in fish, acetate is carried into the portal blood and utilized as energy source for skeletal muscle or lipid synthesis and butyrate is attributed for most of the oxygen requirements for gut (Lauzon et al. 2014; Tran et al. 2020).

SCFAs production leads to the modulation of blood lipid metabolism, gastrointestinal/systemic immunomodulation, energy sources resulting in intestinal cell proliferation, and improved intestinal barrier function (Lauzon et al. 2014). In addition, their synergistic stimulation of commensal and symbiotic bacteria grants competitive exclusion of pathogens, incidentally heightening pathogen resistance, decreasing toxic microbial metabolites, and repressing intestinal inflammation (Lauzon et al. 2014; Llewellyn et al. 2014). Specifically, SCFA production leads to a lowered pH in the GI tract which aids in mineral absorption and general nutritional support by enhancing digestive enzymes and the bioavailability of dietary minerals cells (Lauzon et al. 2014; Hoseinifar et al. 2017). To add, SCFAs inhibit the growth of pathogenic microbes; for instance, Gram-positive bacteria are inhibited by dissociating acids and the anions produced in bacterial cells (Ebrahimi et al. 2017; Hoseinifar et al. 2017).

SCFAs contribute significantly to the energy requirements of fish; they are absorbed and metabolized by the enterocytes, accounting for a large proportion of enterocyte energy needs and stimulating growth of gut beneficial bacteria, resulting in proliferation of epithelia and maintenance of gut health homeostasis (Ebrahimi et al. 2017; Hoseinifar et al. 2017; Guerreiro et al. 2018; Nawaz et al. 2018). In mammals SCFAs (mostly acetate, butyrate and propionate) seem to act as signaling molecules in cellular activities via the binding of receptors, G-protein-coupled receptors 41 (GPR41), GPR43, GPR109A, and Olfactory receptor 78 (OLFR78) (Tran et al. 2020).

The expression of these receptors in different tissues and cell types indicates that SCFAs have a role in modulating substrate and energy metabolism together with the immune response of the host by leading to a rise in immune components and improved regulation of immune-related gene expression (Tran et al. 2020). While these receptors have not been substantiated in fish to date, it is likely that the fish mucosal immune response is regulated in the same way (Hoseinifar et al. 2017).

The dietary supplementation of SCFAs and their salts led to the immunomodulation of fish and shrimp ensuing the up-regulation of favorable immune components, at the same time matching a reduction in immune components that are harmful to the host, subsequently aiding fish in the fight against pathogens (Hoseinifar et al. 2017). Therefore, consideration should also be taken to incorporating SCFAs as dietary supplements due to their positive impact on growth performance and feed utilization and the health status of the fish as well as in maintaining intestinal homoeostasis, acting as energy sources and anti-inflammatory agents (Hoseinifar et al. 2017; Tran et al. 2020).

5.3.4 Immunomodulation

The fish immune system is a sophisticated network made up of genes, proteins, and cells that perform a vital role in protecting the fish against invading pathogens and stress (Caipang and Lazado 2015). In fish, cellular and humoral immunity consists of phagocytic cells, neutrophils, natural killer cells, lymphocytes, lysozyme, hemolysin, immunoglobulin, and complement molecules (Wang et al. 2017; Dawood et al. 2018).

There are four mechanisms of fish immunity: Firstly, phagocytosis, whereby neutrophils, monocytes, and macrophages engulf pathogens and then secrete degradative enzymes and antimicrobial peptides, which helps destroy pathogens (Song et al. 2014; Akhter et al. 2015; Caipang and Lazado 2015; Carbone and Faggio 2016). Secondly, respiratory burst, the invigorated release of reactive oxygen species (hydrogen peroxide, superoxide anions, and hydroxyl radicals) by phagocytic cells responsible for degrading engulfed material and measured by nitro blue tetrazolium (NBT) or myeloperoxidase (MPO) tests (Song et al. 2014; Akhter et al. 2015; Caipang and Lazado 2015; Carbone and Faggio 2016). Thirdly, lysozyme, responsible for the degradation of peptidoglycan in bacterial cell walls by hydrolyzing of β-(1, 4) glycosidic linkages in N-acetylmuramic acid and N-acetylglucosamine; they are synthesized by macrophages and neutrophils and are found in mucus, plasma, and lymphoid tissues (Song et al. 2014; Akhter et al. 2015; Caipang and Lazado 2015; Carbone and Faggio 2016). Lastly, cytokines, produced by macrophages, lymphocytes, and other cells, include chemokines, interferons, interleukins, lymphokines, and tumor necrosis factors, and they regulate and link innate and adaptive immune responses for maximum immunity as well as stimulate hematopoiesis (Song et al. 2014; Akhter et al. 2015; Caipang and Lazado 2015; Carbone and Faggio 2016).

Prebiotics modulate the immune system by directly stimulating the innate immune system or indirectly by enhancing the growth of beneficial microbiota (Song et al. 2014). The mucosal immune response is the line of defense where pathogens may enter the host and is vital in securing the host immunity for better health (Nawaz et al. 2018). Prebiotics directly impact the epithelial barrier by interlinking epithelial cells via tight junctions reducing the penetration of pathogens; they block pathogen adhesion on mucus lowering the number of pathogens that invade the mucosa; they as well bind the active site of pathogens to decrease their activity; and they facilitate the initiation of immunoglobulin A (IgA) and dendritic cells increasing permeability (Nawaz et al. 2018). Furthermore, prebiotics directly activate the innate immunity by interacting with pattern recognition receptors (PRR) (β-glucan or dentin-1) expressed on macrophages (Song et al. 2014; Hoseinifar et al. 2015).

On the other hand, prebiotics indirectly effect immunity by promoting the growth of beneficial bacteria which hinder the adhesion and invasion of pathogens in the epithelia by competing for adhesion sites in epithelia, lowering the pH, enhancing mucus production, producing SCFAs and antimicrobial peptides, and stimulating cytokine production (Akhter et al. 2015). The SCFAs produced by fermentation of prebiotics seem to be a significant mechanism of this indirect impact on immunity. SCFAs provide energy to epithelial cells and they positively impact anti-inflammatory properties and cytokine expression (Nawaz et al. 2018). To add, because they lower the pH in the intestine, they prevent pathogen growth. Prebiotics may also associate with MAMPs (teichoic acid, peptidoglycan, glycosylated protein, or the capsular polysaccharide of bacteria), resulting in the activation of innate immune cells (Song et al. 2014; Hoseinifar et al. 2015). Other indirect effects include the stimulation of natural killer cells, stimulation of phagocytosis, stimulation of neutrophils, stimulation of the alternative complement system, an increase in lysozyme activity, and antibody response in the host (Akhter et al. 2015). Without a doubt, a boosted immune status will bring about a heightened immune response, manifested in higher survival rates post-bacterial or environmental challenges, disease resistance, and improved growth performance and feed utilization (Guerreiro et al. 2018). The effects of prebiotics may vary depending on the fish species investigated; hence, effects should not be extrapolated between species; rather, the actual effect should be primarily demonstrated before claiming its potential use (Caipang and Lazado 2015; Hoseinifar et al. 2015).

5.3.5 Growth Performance and Feed Utilization

Several elements influence the growth of the fish, such as nutrient digestion, assimilation rate, or feed conversion efficiency (Torrecillas et al. 2014). The mechanism of action of prebiotics' effect on growth performance and feed utilization is closely linked to greater nutrients availability owing to changes in digestive enzymes activities or in gut morphology (Guerreiro et al. 2018). The improvement in growth performance could be related to prebiotics that stimulate beneficial microbes that produce digestive enzymes and SCFAs that aid in improving nutrient availability and intermediary metabolism (Huynh et al. 2017; Guerreiro et al. 2018). Prebiotics also improve gut morphology by enhancing gut integrity, for example, microvilli density, intestinal fold height, enterocyte height, and absorption area, resulting in heightened functioning of enterocytes and transport of nutrients across the intestine (Gatlin III and Peredo 2012). Moreover, they improve immune response, confer disease resistance, and positively affect oxidative status in fish by either reducing oxidative damage or improving antioxidant potential (Gatlin III and Peredo 2012; Huynh et al. 2017; Guerreiro et al. 2018; Boyd et al. 2020).

All these effects lead to increased nutrient absorption, resulting in improved nutrient utilization and enhanced metabolism culminating in increased weight gain and feed efficiency (Gatlin III and Peredo 2012). Prebiotic effects on growth and feed utilization varies based on numerous factors, for example, prebiotic source, supplementation level, fish species and age, rearing conditions, and diet composition, with some having positive effects, no effects, and sometimes negative effects on the growth of fish supplemented with prebiotics (Das et al. 2017; Guerreiro et al. 2018). Henceforth, Caipang and Lazado (2015) proposed the prospect that growth-promoting properties of prebiotics in fish encompass complex underlying mechanisms which might be random in nature and greatly manipulated by the maturity of the physiological status of the host.

5.4 Conclusions and Future Perspectives

Prebiotics play a significant role in fish quality, and their use in aquaculture has been shown to enhance growth performance and control fish gut microbiota, which in turn improves fish production and health. Numerous elements that affect fish growth performance and gut microbiota diversity may be responsible for the variations in prebiotics application results. This offers the opportunity for prebiotics and other useful additives to be used in African aquaculture systems. Studies focusing on enhancing the growth and general health of farmed fish leading to improved production are of utmost importance as aquaculture develops in Africa and the world. More research is required to examine various prebiotic percentage/ratio inclusion levels and methods of incorporation, such as adding prebiotics to the feed formulation before pelleting, as well as functional feed additives and prebiotics, like mushrooms and MOS in aquaculture diets. Studies on common pathogens (bacteria and parasites) and stress, along with the administration of prebiotics, should also be encouraged to better optimize the positive effects. This will help maximize fish growth and increase fish production to meet national demands for African countries and ensure food security in Africa.

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Chapter 6

The Potential Benefits of *Aloe vera* Products in Aquafeed: Current Knowledge and Prospects

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Abstract There has been an increasing effort to use medicinal plants as alternative pharmaceutical drugs, primarily to improve production in intensive aquaculture systems sustainably. Similarly, the potential of aloe vera *(Aloe vera*) in aquaculture has recently received much attention due to its biological properties, such as anti-inflammatory, immune stimulating, antioxidant, gut health enhancement, and hepatoprotective. This study reviewed the progress of research on the use of *A. vera* products in aquaculture, as well as the limitations of existing knowledge and prospects. Many studies have shown that some concentrations of *A. vera* products (especially less than 2%) significantly increase fish growth and appetite, improve general health, and increase resistance to physiological stressors. However, these findings are insufficient to recommend the use of *A. vera* products in aquaculture because of toxicological studies and validation of growth and immune-stimulating effects in different fish species, as well as improved research designs incorporating various vital factors, are still required.

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This review will encourage the optimisation of various *A. vera* products in the aquaculture industry, as well as future studies to maximise production and improve fish welfare.

Keywords Aloe Vera · Intensive aquaculture · Feed additives · Growth promoters · Immune stimulants · Medicinal plants

6.1 Introduction

Aquaculture has been the fastest growing food-producing sector for decades, contributing significantly to meeting global seafood demand. Intensification is one of the factors that contribute to aquaculture's success. Yields are typically higher in intensive and extensive systems, owing to high stocking density. Higher fish stocking density, on the other hand, can be stressful to the fish and create an environment conducive to pathogen proliferation (i.e. viruses, bacteria, and parasites); fish reared in intensive systems are susceptible to diseases and death if not treated (Amal et al. 2018; Kibenge 2019; Maulu et al. 2021; Vaseeharan and Thaya 2014). Nonetheless, the aquaculture industry as a food-producing sector has yet to reach its full potential.

Farmers in the past began to use pharmaceutical and chemical drugs to maintain the excellent health of farmed fish to reap the economic benefits associated with intensive farming systems in aquaculture. The use of these drugs in aquaculture was later shown to be unsustainable for a variety of reasons, including pathogens developing drug resistance, such as *Vibrio harveyi* to trimethoprim-sulfamethoxazole, chloramphenicol, erythromycin, and streptomycin (Miller and Harbottle 2018), immunosuppression, environmental pollution, and the accumulation of potentially hazardous chemical residues (Bojarski et al. 2020). As a result, many countries, including the United States, the European Union (Bulfon et al. 2015), and some Asian countries, have a high demand for aquatic products free of synthetic pharmaceutical drugs (Rico et al. 2013). As a result, it has become increasingly important to replace pharmaceutical drugs with ingredients or additives that can improve fish health, growth, feed utilisation ability, and ensure safe and high-quality aquatic products from aquaculture.

The number of studies on the application of herbal extracts in aquaculture has increased over the last three decades, with the majority concluding that herbs have the potential to eliminate the use of synthetic pharmaceutical drugs in fish farming. Herbs contain a variety of biologically active metabolites, including polysaccharides, alkaloids, flavonoids, volatile oils, organic acids, tannins, and nutrients (amino acids, carbohydrates, minerals, and vitamins) (Pu et al. 2017). These metabolites, if properly administered, could boost growth and feed intake, improve antioxidative capacity, antidepressants, and modulate immunity in fish (Gabriel et al. 2015a; Pu et al. 2017; Raissy et al. 2022; Reverter et al. 2014), and improve meat quality (Ning et al. 2021). Other advantages of using herbs in aquaculture include their ease of access, low cost for small-scale rural fish farmers, and biodegradability and eco-friendliness (Reverter et al. 2014). However, the current challenges of using herbs in aquaculture may be difficulties with standardisation because they are diverse (with complex bioactive compounds), and their biological metabolites may not be consistent (Pu et al. 2017) for a variety of reasons, including geographical location, extraction methods, and storage/post-harvest treatments (Baptiste Hzounda Fokou et al. 2020), and their modes of action are not fully understood. As a result, more research is required before medicinal herbs can be fully implemented in aquaculture worldwide.

Thus, the current study reviewed the research progress on applying aloe vera (*Aloe vera*) products in aquaculture and presents the gaps in existing knowledge and prospects.

6.2 The Composition of *Aloe vera*

Aloe vera (synonym *A. barbadensis* Miller) is a stemless, drought-resistant cactus-like herb from the genus *Aloe* of the Aloeaceae family native to South and East Africa (Reynolds and Dweck 1999). *Aloe vera* is the most studied and commercially important *Aloe* species, and it is used as traditional medicine by many nations worldwide (Maan et al. 2018). *Aloe vera* is best known for its high water content, which accounts for 99–99.5% (Hamman 2008), with the remaining 0.5–1.0% containing approximately 70 biologically active compounds such as water-soluble and fat-soluble vitamins, minerals, enzymes, simple/complex polysaccharides, phenol compounds, and organic acids (Radha and Laxmipriya 2015) (Fig. 6.1). These bioactive compounds are found in the *A. vera* leaf's gel (inner transparent mucilaginous jelly-like tissues), latex (middle layer), and/or rind (outer thick layer) (Fig. 6.1).

The gel contains active ingredients such as polysaccharides (glucomannans, xylose, rhamnose, galactose, and arabinose), vitamins (A, C, E, B1, B2, B12, niacin, choline, and folic acid), minerals (potassium, chloride, sodium, calcium, magnesium, copper, zinc, chromium, and iron), enzymes (catalase, amylase, oxidase) (Radha and Laxmipriya 2015). Anthraquinones can be found in the leaf's latex (Hamman 2008) (Fig. 6.1). The rich composition of aloe vera justifies its widely recognised pharmacological properties, which include anti-inflammatory, antioxidant, immune-boosting (Sánchez-Machado et al. 2017), wound-healing properties (Reynolds and Dweck 1999), intestinal absorption enhancement, and hepatoprotective effects (Baruah et al. 2016).

6.3 Applications of *Aloe vera* Extracts in Aquaculture

Aloe vera studies in humans have already progressed from the experimental phase to the application phase (i.e. cosmetics, food, and beverages). However, *A. vera* research in aquaculture has yet to fully translate into practical applications. Kim

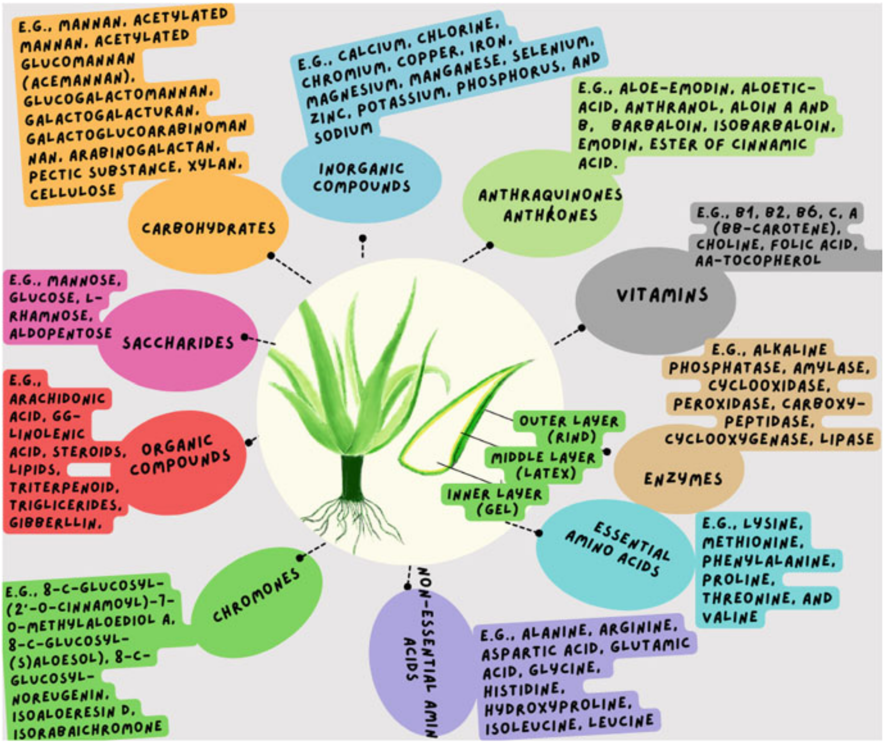

Fig. 6.1 *Aloe vera* plant, leaf cross-sectional view, and bioactive ingredients present in the leaf gel and latex (Boudreau and Beland 2006; Gupta and Malhotra 2012)

et al. (1999) were the first to report on the effects of *A. vera* on nonspecific immune response and disease resistance in rockfish (*Sebastes schlegeli*). Aquaculture research interest in *A. vera* has only recently increased. Several authors have investigated various *A. vera* extracts, including crude powder (Gabriel et al. 2015a, b, 2017; Zanuzzo et al. 2015a, b, 2017; Mehrabi and Firouzbakhsh 2020), gel (Fehrmann-Cartes et al. 2019; Golestan et al. 2015; Mehrabi et al. 2019; Soltanizadeh and Mousavinejad 2015), solvent extracts (Mahdavi et al. 2013), nanoparticles (Pati 2021; Rohani et al. 2017), aloin (Srivastava et al. 2018), and eloe-emodin (Devi et al. 2019) in fish for different purposes (Fig. 6.2). Overall, these studies concluded that *A. vera* extracts have the potential to be used as aquaculture remedies.

6.3.1 Growth Performance and Feed Utilisation

Several studies have found that various *A. vera* products improve growth and feed utilisation efficiency in various fish species (Table 6.1). Different levels of different

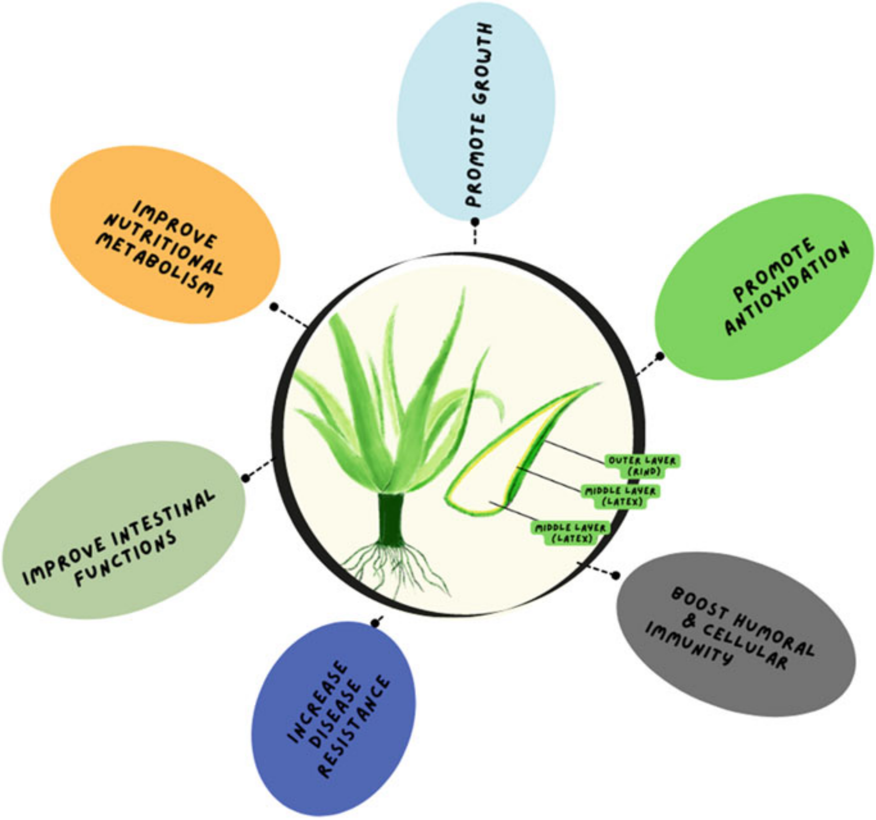

Fig. 6.2 The benefits of *A. vera* in aquaculture

A. vera products, ranging from 0.5 to 4.0%, have been tested with varying results. For example, after 84 days, *A. vera* leaf paste (10 g/kg diet) significantly improved growth performance parameters such as final weight (FW), weight gain, specific growth rate (SGR), and feed utilisation indices such as feed conversion ratio (FCR), protein efficiency ratio (PER), and apparent net protein utilisation (ANPU) in *C. gariepinus* fingerlings (Adegbesan et al. 2018). When *Cyprinus carpio* juveniles were fed a diet supplemented with *A. vera* ethanolic extract (25 g/kg diet) for 56 days, the same parameters improved significantly (Mahdavi et al. 2013). According to Alishahi and Abdy (2013), feeding *C. carpio* juveniles a diet supplemented with *A. vera* gel (5 g/kg) resulted in a significant improvement in growth and feed utilisation parameters. After 42 days, aloe vera gel (1.0–10 g/kg diet) increased growth and feed utilisation indices in *Oncorhynchus mykiss* juveniles (Heidarieh et al. 2013). Diets supplemented with *A. vera* leaf powder (10–20 g/kg diet) were also found to improve growth and feed utilisation efficiency in juvenile *Oreochromis niloticus* (Gabriel et al. 2015a; Syed et al. 2021). This implies that *A. vera* could be used to improve fish growth performance and increase farmed fish

Table 6.1 The effects of various *A. vera* products on fish growth performance and feed utilisation indices in aquaculture

Types of *A. vera* extracts	Dosages (g/kg diet)	Optimum dosage/s	Experiment duration	Growth/Feed utilisation	Fish species	Initial wt. (g)	References
Gel	0.1, 1.0, 10,	1.0–10	42 days	SGR (>), WG (>), IVL (>) IVW (>), FCR (<)	*O. mykiss*	50.3	Heidarieh et al. (2013)
Ethanolic extract (EE)	1, 5, 25	5–25	56 days	FW (>), SGR (>), FL (>) PE (>), FCR (<), FCE (>)	*C. carpio*	29.74	Mahdavi et al. (2013)
EE	2, 4, 8, 16	4–8	90 days	WG (>), SGR (>), FCR (<) FER (>), PER (>)	*C. carpio*	1.73	Khanal et al. (2021)
Gel	0.5, 1.0, 2.0	(–)	56 days	FW (=), SGR (=), WG (=) RGR (=), CF (=), FCR (=)	*O. mykiss*	9.5	Golestan et al. (2015)
Gel	1, 5, 10	5	60 days	GR (>), SGR (>), FCR (<)	*C. carpio*	45	Alishahi and Abdy (2013)
Leave paste	10, 20, 30	10	84 days	FW (>), SGR (>), WG (>) FI (>), FCR (>), PER (<) ANPU (>)	*C. gariepinus*	2.33	Adegbesan et al. (2018)
Powder	5	(–)	42 days	WG (=), SSI (=),	*O. mykiss*	133.9	Zanuzzo et al. (2015a)
Powder	5, 10, 15	15	28 days	WG (>), SGR (>), FW (>) FCR (<), FER (>)	*O. mykiss*	10.80	Mehrabi and Firouzbakhsh (2020)
Nanoparticles	5, 10, 15	10–15	60 days	FW (>), FL (>), WG (>)	*Acipenser baerii*	10.95	Rohani et al. (2017)

				SGR (>), FCR (<), PER (>)			
Aqueous crude extract	5, 10, 15	15	56 days	WG (>), SGR (>), FCR (>)	*O. mykiss*	10.89	Mehrabi et al. 2019)
Powder	2%	(–)	30 days	WG (=), SGR (=)	*C. auratus*	4–7 cm	Palermo et al. (2013)
Powder	5, 10, 20, 40	10–20	60 days	WG (>), SGR (>), AGR (> FI (<), VSI (=), HSI (=) FCR (<), FER (>)	GIFT-*O. niloticus*	4.83	Gabriel et al. (2015a)
Methanol extracts	1, 2, 3%	1–2%	105 days	WG (>), SGR (>), FW (>) FCR (>), FCE (=)	*O. niloticus*	4.04	Syed et al. (2021)
Powder	0.5, 1, 2, 4%	1–2%	60 days	WG (>), FW (>), SGR (>) FCR (<), FER (=), PER (>)	*C. gariepinus*	3.16	Gabriel et al. (2019)

SGR Specific growth rate, *WG* Weight gain, *FL* Fish length, *IVL* Intestinal villus length, *IVW* Intestinal villus width, *FCE* Feed conversion efficiency, *RGR* Relative growth rate, *CF* condition factor, *VSI* Viscerosomatic index, *HSI* Hepatosomatic index, *wt* Weight, *FI* feed intake, *FW* Final weight, *ANPU* Apparent net protein utilisation protein, *PER* Protein efficiency ratio, *FCR* Feed conversion ratio, *FI* Feed intake, *FER: FCE* Feed conversion efficiency: Feed efficiency ratio, *(–)* Not available, *(>)* Significantly increased, *(<)* Significantly decreased, *(=)* Not affected production. However, some studies have found that dietary *A. vera* extracts do not affect fish growth. Following a 42-day feeding trial, dietary *A. vera* crude powder supplementation (5 g/kg basal diet) did not affect the WG and SSI (spleen somatic index) in *O. mykiss* (Zanuzzo et al. 2015a). Similarly, after 30 days of administration, 2% *A. vera* powder did not affect the WG and SGR of goldfish (*Carassius aurata*) (Palermo et al. 2013).

The presence of compounds in the leaves, such as complex polysaccharides and phenolic compounds, may be responsible for improved growth in fish following *A. vera* supplementation (Hamman 2008; Radha and Laxmipriya 2015). The polysaccharides in medicinal herbal extracts have been linked to growth-promoting effects in fish (Tremaroli and Bäckhed 2012; Zahran et al. 2014). Polysaccharides aid fish in maintaining the balance of their gut microbial community in favour of health-promoting microbes (Tremaroli and Bäckhed 2012), as well as promoting health status by increasing resistance to bacterial and viral infection (Chen et al. 2003) or directly influencing pathogenic gut microbiota (Yu et al. 2018). All of this improves feed digestibility and nutrient availability from feedstuffs, as well as shortens the feed transition time, which may have a beneficial effect on digestive enzymes (Platel and Srinivasan 2004) and reduces the amount of feed substrate available for pathogenic bacteria proliferation (Citarasu 2010). In order to be certain that the growth-promoting effects of *A. vera* are due to their polysaccharide, more research is needed.

6.3.2 Effects of **A. vera** *on Fish Health*

Blood is the most commonly examined tissue to assess the health or physiological status of fish after the administration of herbal extracts. Oxygen-carrying capacity, for example, has been determined directly using primary haematological indices such as red blood cell (RBC), haemoglobin concentration (Hb), percentage of blood volume made up of red blood cells, and haematocrits (Hct). Secondary health indices such as Mean Corpuscular Volume (MCV) = (Hct × 10/RBC), Mean Corpuscular Haemoglobin (MCH) = (Hb × 10/RBC), and Mean Corpuscular Haemoglobin Concentration (MCHC) = (Hb × 100/Hct) could be deduced from primary indices for the classification of anaemia conditions, as illustrated by Gabriel et al. (2015a). Other indices such as white blood cell (WBC) and a number of their differential counts (i.e. leucocyte counts such as lymphocytes, neutrophils, eosinophils, monocytes, and basophils) as well as expression of immune-related genes have been assessed to measure the immune status of fish supplemented with herbs, particularly during stressful conditions (Zanuzzo et al. 2015a). Aside from promoting growth, various *A. vera* extracts have been shown to significantly improve immune indices and, to a lesser extent, specific immune responses in fish (Table 6.2). Mehrabi et al. (2019) discovered that feeding *A. vera* extract to O. mykiss fingerlings for 56 days could significantly increase haematological parameters (RBC, WBC, Hct, and Hb) as well as some blood serum parameters (the total protein, albumin, globulin,

Table 6.2 The effects of *A. vera* extracts on health indices of some of aquaculture fish species

Aloe products	Delivery	Dosages (g/kg diet)	Duration of exposure	Health indices	Fish species	References
Gel	Oral	0.5, 1.0, 2.0	56 days	FRA (>), MDA (<)	*O. mykiss*	Golestan et al. (2015)
Crude powder	Immersion	0.02, 0.2, 2.0 mg/L	9 h	Glu. (=), RBA (>)	*B. amazonicus*	Zanuzzo et al. (2015b)
Gel	Oral	1.0, 5.0, 10.0	60 days	SBA (<), NBT (>), CSA, TP (>) IgM (>), PCV (>), Hb (>), MCV (=) MCHC (=), MCH (=), RBC (>), HETR (=) LYMP (=), MON (=), EOS (=), LYZ (>)	*C. carpio*	Alishahi and Abdy (2013)
Leave paste	Oral	10.0, 20.0, 30.0	84 days	PCV (>), Hb (>), RBC (>), MCH (=); MCV (=), MCHC (=), WBC (>) NEU (<), LYMP. (>), EOS (<) MON (=), BASO (>)	*C. gariepinus*	Adegbesan et al. (2018)
Gel	Injection	100 µL added 5 mL TSB 0.1 mL injected into a fish	42 days	ACH50 (>), LYZ (>), BCIDAL (<)	*C. carpio*	Abdy et al. (2017)
Gel	Oral	5.0	56 days	CL (>), PHAGO (>)	*Sebastes schlegeli*	Kim et al. (1999)
Powder	Oral	5.0	42 days	RBA (=), LYZ (=), CSA (=) Ferritin heavy chain (>), IRF-1 (>) TNFα-1 (>), TNFα-2 (>), IL-8 (>) CATH-1 (>), CATH-2 (>), IL-1β) (>)	*O. mykiss*	Zanuzzo et al. (2015a)
		4.0	28 days	MR (=), MO2 (8% lower), CORT (=)		Zanuzzo et al. (2015b)
Aloin	Injection	1 mg/body wt.	7 days	LYZ (>), Protease (>), CARBOX. (>) ALP (>) AP (>) CAT (>), PEROX (>)	*L. rohita*	Srivastava et al. (2018)

(continued)

Table 6.2 (continued)

Aloe products	Delivery	Dosages (g/kg diet)	Duration of exposure	Health indices	Fish species	References
Aqueous extracts	Oral	0.5, 1.0, 2.0 (w/w)	10 days	RBA (>), Glu. (<), NBT (>), LYZ (>) CSA (>)	*P. mesopotamicus*	Zanuzzo et al. (2017)
Aqueous extracts	Oral	5.0	42 days	WBC (>), IgM (>), LYZ (>), BCIDAL (>) RBC (=), PVC (=), CSA (=)	*C. carpio*	Alishahi et al. (2010)
Aloe-emodin	Oral	0.001, 0.005, 0.01 (mg/kg diet)	Days interval (14, 28, 42, 56)	ALB (>), GLOB (>), PHAGO (>), RBA (>) CC3 (>), LYZ. Act. (>)	*L. rohita*	Devi et al. (2019)
Aqueous extracts	Oral	5,10, 15	56 days	RBC (=), WBC (>), Hct (>), Hb (>) TP (>), ALB (>), GLOB (>), RBA (>) LYZ (>). CSA (>)	*O. mykiss*	Mehrabi et al. (2019)
Crude powder	Oral	2 mg/g diet	30 days	CHOL (<), LDL (=), HDL (=), TG (=)	*C. auratus*	Palermo et al. (2013)
Crude powder	Oral	5, 10, 20, 40	60 days	WBC (>), RBC (>), Hb (>), Hct (>), MON (=), LYMP (<), NEU (>), EOS (>)	*O. niloticus*	Gabriel et al. (2015a)
Crude powder	Oral	5, 10, 20, 40	60 days	TCHO (<), TG (<), LDL (=), HDL (>) CAT (>), GSH-Px (>), SOD (=)	*O. niloticus*	Gabriel et al. (2015b)
Powder	Oral	10, 20, 30	105 days	Hb (>), NEU (>), LYMP (>), MON (>), EOS (>) RBC (=), MCV (>), MCHC (=), WBC (>), ALB (=) GLOB (=), TP (>)	*O. niloticus*	Syed et al. (2021)
Powder	Oral	5, 10, 20, 40	60 days	RBC (=), Hct (=), Hb (=), MCV (=), MCHC (=) WBC (>) LYMP (=), MON (=), ALT (<), AST (<) Glu (=), TCHO (=), TG (=)	*C. gariepinus*	Gabriel et al. (2019)

Nature's oil (Batch no 24228)	Oral	5, 10, 20	7 days	RBA (>), LYZ (>), CSA (>), TG (<), TCHO (<)	*P. mesopotamicus*	de Assis and Urbinati (2020)
Powder	Oral	1	72 h	TCTP (<), SOD (>), HSP 70 (>)	*Penaeus vannamei*	Trejo-Flores et al. (2018)

FRA Ferric-reducing ability, *CAT* Catalase, *MDA* Malondialdehyde, *SBA* Serum bactericidal, *CL* Chemiluminescent response, *CORT* Cortisol, *TG* Triglycerides, *TCHO* Total cholesterol, *CHOL* Cholesterol, *NBT* Nitroblue tetrazolium, *CSA* Complement system activity, *Hct* Hematocrits, *Hb* Haemoglobin, *WBC* White blood cells, *MCV* Mean corpuscular volume, *SOD* Superoxide dismutase, *LYZ* Lysozyme activity, *GSH-Px* Glutathione peroxidase, *Glu* Glucose, *MR* Metabolic rate, MO_2 Oxygen consumption, *HDL* High-density lipoprotein, *LDL* Low-density lipoproteins, *PEROX* Peroxidase, *CARBOX* Carboxylesterase, *ALP* Alkaline phosphatase, *AP* Acid phosphatase, *IgM* Immunoglobulin M, *PCV* Packed cell volume, *HETR* Heterophil, *ACH50* Serum-alternative complement activity, *TP* Total protein, *CC3* Complement C3, *ALB* Albumin, *GLOB* Globulin, *RBC* Red blood cells, *MCH* Mean corpuscular haemoglobin, *MCHC* Mean corpuscular haemoglobin concentrate, *NEU* Neutrophils, *LYMP* Lymphocytes, *AST* Aspartate aminotransferase, *ALT* Alanine aminotransferase, *PHAGO* Phagocytic activity, *RBA* Respiratory burst activity, *MON* Monocytes, *(>)* Significantly increased, *(<)* Significantly decreased, *(=)* Not affected, *BASO* Basophils, *TCTP* Translationally controlled tumour protein, *HSP 70* Heat shock protein 70 respiratory burst activity, and lysozyme, and complement system activity). For only 7 days, *A. vera* extracts in pacu (*Piaractus mesopotamicus*) reduced stress, stimulated innate immunity, protected triglyceride levels in the blood, lipid depots in the liver and muscle, and directed energy mobilisation to visceral depots (de Assis and Urbinati 2020). Moreover, aloin (*A. vera* extract) has been shown to improve innate immunity (increased lysozyme activity) and antioxidant activity (increased catalase activity) in *Labeo rohita* 7 days after a 1 mg aloin/kg fish body weight injection (Srivastava et al. 2018). *Aloe vera* extracts, including emodin in *L. rohita* (Devi et al. 2019), aqueous extracts in *C. carpio* (Abdy et al. 2017), and *P. mesopotamus* (Zanuzzo et al. 2017), crude powder in *O. mykiss* (Zanuzzo et al. 2015a, b), *Carassius auratus* (Palermo et al. 2013), and *O. niloticus* (Gabriel et al. 2015a, b; Syed et al. 2021) were also reported to improve the overall health status of target species significantly. Based on these findings, *A. vera* extracts have the potential to be used as immunostimulants in aquaculture.

Previous research has shown that supplementing *A. vera* extracts improves haematological indices in fish, indicating that *A. vera* can stimulate erythropoiesis (the generation of mature red blood cells), increasing oxygen-carrying capacity and strengthening the body to better tolerate physiological stresses. Iji et al. (2010) reported erythropoietin effects of *A. vera* extracts in hematopoietic cells of bone marrow. The assumption is that these effects are due to the presence of vitamins (beta carotene, C, E, B12, riboflavin, thiamine, and folic acid), minerals (calcium, chromium, copper, selenium, manganese, potassium, sodium, and zinc), and essential and non-essential amino acids in *A. vera* that are required for haemoglobin synthesis (Olaifa 2016). The presence of polysaccharides in *A. vera* leaves has also been linked to erythropoiesis and leukopoiesis (the formation of white blood cells in bone marrow) (Hamman 2008; Im et al. 2005; Tai-Nin Chow et al. 2005). Some immunomodulatory effects have been linked to lectins, glycoproteins found in *A. vera* gel (Reynolds and Dweck 1999). *Aloe vera* extracts have been shown to elicit specific immune responses in fish, in addition to innate immune responses. Diets supplemented with *A. vera* powder, for example, reportedly resulted in a robust immune response following bacterial antigen exposure, which was expressed by all eight selected antibacterial biomarker genes (i.e. ferritin heavy chain, IRF-1, TNF-1, TNF-2, IL-8 CATH-1, CATH-2, IL-1) in *O. mykiss* (Zanuzzo et al. 2015a). Abdy et al. (2017) also found that 0.5% dietary *A. vera* increased serum bactericidal activity and immunoglobulin M (IgM) antibody levels in *C. carpio* infected with *Aeromonas hydrophila*. *A. vera* has been shown to boost fish resistance to various physical and biological stressors. For example, *A. vera* (0.2 mg/L of water) was found to significantly increase the innate immune response (respiratory burst activity) in *Brycon amazonicus* after transport stress (Zanuzzo et al. 2015b). Gabriel et al. (2015a) found that *O. niloticus* (GIFT strain) juveniles fed a diet supplemented with *A. vera* powder had significantly lower glucose levels, cortisol levels, and neutrophil/lymphocyte ratios after *Streptococcus inae* experimental challenge than control fish. Similarly, *Oreochromis* sp. (Raina Manaf and Mohd Daud 2016) and *P. mesopotamicus* (Zanuzzo et al. 2017) were fed an *A. vera* supplemented diet exposed to pathogenic bacteria of *Streptococcus agalactiae* and *A. hydrophila*, respectively; similar results were obtained. Following *A. hydrophila*, *S. agalactiae*, and *Saprolegnia parasitica* (parasite) exposure, dietary *A. vera* supplementation increased the survival probability in *C. carpio* (Abdy et al. 2017) and *O. mykiss* (Heidarieh et al. 2013; Mehrabi et al. 2019). According to the literature review, dietary supplementation with *A. vera* extracts can improve fish health and produce animals that are more resistant to physiological stresses. This suggests that *A. vera* can help prevent disease outbreaks and negative fish reactions to other types of stresses in aquaculture.

Medicinal herbs, on the other hand, have been reported to be toxic to fish and even fatal in high doses (Ponnusamy et al. 2011). Anaemia and tissue necrosis are two of the adverse effects of *A. vera* reported in fish following dietary supplementation by Gabriel et al. (2015a, b) and Taiwo et al. (2006). In mice supplemented with *A. vera* extracts, spermatogenesis dysfunction decreased central nervous system activity, and a decrease in red blood cell count was observed (Boudreau et al. 2013). Anaemia in animals is thought to be caused by herbal extracts' ability to disrupt some biological functions such as erythropoiesis, haemoglobin synthesis, and osmoregulation (Gabriel et al. 2015a). In animals, *A. vera* has also been linked to haematuria (the presence of red blood cells in the urine), metabolic acidosis (an acid–base imbalance in the blood), malabsorption (the inability to absorb nutrients and fluids), and electrolyte disturbance (mineral imbalance) (Müller-Lissner 1993). These adverse effects could explain why some studies found poor hemato-biochemical parameters and a decrease in growth (Adegbesan et al. 2018; Gabriel et al. 2015a; Zanuzzo et al. 2015b). As a result, an upper limit dosage of *A. vera* supplementation is critical for improving immune responses and resistance to physiological stressors.

6.4 Limitations in Current Knowledge and Perspectives for the Future

This review has presented strong evidence that *A. vera* is becoming more popular in aquaculture for various uses, but mainly as a feed supplement. However, the following issues have been noted in the literature:

It is difficult to compare and substantiate the effects of this herb in fish because of the following factors: (1) this herb was only studied in a small number of fish species, and conclusions were sometimes drawn using insufficient doses or testing durations; (2) different *A. vera* products, such as powder, gel, methanolic, and ethanolic extracts, were presented in the literature; and (3) many studies repeatedly failed to characterise the composition of the used *A. vera* products or quantify the beneficial compounds. Furthermore, (4) there are insufficient studies on the toxicological effects of *A. vera* in fish, the durability of the herb in the water (culture environment), digestibility in fish, and product quality, which would help determine the ideal incorporation levels of *A. vera*; and (5) there is a lack of in-depth understanding on the physiology of how *A. vera* and other herbs affect growth performance, immune function, and their tolerance to stressors.

This study recommends that future studies include the following topics: (1) investigating the interactive effects of *A. vera* on fish growth and immune response; (2) herbal extracts have been praised for their ability to improve the intestinal microbiota, which improves fish growth and health. To confirm this mechanism, future research should look at the composition and diversity of bacterial communities in the fish gut after herbal product administration. (3) Furthermore, since *A. vera* has antimicrobial activity, future research should investigate its protective and reparative effects in fish against harmful bacteria that are problematic in aquaculture. (4) Because *A. vera* is known to have bitter tastes, future studies should include a sensory test to determine the sensory quality in *A. vera* supplemented fish. (5) Future research should include a cost-benefit analysis of using *A. vera* extracts in aquaculture versus pharmaceutical drugs. (6) Since many *A. vera* products used in the literature are crude, effective extraction and screening methods for the primary components must be investigated to develop a better understanding of their functions. (7) Finally, to ensure the long-term development of the aquaculture industry, mass production of these herbs should be investigated, as their use in aquaculture could double the tension already imposed by agricultural sectors and humans.

In conclusion, this study demonstrated that *A. vera* has the potential to improve growth and immune parameters in fish. However, a lack of sufficient knowledge may limit the practical and industrial application of this herb in aquaculture. More research, as recommended in this paper, is needed to better optimise the use of *A. vera* products without endangering farmed fish, consumers, or the environment.

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Chapter 7
Use of Plant Extracts to Control Reproduction in Tilapia Production Systems: An Emerging Eco-Friendly Innovation

Ivan Abaho, Ndakalimwe Naftal Gabriel, and Andrew Arinaitwe Izaara

Abstract This chapter gives an account of the usage of plant extracts to control-prolific spawning in tilapia production systems. The culture of mixed-sex tilapia results in overcrowding, leading to stunted fish that attract low market price, hence, making the investment less profitable. All-male tilapia has, however, proven to be a viable option towards solving this challenge. Besides, all-male sex individuals grow faster and bigger than females. Currently, farmers mainly use 17-α-methyltestosterone (MT) synthetic hormone to convert newly hatched fish into males. There is, however, increasing public concern on use of chemicals and drugs in aquaculture, accompanied by the increasing demand for safe food fish. For example, MT is a known carcinogenic substance; thus, prolonged exposure by fish farmers during application processes can adversely affect their health. Research has now embarked on the search for potential alternatives focusing on use of organic, plant-based products for control of tilapia reproduction. Contrary to synthetic hormones, plant extracts are easily accessible, safe, eco-friendly, and affordable. Presently extracts from several plant species mainly *Tribulus terrestris, Mucuna pruriens, Carica papaya, Asparagus racemosus, Aloe vera,* and *Pinus tabulaeformis,* have shown positive results towards controlling unwanted breeding in tilapia production systems. However, *C. papaya* and *Azadirachta indica* extracts have been more utilized in Africa at experimental level, which represent 31% and 17% of the

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reviewed studies, respectively. The commercialization of the plant extracts is limited by lack of a standard application protocol. In-depth studies on extraction and refining of extracts, optimal dosages, mechanism of action, and likely effects on fish and human health are required to facilitate the commercial adoption of plant extracts in tilapia aquaculture.

Keywords All-male Tilapia · Aquaculture · Bioactive compounds · Phytochemicals · Synthetic hormones · 17α-methyltestosterone

7.1 Introduction

Tilapia are freshwater cichlids, which are native to Africa (Tibihika et al. 2018; Lind et al. 2019), despite with a wide distribution across tropics, subtropics, and in some temperate regions (Baroiller and D'Cotta 2019). Amongst the tilapia species, Nile tilapia (*Oreochromis niloticus*) is the widest distributed tilapia appearing on all continents except the Antarctica (Zambrano et al. 2006). It is presently the most farmed species of all tilapia, grown in 78 countries (Lind et al. 2019) and accounted for 4.5 million tons valued at $8.2 billion in 2018 (FAO 2020). In Africa, Nile tilapia and Mozambique tilapia (*Oreochromis mossambicus)* are the most cultured tilapia species (Hishamunda 2007; Moyo and Rapatsa 2021). Egypt contributes 71% of Africa's tilapia production (FAO 2017, 2020), with Nigeria, Uganda, Ghana, Tunisia, Kenya, Zambia, Madagascar, Malawi, and South Africa also contributing significantly to the overall production (Adeleke et al. 2021; Mapfumo 2022). The success of tilapia in aquaculture is attributed to its ability to breed easily in captivity, obtain nutrition at different trophic levels; readily grow on diets formulated using a wide range of feed raw materials, tolerate a wide range of environmental conditions, as well as technological advances such as the development of intensive culture systems, formulated feeds, and fast-growing strains (Pandit and Nakamura 2010; Wang et al. 2017; Mustapha and Atolagbe 2018; Baroiller and D'Cotta 2019; El-Sayed 2019; Rahmah et al. 2020; Levina et al. 2021).

However, for all its positive attributes, tilapia exhibits precocious maturation and prolific spawning, with a tendency to attain sexual maturity before realizing harvestable size (Abdel-Tawwab 2005). Hence, when left unchecked, the female individuals produce fry continuously in monthly batches, which result in overpopulation of the culture units. Overpopulation leads to crowding, which in turn induces stress and depresses growth of fish. In order to improve the economic returns from tilapia production enterprises, it is imperative that unwanted reproduction is controlled. Several approaches have been proposed: periodic harvesting of fry and fingerlings, biological control (polyculture), sterilization, and all-male culture for control of prolific spawning in the tilapia production systems (Mair and Little 1991; Beardmore et al. 2001; Abdel-Tawwab 2005; Fortes 2005; Wang and Lu 2016). Amongst these methods, all-male production is considered ideal, deriving its importance from the ability to reduce sex-directed territorial behavior and overall ensuring higher average growth rate of fish (Beardmore et al. 2001; Baroiller and D'Cotta 2019). The male individuals are desirable over female ones because they tend to reduce size variation at harvest and gain more weight than females of the same cohort (Beardmore et al. 2001; Toguyeni et al. 2002; Ridha 2011; Srisakultiew 2013; Mukti et al. 2020).

Presently, most tilapia hatcheries produce all-male individuals through feeding tilapia fry with diets mixed with synthetic hormones, especially 17-α-methyltestosterone hormone (MT), for a period of 3–4 weeks after hatching (Vera Cruz and Mair 1994; Mateen and Ahmed 2007). However, the use of synthetic hormones continues to attract public criticism of their after-use effects on humans and, overall, on environmental health (Jegede 2010; Baroiller and D'Cotta 2019). For example, MT is a carcinogenic substance, and therefore, prolonged exposure by fish farmers during fish feeding processes can adversely affect their health (Velazquez and Alter 2004; Megbowon and Mojekwu 2014). Some reported adverse health effects include hepatotoxicity, menstrual irregularities, and prostatic hypertrophy (Hartleb and Nowak 1990; Vick and Hayton 2001). Furthermore, the likely leakages of MT into the aquatic environment from uneaten or un-metabolized food pose a risk to non-target organisms, especially eliciting reproductive abnormalities, hence, disrupting aquatic ecosystem robustness (Hulak et al. 2008; Ramirez-Godinez et al. 2013; Abo-Al-Ela et al. 2017; Abo-Al-Ela 2018). With the indiscriminate use of different synthetic hormones associated with inexperienced fish farmers and weak aquaculture regulatory systems, adverse health and environmental effects are likely to increase in Africa (Fortes 2005; Gabriel et al. 2017).

Consequently, studies have focused on exploring the possibility of utilizing plant extracts as alternatives to synthetic hormones in the production of all-male tilapia. Plant extracts are envisioned as plausible alternatives since they are more biodegradable, with less minimal adverse. Various research efforts have generated promising results from using plant extracts for population control in tilapia aquaculture. However, this information remains scattered and sometimes reports inconsistent results. Therefore, the present chapter reviewed and compiled results from various studies on the application of plant extracts to control-prolific spawning in tilapia production systems in Africa. The information from other continents has been included, too, in order to generate a comprehensive inventory of phyto-extracts, which will play a key role in sustainable aquaculture production.

7.2 Plant Extracts Used to Control Tilapia Reproduction, Their Bioactive Compounds, and Used Extractants

Due to the increasing demand for chemical-free fish products, many countries are advocating for organic fish production and, hence, have banned use of synthetic chemicals in some aquaculture operations (Leet et al. 2011; Chakraborty et al. 2014; Mlalila et al. 2015). As a result, the interest in using organic plant extracts has recently increased. For instance, owing to the adverse effects of synthetic hormones in the production of all-male tilapia, various interventions are exploring plant-based products as alternatives (Table 7.2). In Africa, aquaculture is still in its infancy stage, despite on a steady growth trajectory, and hence, the adoption of sustainable production practices is vital. A significant increase in various studies exploring the use of plant extracts to control unwanted breeding in tilapia production systems is noticeable (Ampofo-Yeboah 2013; Gabriel et al. 2015; Omeje 2016; Kapinga et al. 2018; Kapinga et al. 2019; Linda 2019; Abaho et al. 2021). The extracts are easily accessible, less costly and safe for the environment and humans since they are more biodegradable compared to synthetic hormones (Logambal et al. 2000; Chakraborty et al. 2014; Reverter et al. 2014; Gabriel et al. 2015; Gabriel 2019; Abaho et al. 2021). Consequently, plant extracts are considered economically viable and eco-friendly alternatives to synthetic hormones for smallholder tilapia farmers in Africa.

The present review noted 20 plant species that have been studied for possible utilization in the control tilapia reproduction globally (Tables 7.1 and 7.2). However, only 12 species, mainly *C. papaya* and *A. indica,* have been explored in Africa (Fig. 7.1), with more research studies in Nigeria (45.7%), followed by Egypt (17.1%). The other African countries that have explored this innovation are Cameroon, Ivory Coast, Tanzania, Kenya, South Africa, and Namibia (Fig. 7.2; Gabriel 2019; Abaho et al. 2021). Regarding fish species, Nile tilapia and Mozambique tilapia have been studied.

In all studies, a significant shift in sex ratio from the normal 1:1 tilapia sex ratio, favoring male individuals, was observed (Table 7.2). Generally, results from the reviewed studies showed higher levels of tilapia masculinization by methanolic and ethanolic extracts from Velvet bean (*Mucuna pruriens*) and Shatavari (*Asparagus racemosus*) (Mukherjee et al. 2018), Red kwao krua (*Butea superba*) (Kiriyakit 2014), and Puncture vine (*Tribulus terrestris*) (El Deen et al. 2020; Ghosal et al. 2021; El-Kady et al. 2022). Comparable results were obtained when Nile tilapia was fed diets supplemented with pollen from pine tree (*Pinus tabulaeformis*) (Nian et al. 2017; Nieves 2017). Pawpaw (*C. papaya*), the mostly utilized plant extract in Africa, also induced 77.8% masculinization of Mozambique tilapia-fed diets supplemented with 20 g kg^{-1} of feed (Omeje et al. 2018). In addition to these findings, supplementation of tilapia diets with lower doses of *C. papaya* and *Moringa. oleifera* seed extracts (2.0–5.0 g kg^{-1} of diet) in both sexually immature and mature tilapia disintegrates gonadal cells, thus, altering their development and subsequently resulting in anti-fertility (Jegede and Fagbenro 2008; Ampofo-yeboah 2013; Solomon et al. 2017; Ugonna et al. 2018). However, higher doses of C. papaya (120 g kg^{-1} of diet) can result in permanent sterility in Nile tilapia (Abdelhak et al. 2013). Notably, however, the findings of reviewed studies were not consistent, even for similar doses of the same plant extract and treatment periods (Table 7.2; Stadtlander et al. 2008; Ampofo-Yeboah 2013; Olusola et al. 2013; Mukherjee et al. 2015a, b; Ghosal et al. 2016; Nian et al. 2017; Nieves 2017; Mukherjee et al. 2018).

From the reviewed literature, extracts are obtained from different parts of the plant, i.e., seeds, roots, leaves, and flowers, although leaf and seed extracts are mostly used (Table 7.1). The extraction yield and biological activity of the extracts greatly depend on the extraction technique as well as the extraction solvent used

Table 7.1 Plant species, used parts, and their respective bioactive compounds hypothesized to be responsible for reproduction control in tilapia

Family	Common and scientific names	Plant part used	Bioactive agent	References
Anacardiaceae	Mango, *Mangifera indica*	Leaves	Saponins	Obaroh and Nzeh (2013)
Asparagaceae	Shatavari, *Asparagus racemosus*	Roots	Steroidal saponins	Thakur et al. (2009); Aloka et al. (2013)
Asphodelaceae	True aloe, *Aloe vera*	Leaves	Saponins and flavonoids	Patel et al. (2012)
Basellaceae	Indian spinach, *Basella alba*	Leaves	Steroids	Moundipa et al. (2005); Nantia et al. (2011); Ghosal et al. (2015)
Caricaceae	Pawpaw, *Carica papaya*	Seeds	Saponin (oleanolic acid 3-glucoside)	Ampofo-Yeboah (2013); Waweru et al. (2019)
Clusiaceae	Bitter kola, *Garcinia kola*	Seeds	Flavonoids (apigenin)	Sulem-Yong et al. (2018)
Compositae	Aspilia plant, *Aspilia mossambicensis*	Leaves	Saponins and flavonoids	Musyimi et al. (2008); Kapinga et al. (2018, 2019)
Fabaceae	Fenugreek, *Trigonella foenum-graecum*	Seeds	Steroidal saponins (Diosgenin)	Murakami et al. (2000); Raju et al. (2004)
Leguminosae	Red kwao krua, *Butea superba*	Roots	Flavonol and flavonoid glycoside	Manosroi and Manosroi (2005); Cherdshewasart et al. (2008)
Leguminosae	Velvet bean, *Mucuna pruriens*	Seeds	Steroid	Mukherjee et al. (2018); Abaho et al. (2021)
Malvaceae	Cotton, Gossypium herbaceum	Seeds	Polyphenol (gossypol)	Akin-Obasola and Jegede (2016); Tope-Jegede et al. (2019)
Malvaceae	Red hibiscus, *Hibiscus rosa-sinensis*	Roots, leaves and flowers	Flavonoids	Jegede (2010)
Meliaceae	Neem tree, *Azadirachta indica*	Leaves	Saponins and flavonoids	Atangwho et al. (2009); Kapinga et al. (2018, 2019)
Meliaceae	Honeysuckle tree, *Turraea heterophylla*	Roots, leaves and flowers	Steroids	El Deen et al. (2020)

(continued)

Table 7.1 (continued)

Family	Common and scientific names	Plant part used	Bioactive agent	References
Moringaceae	Moringa, *Moringa oleifera*	Leaves and roots	Triterpenoids (oleanolic acid-3-glucoside and β-sitosterol)	Lambole and Kumar (2011); Ampofo-yeboah (2013)
Myrtaceae	Guava, Psidium guajava	Leaves	saponins and flavanoids	Uboha et al. (2010); Tarigan et al. (2016)
Pinaceae	Pine trees, *Pinus spp.*	Pollen from male cones	Steroids (testosterone, epitestosterone, and androstenedione)	Jones and Roddick (1988); Adenigba et al. (2017); Velasco et al. (2018)
Simaroubaceae	Jack plant, *Eurycoma longifolia*	Roots	Phytosterol (stigmasterol)	Low et al. (2013b); Abubakar et al. (2017)
Quillajaceae	Soapbark tree, *Quillaja saponaria*	Stems	Triterpenoidal saponins (triterpene glycoside)	Francis et al. (2005); Stadtlander et al. (2008)
Zygophyllaceae	Puncture vine, *Tribulus terrestris*	Seeds	Steroidal saponin (protodioscin)	Ganzera et al. (2001); Dinchev et al. (2008); Yılmaz et al. (2013)

(Ajanal et al. 2012; Mahdi-Pour et al. 2012). Therefore, a technique, especially using a solvent with appropriate polarity, to maximize the desired bioactive compound is crucial (Dhanani et al. 2017). Solvent extraction of bioactive compounds from various plant materials is the widely used method with the following solvents: methanol, dichloromethanol, ethanol, ethyl acetate, hexane, ether, chloroform, and water utilized (Sasidharan et al. 2011; Bulfon et al. 2015; Gabriel et al. 2015; Van Hai 2015; Nik et al. 2022). Notably, the present review revealed that extracts obtained with organic solvents, mainly ethanol and methanol, induced higher masculinization of tilapia compared to water-based aqueous extracts (Table 7.2).

The phyto-compounds, i.e., phytoandrogens and phytoestrogens, from plant extracts, mimic the action of the natural sex steroids (testosterone and 17β- estradiol) in animals (Glazier and Bowman 2001). The saponins, flavonoids, and steroids are the main bioactive compounds in plant extracts, which have been hypothesized to induce sex masculinization and fertility impairment in fish (Table 7.1; Musyimi et al. 2008; Lee et al. 2009; Obaro et al. 2012; Gabriel et al. 2017; Kapinga et al. 2018; Velasco et al. 2018; Tarkowska 2019; Ghosal et al. 2021; Abaho et al. 2021). In contrast, the plant extracts may stimulate feminization of tilapia rather than the desired masculinization. For example, the inclusion of soybean in fish diets before gonadal differentiation is known to significantly reduce male individuals (El-Sayed et al. 2012). Soybean contains phytoestrogens, mainly genistein and daidzein, which induce ovarian development in fish (Pelissero et al. 1991). Particularly, the presence of anti-nutritional factors in some plant extracts may also inhibit the growth of

Table 7.2 Effect of plant extracts on the sex ratio, gonadal histology, spawning, and number of hatchlings of tilapia towards reproduction control (Adopted from Abaho et al. 2021, with modifications)

Plant species	Treatment	Doses tested	Duration (days)	Delivery	Tilapia species	Study	Best dose	Summary of results	References
Aloe vera	Crude powder extract	0, 1.0, 2.0, and 4.0% of feed	30	Oral	*O. niloticus*	Sex ratio	4.0% of feed	Induced 67.62 ± 4.37% male individuals after the treatment period	Gabriel et al. (2017)
	Aloe vera latex	0, 0.5, 1.0, 1.5, and 2.0 mL kg^{-1} feed	60	Oral	*O. niloticus*	Gonadal histology	2.0 mL kg^{-1}	Disintegration of spermatids in males, ruptured follicles, and gonadal necrosis in females	Jegede (2011); Kushwaha (2013)
Asparagus racemosus	Root methanol extract	0.1, 0.15, and 0.2 g kg^{-1} of feed	30	Oral	*O. niloticus*	Sex ratio	0.2 g kg⁻1 of feed	Induced 92.24 ± 0.13% male individuals	Mukherjee et al. (2018)
	Root aqueous extract	0.01, 0.015, and 0.02 g L^{-1}	30	Immersion	*O. niloticus*	Sex ratio	0.015 g L^{-1}	Sex inversion results produced 90.60 ± 1.56% males	Mukherjee et al. (2015a)
Aspilia mossambicensis	Leaf powder	1.0, 2.0, 4.0, and 8.0 g kg^{-1} feed	90	Oral	*O. niloticus*	Hatchlings production	8 g kg^{-1}	Low hatchlings number (101.9 ± 19.7)	Kapinga et al. (2018)
	Leaf powder	1.0, 2.0, 4.0, and 8.0 g kg^{-1} of diet	90	Oral	*O. niloticus*	Gonadal histology	2.0 g kg^{-1}	Degenerated of seminiferous tubules and atretic follicles	Kapinga et al. (2019)
Azadirachta indica	Crude ethanol extract	0.0, 0.5, 1.0, 2.0, 4.0, and 8.0 g kg^{-1} diet	56	Oral	*O. niloticus*	Hatchlings number	1.0 g kg^{-1}	No breeding from the 5th week of the treatment	Obaroh and Achionye-Nzeh (2011)

(continued)

Table 7.2 (continued)

Plant species	Treatment	Doses tested	Duration (days)	Delivery	Tilapia species	Study	Best dose	Summary of results	References
	Leaf crude extract (Saponin)	0.0, 0.5, 2.0, 4.0, and 8.0 g kg^{-1} feed	56	Oral	*O. niloticus*	Hatchlings number	4.0 and 8.0 g kg^{-1}	No spawning observed	Obaro et al. (2012)
	Leaf powder	0.0, 0.5, 1.0, 2.0, 4.0, and 8.0 g kg^{-1} feed	56	Oral	*O. niloticus*	Hatchlings number	1.0, 2.0, 4.0, and 8.0 g kg^{-1}	No spawning observed	Obaroh and Nzeh 2013)
	Leaf powder	0, 0.5, 1.0, 1.5, and 2.0 g kg^{-1} diet	60	Oral	*Tilapia zilli*	Gonadal histology	2.0 g kg^{-1}	Rendered the testes and ovaries devoid of spermatids and oocytes	Jegede and Fagbenro (2008)
	Leaf powder	1.0, 2.0, 4.0, and 8.0 g kg^{-1} feed	90	Oral	*O. niloticus*	Hatchlings production	8 g kg^{-1}	Low hatchlings number (62.5 ± 6.2)	Kapinga et al. (2018)
Basella alba	Leaf powder of aqueous, methanol, ethanol, dichloromethane, hexane, and successive methanol extracts	0.5, 1.0, and 1.5 g kg^{-1} of feed	30	Oral	*O. niloticus*	Sex ratio	1.0 g of ethanol extract kg^{-1} of feed	Sex inversion with 83.2 ± 0.7% males were observed	Ghosal et al. (2015)
	Leaf aqueous extract	0.00, 0.05, 0.10, and 0.15 g L^{-1}	30	Immersion	*O. niloticus*	Sex ratio	0.1 g L^{-1}	Skewed sex ratio with 70.3 ± 1.9% males obtained	Ghosal and Chakraborty (2014a)
	Leaf powder	0.0, 5.0, 10.0, and 15.0 g kg^{-1} of feed	30	Oral	*O. niloticus*	Sex ratio	10.0 g kg^{-1} of feed	Triggered sex inversion to 70.3 ± 1.2% males	Ghosal et al. (2016)
	Leaf aqueous extract	0.05, 0.10 and 0.15 g L^{-1}	30	Immersion	*O. niloticus*	Sex ratio	0.1 g L^{-1}	Sex masculinization producing 71.9 ± 1.9% males observed	Ghosal et al. (2016)

Butea superba	Root powder	100, 200, and 300 g kg^{-1} of feed	30	Oral	*O. niloticus*	Sex ratio	200 g kg^{-1} of feed	Male individuals increased to 72.2 ± 25.5% from the normal 1:1 sex ratio	Mengumphan et al. (2006)
	Root powder ethanol extract	0.00, 0.04, 0.08, 0.12, 0.16, and 0.20 g kg^{-1} of feed	21	Oral	*O. niloticus*	Sex ratio	0.20 g kg^{-1} of feed	Induced 100% testicular development	Kiriyakit (2014)
Carica papaya)	Seed powder	15 g kg^{-1} of feed	30	Oral	*O. mossambicus*	Sex ratio	15 g kg^{-1} of feed	Low level of masculinization observed with 65% male individuals	Ampofo-Yeboah (2013)
	Seed powder	10, 15, 20, 25, and 30 g kg^{-1} of feed	120	Oral	*O. mossambicus*	Sex ratio	20 g kg^{-1} of feed	The treatment sex inversed tilapia producing 77.8% males	Omeje (2016)
	Seed powder	6 g kg^{-1} of feed	45	Oral	*O. niloticus*	Sex ratio	6 g kg^{-1} of feed	68% male individuals observed at the end of the study	Mehrim et al. (2019)
	Seed powder	0, 0.5, 1.0, 2.0, 5.0, and 10.0 g kg^{-1} diet	60	Oral	*O. mossambicus*	Gonadal histology	2.0 g kg^{-1}	Anti-fertility effect, preventing reproduction in both genders of sexually immature fingerlings	Ampofo-Yeboah (2013)
	Seed powder	0, 0.5, 1.0, 5.0, 10.0, 15.0 g kg^{-1} diet	60	Oral	*O. mossambicus*	Gonadal histology	5.0 g kg^{-1}	Anti-fertility effect, preventing reproduction in both genders of sexually mature juveniles	Ampofo-Yeboah (2013)

(continued)

Table 7.2 (continued)

Plant species	Treatment	Doses tested	Duration (days)	Delivery	Tilapia species	Study	Best dose	Summary of results	References
	Seed powder	0, 4, 8, and 12 g kg^{-1} feed	60	Oral	*O. niloticus*	Gonadal histology	8 g kg^{-1}	Atretic follicles in ovaries and degenerated spermatozoa in testes	Waweru et al. (2019)
	Seed powder	3 and 6 g kg^{-1} of diet	30	Oral	*O. niloticus*	Gonadal histology	6 g kg^{-1}	Permanent sterility in mature male tilapia	Abbas and Abbas (2011)
	Seed powder	0, 2, 4, 6, and 8 g kg^{-1} of feed	28	Oral	*O. niloticus*	Gonadal histology	4 g kg^{-1}	Gonadal deformity resulting into sterility of female individuals	Solomon et al. (2017)
	Seed powder	4.9, 9.8 g kg^{-1} of feed per day	30	Oral	*O. niloticus*	Gonadal histology	9.8 g kg^{-1} per day	Permanent sterility	Ekanem and Okoronkwo (2003)
	Seed powder	0, 0.5, 1.0, 1.5, and 2.0 g kg^{-1} diet	60	Oral	*O. niloticus*	Gonadal histology	2.0 g kg^{-1}	Disintegration of gonadal cells, rendering the testes, and ovaries devoid of spermatids and oocytes, respectively	Jegede and Fagbenro (2008)
	Seed powder	60, 90, and 120 g kg^{-1} of feed	60	Oral	*O. niloticus*	Gonadal histology	120 g kg^{-1}	Permanent sterility	Abdelhak et al. (2013)
Eurycoma longifolia	Root methanol extract	0.00, 0.03, 0.06, and 0.09 g kg^{-1} of feed	30	Oral	*O. niloticus*	Sex ratio	0.06 g kg^{-1} of feed	82.10% male individuals were obtained	Yusuf et al. (2019)

	Root powder ethanol extract	0.00, 0.02, 0.04, and 0.06 g L^{-1}	60	Immersion	*O. niloticus*	Sex ratio	0.06 g L^{-1}	Altered gonadal differentiation to 67.44% males	Rinaldi et al. (2017)
Garcinia kola	Seed powder	0, 6, and 10% feed	70	Oral	*O. niloticus*	Gonadal histology	6%	Impaired gonadal development in female individuals	Nyadjeu et al. (2019)
	Seed powder	0, 1, 3, and 6% diet	44	Oral	*O. niloticus*	Number of eggs spawned	83.45%	Significantly reduced fecundity	Sulem-Yong et al. (2018)
	Seed powder	0, 10, 20, and 30 g kg^{-1} of feed	28	Oral	*O. niloticus*	Sex ratio	30 g kg^{-1} of feed	Treatment resulted in 65.75 ± 4.19% males individuals	Tigoli et al. (2018)
Gossypium (Herbaceum)	Root bark powder	0, 5, 10, 15, and 20 g kg^{-1} diet	70	Oral	*O. niloticus*	Gonadal histology	20 gkg^{-1}	Disintegration in seminiferous lobule and oocytes damaged plus connective tissue	Akin-Obasola and Jegede (2016)
	Cotton seed meal	0, 25, 50, 75, and 100% of soybean meal protein substituted	90	Oral	*O. niloticus*	Gonadal histology	25, 50, 75, and 100%	Destroyed spermatocytes and distorted vitellogenic stages	Tope-Jegede et al. (2019)
Hibiscus rosa-sinensis	Leaf powder	0, 1.0, 2.0, 3.0, and 4.0 g kg^{-1} feed	60	Oral	*O. niloticus*	Gonadal histology	3.0 and 4.0 g kg^{-1}	Induced sterility by destructing testes and ovary tissues	Jegede (2010)
Mangifera indica	Leaf powder	0.0, 0.5, 1.0, 2.0, 4.0, and 8.0 g kg^{-1} feed	56	Oral	*O. niloticus*	Hatchlings number	2.0, 4.0, and 8.0 g kg^{-1}	No spawning observed during the experiment	Obaroh and Nzeh (2013)

(continued)

Table 7.2 (continued)

Plant species	Treatment	Doses tested	Duration (days)	Delivery	Tilapia species	Study	Best dose	Summary of results	References
Moringa oleifera Lam.	Seed powder	15 g kg^{-1} of feed	30	Oral	*O. mossambicus*	Sex ratio	15 g kg^{-1} of feed	Induced sex masculinization producing 65.5% males	Ampofo-Yeboah (2013)
	Seed powder	0.0, 0.5, 1.0, 2.0, 5.0, and 10.0 g kg^{-1} diet	60	Oral	*O. mossambicus*	Gonadal histology	2.0 g kg^{-1}	Anti-fertility effect, preventing reproduction in both genders of sexually immature fingerlings	Ampofo-Yeboah (2013)
	Seed powder	0.0, 0.5, 1.0, 5.0, 10.0 15.0 g kg^{-1} diet	60	Oral	*O. mossambicus*	Gonadal histology	5.0 g kg^{-1}	Anti-fertility effect, preventing reproduction in both genders of sexually mature juveniles	Ampofo-Yeboah (2013)
	Leaf powder	0%, 5%, 10%, and 15% of total dietary protein	90	Oral	*O. niloticus*	Gonadal histology	5% of total dietary protein	Severe oocyte cytoplasm degeneration with normal hepatocytes	Nwankpa (2017)
Mucuna pruriens	Seed methanol extract	0.1, 0.15, and 0.2 g kg^{-1} of feed	30	Oral	*O. niloticus*	Sex ratio	0.2 g kg^{-1} of feed	Masculinization producing 93.79 ± 0.95% males observed	Mukherjee et al. (2018)
	Seed powder	0.0, 2.0, 3.5, and 5.0 g kg^{-1} of feed	30	Oral	*O. niloticus*	Sex ratio	5.0 g kg^{-1} of feed	73.33 ± 0.67% of males were obtained	Mukherjee et al. (2015b)
	Seed aqueous extract	0.02, 0.035, and 0.05 g L^{-1}	30	Immersion	*O. niloticus*	Sex ratio	0.05 g L^{-1}	Induced sex masculinization producing 74.67 ± 0.33% males	Mukherjee et al. (2015b)

Pinus tabulaeformis	Pollen powder	0.00, 0.08, 0.16, 0.32, and 0.64 g kg^{-1} of feed	60	Oral	*O. niloticus*	Sex ratio	0.32 g kg^{-1} of feed	Increased male individuals to 89.1 ± 3.6% from the ideal 50%	Nian et al. (2017)
Pinus kesiya	Pollen powder	(0.5 g of pine pollen +0.5 g MT) kg^{-1} of feed and 1.0 g of pine pollen kg^{-1} of feed	28	Oral	*O. niloticus*	Sex ratio	1.0 g of pine pollen kg^{-1} of feed	Sex inversion with 88% males was observed	Nieves (2017)
Psidium guajava	Crude leaf extract	0.0, 0.5, 1.0, 2.0, 4.0, and 8.0 g kg^{-1} diet	56	Oral	*O. niloticus*	Gonadal histology	4 .0, 8.0 g kg^{-1}	Atrophy of the testicular tissues and ripe oocytes	Obaroh et al. (2018)
Quillaja saponaria	Saponin (QS; Sigma, St. Louis, MO, USA)	0.05, 0.15, 0.30, 0.50, and 0.70 g kg^{-1} of feed	60	Oral	*O. niloticus*	Sex ratio	0.70 g kg^{-1} of feed	69% male individuals obtained	Francis et al. (2002)
	Saponin methanol extract	40, 60, and 80% QS (0.15 and 1.00 g kg^{-1} of feed)	120	Oral	*O. niloticus*	Sex ratio	80% QS (0.15 g kg^{-1} of feed)	Sex masculinization with 73% male individuals was observed	Stadtlander et al. (2008)
Tribulus terrestris	Seed powder aqueous, methanol, ethanol, dichloromethane, hexane, and successive methanol extracts	0.5, 1.0, and 1.5 g kg^{-1} of feed	30	Oral	*O. niloticus*	Sex ratio	1.5 g of ethanol extract kg^{-1} of feed	Altered the normal 1:1 sex ratio producing 88.9 ± 1.1 % male individuals	Ghosal et al. (2015); Ghosal and Chakraborty (2020)
	Trib 60 Extract (Tonvara Premium Natural Supplements, UK)	0.0, 1.0, 1.5, 2.0, and 2.5 g kg^{-1} of feed	42	Oral	*O. niloticus*	Sex ratio	2.5 g kg^{-1} of feed	Induced sex inversion producing 83.67 ± 4.04% males	Omitoyin et al. (2013)

(continued)

Table 7.2 (continued)

Plant species	Treatment	Doses tested	Duration (days)	Delivery	Tilapia species	Study	Best dose	Summary of results	References
	Seed powder	0.0, 5.0, 10.0, and 15.0 g kg^{-1} of feed	30	Oral	*O. niloticus*	Sex ratio	15.0 g kg^{-1} of feed	76.6 ± 0.5% male fish were obtained	Ghosal et al. (2016)
	Seed aqueous extract	0.05, 0.1, and 0.15 g L^{-1}	30	Immersion	*O. niloticus*	Sex ratio	0.15 g L^{-1}	Sex inversion producing 81.4 ± 0.5% males observed	Ghosal et al. (2016)
	Seed aqueous extract	0.00, 0.05, 0.10, and 0.15 g L^{-1}	30	Immersion	*O. niloticus*	Sex ratio	0.15 g L^{-1}	81.4 ± 0.5% male individuals obtained	Ghosal and Chakraborty (2014b)
	Seed powder ethanol extract	0.0, 2.0, 2.5, and 3.0 g kg^{-1} of feed	30	Oral	*O. niloticus*	Sex ratio	2.0 g kg^{-1} of feed	Sex masculinization resulting in 91.85 ± 0.38% males observed	Ghosal et al. (2021)
	N/S	1.0 and 2.0 g kg^{-1} of feed	28	Oral	*Oreochromis sp.* (Red tilapia)	Sex ratio	2.0 g kg^{-1} feed	Altered gonadal differentiation producing 84.4% male individuals	Zaki et al. (2021)
	Root, flower, and leaf aqueous extract	0.0, 1.0, 2.0, and 3.0	28	Oral	*O. niloticus*	Sex ratio	2.0 g kg^{-1} feed	Sex inversion was effective producing 97.43 ± 0.13% males	El Deen et al. (2020)
Trigonella foenum-graecum	Saponin methanol extract	0.15 and 0.30 g kg^{-1} of feed	30	Oral	*O. niloticus*	Sex ratio	0.30 g kg^{-1} of feed	Low levels of masculinization with 56 ± 12.6% males	Stadtlander et al. (2013)
	Saponin methanol extract	40, 60, and 80% TS (0.15	120	Oral	*O. niloticus*	Sex ratio	80% TS (0.15 g	Induced sex change to mainly males at 73% at	Stadtlander et al. (2008)

		and 1.00 g kg^{-1} of feed)					kg^{-1} of feed)	the end of the experiment	
Turraea heterophylla	Root powder	0, 10, 20, and 30 g kg^{-1} of feed	28	Oral	*O. niloticus*	Sex ratio	30 g kg^{-1} of feed	Resulted in 76.82 ± 3.34% male individuals	Tigoli et al. (2018)

MT 17α-methyltestosterone, *N/S* Not specified, *QS Quillaja saponaria* saponin, *TS Trigonella foenum-graecum* saponin

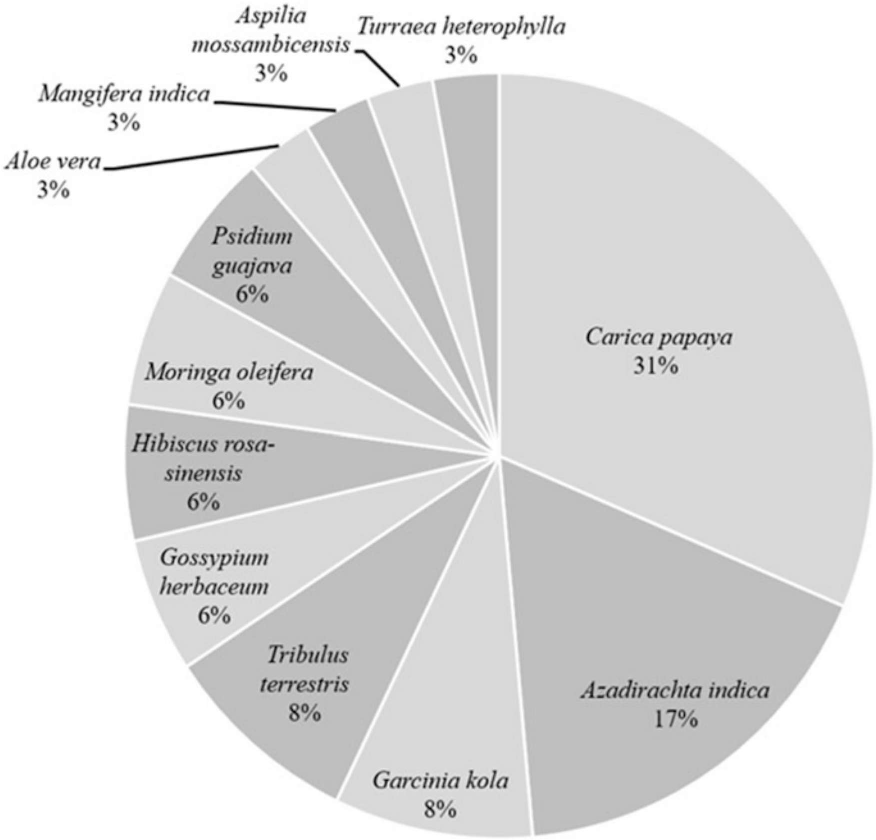

Fig. 7.1 Commonly utilized plant extracts to control-prolific breeding of tilapia in Africa

tilapia. Gossypol, a natural phenolic compound in cotton, is reported to be an anti-nutritional factor and hence, elicits retarded growth of fish (Mbahinzireki et al. 2001). It is, therefore, necessary to exclude extracts with feminization agents and anti-nutritional factors in the ingredients while formulating diets to be fed tilapia fry during sex inversion period.

Besides sex masculinization potential, the phyto-extracts have innate immunity enhancement properties and can improve the parameters of the culture water and survival rate, as well as stimulate the appetite of the fish, which ultimately boosts fish growth (Citarasu 2010; Chakraborty and Hancz 2011; Gabriel et al. 2015; Nian et al. 2017; Nieves 2017; Baluran et al. 2018; Baldove et al. 2019; Gharaei et al. 2020; Ghosal et al. 2021; Zaki et al. 2021). As such, the benefits from the plant extracts are twofold, which make them a better alternative to synthetic hormones in the production of all-male tilapia (Logambal et al. 2000; Olusola et al. 2013; Reverter et al. 2014; Nian et al. 2017; Baluran et al. 2018; Abaho et al. 2021; Gabriel et al. 2022).

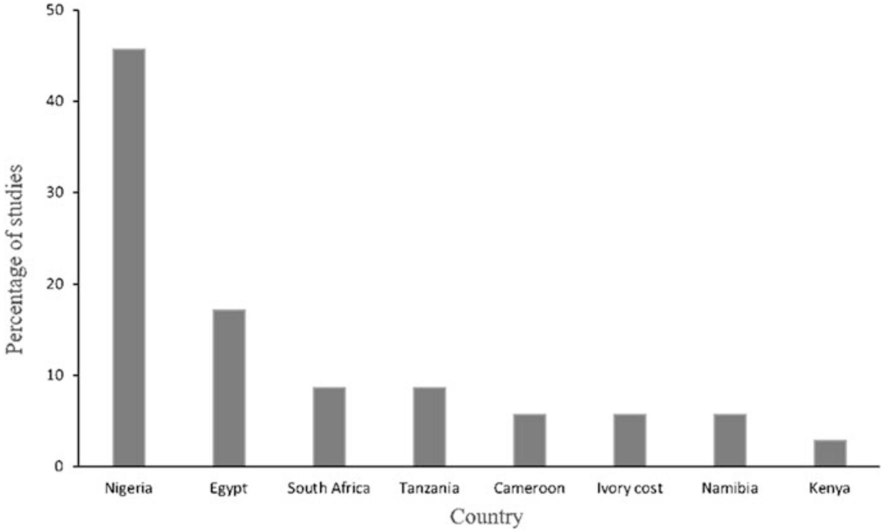

Fig. 7.2 Number of studies on plant extracts used to control tilapia reproduction by country in Africa

Despite the potential of plant extracts to control tilapia reproduction and the associated benefits, the discrepancy observed in the results continues to cause uncertainty over their application. This inconsistency in results is attributed to (1) variations in the composition of bioactive compounds due to plant growing stage, locations, and season, (2) extraction technique, solvent, and storage conditions of the extract; and (3) varied conditions during the experiment such as environment, age of fish, genetics, basal diets, and the health status of fish (Dinchev et al. 2008; Akula and Ravishankar 2011; Dhanani et al. 2017; Isah 2019; Nhu et al. 2019). Research focused on addressing these limitations will be a step forward towards improving their biological activity, and hence, commercial application of the plant extracts in tilapia hatcheries.

7.2.1 Route of Administration of Plant Extracts

Overall, three approaches, i.e., oral, immersion/baths, and injection (intraperitoneal), are utilized to administer plant extracts to the fish in aquaculture (Reverter et al. 2014, 2017; Gabriel 2019; Abaho et al. 2021). The injection method of administering extracts is considered to be rapid and efficient (Reverter et al. 2014). However, it is stressful to the fish, laborious, especially for small-sized fish and is costly (Yoshida et al. 1995; Beardmore et al. 2001; Reverter et al. 2014, 2017). Hence, oral and immersion administration methods are mostly used. For reproduction control in tilapia production systems, 88.5% of the reviewed studies utilized the oral method, while 11.5% used the immersion approach. No study used the injection technique (Table 7.2).

Generally, the immersion technique resulted in inferior sex inversion of tilapia compared to the oral method. As such, the incorporation of plant extracts in fish diets is mostly preferred administration method. This method is less costly and more practical since it allows for treatment of large numbers of fish at the same time, with either reduced or no stress (Sakai 1999; Bulfon et al. 2015; Awad and Awaad 2017). Besides, this method is effective with reports of up to 95% sex masculinization (Phelps and Popma 2000; El-Greisy and El-Gamal 2012). Nevertheless, the oral method can be relatively ineffective due to the slow absorbance of bioactive compounds from the extract. In addition, the targeted phytocompound may not be uniformly distributed in the diet during feed mixing, which leads to variations in the amounts of the bioactive compound accessed by the fish. This further reduces the effectiveness of the extracts (Budd et al. 2015; Bulfon et al. 2015).

7.2.2 Mechanism of Reproduction Control in Tilapia by Plant Extracts

In tilapia, the labile period for gonadal differentiation is from 10 days post fertilization (dpf) after the fish has absorbed yolk sac, to 25–30 dpf (Kobayashi et al. 2008). Research has demonstrated that the application of androgenic and estrogenic treatments during this period alters the sex differentiation pathway (Pandian and Sheela 1995; D'Cotta et al. 2001; Devlin and Nagahama 2002; Leet et al. 2011; Baroiller and D'Cotta 2019; Muniasamy et al. 2019). As such, plant extracts should be applied during this critical period while exploring how they modify the sex differentiation pathway in tilapia. The current knowledge on the precise mechanism of plant extracts in the control of tilapia reproduction is not clear. They are, however, thought to follow a similar pathway like natural sex steroids during the process of sex differentiation of fish. For instance, the bioactive compounds in the extracts induce either sex masculinization acting as phytoandrogens (Turan and Akyurt 2005), or fertility impairment by obstruction of gonadal functions, mainly through disintegration and rupturing of gonad cells (Table 7.2). The induction of testicular development involves interference with the endocrine system of the fish and, subsequently, the normal gonadal differentiation. Therefore, the bioactive compounds, which re-direct the sex of tilapia, are termed "endocrine disrupting compounds (EDCs)" (Omeje 2016). These phyto-compounds are believed to alter reproduction by changing the levels and activities of hormones involved in reproduction along the hypothalamus–pituitary–gonadal (HPG) axis. They interfere with the androgen–to-estrogen ratio in fish, which ultimately determines the direction of sex differentiation. Since the fate of gonads in fish is influenced by the ratio between endogenous estrogens and androgens, with excess steroids determining the final sex (Devlin and Nagahama 2002; Barannikova et al. 2004; Sandra and Norma 2010; Yarmohammadi et al. 2017), it is hypothesized that plant extracts act on this pathway to modify sex differentiation in tilapia.

Like the synthetic hormones, the phyto-compounds are hypothesized to alter the androgen-to-estrogen concentrations via (1) inhibition of aromatase activity, (2) blocking or altering estrogen nuclear receptors, and (3) activation of androgen receptors (Francis et al. 2002; Rempel and Schlenk 2008; Chakraborty et al. 2014; Golan and Levavi-Sivan 2014; Lee et al. 2017). Firstly, aromatase inhibition averts the aromatization of androgens to estrogens, thus, reducing estrogen levels in the differentiating gonad, which otherwise would elicit ovarian development. Consequently, the androgens are in higher concentrations promoting the development of male gonads (Cheshenko et al. 2008; Takatsu et al. 2013; Golan and Levavi-Sivan 2014). Second, the phyto-compounds can mimic and antagonize the estrogen nuclear receptors by blocking or altering their nuclear binding sites in the cytoplasm. The end result is blocking or attenuating estrogen production, favoring male sex differentiation (Ososki and Kennelly 2003; Matozzo et al. 2008). Third, the bioactive compounds can act as androgen receptor activators. The compounds bind and activate the androgen receptor to function as a transcription factor, which facilitates the expression of the target gene in response to the androgen, subsequently initiating masculinization (Carson-Jurica et al. 1990; O'Malley and Tsai 1992; Golshan et al. 2019). This is facilitated by the structural and binding affinity similarities of these phytochemicals and the natural androgen receptor ligands, i.e., testosterone and 11-ketotestosterone. For instance, treatment of Zebra fish (*Danio rerio*) with *Tribulus terrestris* extract yielded a considerable number of males, corresponding with an increase in testosterone levels in the treated fish. The study concluded that the masculinization capacity of *T. terrestris* was probably due to the presence of protodioscin, a phytochemical that is reported to stimulate testosterone production (Ahmad Gharaei et al. 2020). In rats, it was demonstrated that Eurycomanone, the primary bioactive compound from the root extracts of *E. longifolia,* improved fertility by increasing testosterone and spermatogenesis through the HPG axis (Low et al. 2013a, b). Similarly, *E. longifolia* extracts induced masculinization in tilapia (Table 7.2). Whether the extracts also attenuate 17β-estradiol concentration, hence, altering the androgen-to-estrogen ratio, remains to be confirmed. The flavonoids and saponins, present in many of plant extracts, have been reported to inhibit both the aromatase activity and act as anti-estrogenic compounds (Miyahara et al. 2003; Chen and Chang 2007; Golan et al. 2008; Green and Kelly 2009; Tarigan et al. 2016). Notably, some phyto-compounds such as genistein and daidzein, the phytoestrogens from soya, can modify sex differentiation in fish by promoting the development of female sex characteristics. The plant extracts that contain these phytochemicals should, thus, be avoided while formulating diets for tilapia fry, which are to be inversed to males.

The phytochemicals are also believed to differentially modulate the expression of sex genes in the ovary and testis of fish (Sarasquete et al. 2020). The sex-related genes such as cytochrome P450 (*cyp19a1a*) and forkhead transcriptional factor 2 (*foxl2*) promoted female development, while double-sex/mab-3-related transcription factor 1 (*dmrt1*) and anti-mullerian hormone (*amh*) promoted male development

(Ijiri et al. 2008; Tao et al. 2013; Chen et al. 2016). No previous study has attempted to investigate the effect of phyto-compounds on the expression of sex genes in tilapia. Considering the role of these genes in gonadal differentiation, further research is needed to clearly understand how plant extracts induce sex inversion or fertility impairment at a molecular level.

Lastly, the bioactive compounds from plant extracts stimulate histological changes in tilapia gonads, such as rupture of seminiferous lobules and follicles, and disintegration of spermatids and oocytes. The normal functioning of the gonads is disrupted, thereby inhibiting reproduction fertility (Table 7.2). Saponins from *C. papaya*, *P. guajava,* and *A. indica* were found to degenerate the gonadal cells of Nile tilapia and Mozambique tilapia, subsequently impairing fertility (Jegede and Fagbenro 2008; Khalil et al. 2011; Ampofo-Yeboah 2013; Solomon et al. 2017; Obaroh et al. 2018; Waweru et al. 2019).

7.3 Conclusions and Recommendations

Considering the findings of this review, it is clear that plant extracts present a promising alternative to synthetic hormones to control unwanted reproduction in tilapia culture. Undoubtedly, the application of plant extracts by tilapia farmers in Africa is still low, attributed to low research into their use and lack of standardized application protocol. The lack of holistic research continues to undermine the transition from trials to full-scale commercialization in aquaculture production systems. To maximize plant extracts, research should focus on identifying the active ingredients in different plant extracts, responsible for reproduction control in tilapia. This would facilitate the optimization of extraction procedures, identification of the most potent ingredient, determination of the optimal doses, and their mode of action. Likewise, sufficient data to support the growth, as well as safety benefits of plant extracts on fish are required. Given that studies at the endocrine and molecular levels provide more precise data, it is imperative that research incorporates these aspects, focusing on the expression of genes associated with sex differentiation and sex steroid profiles. Subsequently, effective extracts should be certified and a standard protocol to guide their application by tilapia farmers generated.

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Chapter 8
Pawpaw (*Carica papaya*) Extracts as Potential Growth Promoters and Sex Reversal Agents in Aquaculture

Linda Nuushona Iipinge, Ndakalimwe Naftal Gabriel, and Johannes Angala Iitembu

Abstract Aquaculture is the rearing, breeding, and harvesting of aquatic organisms in a controlled environment for commercial, recreational, or public purposes, such as fish, shellfish, algae, and aquatic plants. Fish in captivity are frequently subjected to various stressors that affect their production performance parameters. Furthermore, fish species such as tilapia are plagued by prolific breeding, which reduces their yield in captivity. Antibiotics, hormones, vitamins, and chemotherapeutics are chemicals used in aquaculture to improve overall health and increase culture fish production. Highly effective chemicals, however, may be hazardous to human health and the environment. *Carica papaya* is one of the medicinal plants used in aquaculture as an alternative to chemicals. Pawpaw crude extracts contain saponins and flavonoids, which have antibacterial, antifertility, antifungal, and pesticide properties. Growth-promoting and sex reversal effects of pawpaw seed powders have been reported in freshwater fish species, according to research. Masculinity is usually required in tilapia species because male fish grow faster than females, and monosex population culture prevents tilapia species from reproducing uncontrollably. More research, however, is necessary to understand the various effects of *C. papaya* extracts in different fish species for better aquaculture optimisation. The properties of pawpaw crude extracts are discussed in this chapter, as well as their potential benefits in aquaculture.

Keywords Aquaculture · Growth promoter · Phytochemicals · 17 α methyltestosterone · Pawpaw extracts · Sex reversal

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8.1 Introduction

Aquaculture is the rearing, breeding, and harvesting of aquatic organisms such as fish, shellfish, algae, and plants in a controlled aquatic environment for commercial, recreational, or human consumption. Aquaculture is the world's fastest-growing food sector, accounting for approximately 50% of global food fish production in 2014 (FAO 2014) and projected to contribute 41% of global fish production by 2020. (Krishen et al. 2009). Similarly, FAO (2012) reported a substantial increase in aquaculture production (an average growth of 6%) between 1990 and 2010. Aquaculture is also essential in developing countries because it employs poor rural communities, thereby alleviating poverty.

Since the ocean world's fish yields have reached their maximum production level, fish culture (which is expanding in new directions, increasing, and diversifying) has become an essential agricultural business industry (Cruz-Garcia et al. 2009; Bud et al. 2009). Tilapia is one of the most important fish species in freshwater aquaculture, serving as a significant source of protein and alleviating food security in rural communities in developing countries such as Sub-Saharan Africa (FAO 2002; FAO 2012). According to FAO statistics, global tilapia production increased from 1.5 million tonnes in 2001 (FAO 2002) to 4.51 million in 2012 (FAO 2014). Although tilapia is ranked second in production after carps, its output in 2010 exceeded 3.2 million metric tonnes, outperforming salmon and catfish (Omeje 2016).

Tilapia species is widely cultured throughout the world because it exhibits desirable characteristics such as rapid growth, acceptance of natural and inexpensive artificial feed, efficient food conversion, adaptability to a wide range of environmental conditions, and disease resistance under cultured conditions (Phelps and Popma 2000; El-Sayed 2006). Furthermore, unlike other species such as African catfish, *Clarias gariepinus* (Reed et al. 1967), which requires exogenous hormones to induce spawning in captivity, tilapia species are hardy, highly prolific, and spawn naturally in captivity. Despite the preceding characteristics, studies have shown that tilapia cultures are negatively impacted by the onset of precocious sexual maturity and uncontrolled spawning, which frequently results in overcrowding of ponds and consequently stunted growth, production of variable fish sizes, more extended culture periods, and low marketable sized fish (Popma and Masser 1999; Toguyeni et al. 2002; Ekanem and Okoronkwo 2003).

The concept of tilapia monosex culture production (preferably male) provides an opportunity to overcome the limitation of precious breeding, which minimises stunted growth, shortens culture duration, and thus, improves yield and economic return (Omeje 2016). All male tilapia cultures are preferred because they grow faster (Beardmore et al. 2001) and spend less energy on reproduction (Popma and Masser 1999). Several techniques, including sex sorting by hand, hybridisation, genetic manipulation, temperature control, and hormonal induction, were developed to produce an all-male population of marketable size (Beardmore et al. 2001). Because it saves time and produces precise results, synthetic sex reversal hormone (17 methyltestosterone) appears to be the most effective and widely used technique

(Toguyeni et al. 2002; Phelps and Popma 2000). To achieve phenotypic sex reversal, synthetic hormones are incorporated into the diet and administered to sexually undifferentiated fry about 2 weeks after hatching (Fuentes-Silva et al. 2013; Baras et al. 2000). The fry-fed steroid hormones (17 methyltestosterone) incorporated in a diet at the appropriate time and dosage (during the fish's undifferentiated gonadal development stage) will be converted from genotypic females to phenotypic males (Omeje 2016; Toguyeni et al. 2002; Pandian and Sheela 1995). Furthermore, fish-farming enterprises use a variety of chemicals, hormones, chemotherapeutics, and vitamins to combat problems such as infectious diseases, health issues, and economic losses (Yılmaz et al. 2013).

Besides the effectiveness of synthetic hormones, concerns have been raised about the health consequences for fish farmers who come into contact with the hormone during feeding (Guerrero III 2008) and the environment when the effluent is discharged into the environment (Heberer 2002). As a result, countries such as India have prohibited using synthetic hormones and antibiotics as feed additives (White et al. 2006). With this ban, the use of natural plant extracts as feed additives has emerged as a promising alternative approach for controlling bacterial diseases, promoting growth performance, and manipulating sex to obtain all-male tilapia production. The World Health Organization also supports using medicinal plants to replace steroid hormones, which pose no health risk to humans, are environmentally friendly, less expensive, and biodegradable for commercial aquaculture use (Farrag et al. 2013).

8.2 Pawpaw (*Carica papaya*) Extracts

One of the medicinal plants used in aquaculture as an infectious disease preventative, stress resistance booster, and growth promoter is the pawpaw. The term "pawpaw" refers to a short-lived, evergreen, tropical herbaceous plant with a height of up to 10 metres (m) (Verma et al. 2017). The *Carica papaya* is primarily native to southern Mexico, Central America, and South America (Carvalho and Renner 2014). It is regarded as one of the Caricaceae family's most economically significant fruits (Oliveira and Almada 1996) (Fig. 8.1). In Sub-Saharan Africa, tropical and subtropical regions, pawpaw is widely available all year around. It is grown for its delicious and nutritious fruit and medicinal purposes (Carvalho and Renner 2014). The plant's various parts, such as the seeds, unripe pulp, latex, and leaves, offer an alternative for controlling diseases and the sex ratio in aquaculture. The fruits were said to contain dietary fibre, calcium, iron, and sodium as well as carbohydrates, protein, fat, vitamin A, B, and C, carotene, and lycopene (Krishna et al. 2008). Other plant parts, including the seed, roots, unripe pulp, flowers, bark, latex, and leaves, have been found to contain vitamins A, B1, B2, and C, as well as chymopapain A and B and papain (Mitchel et al. 1970), all of which support muscle growth and function and aid in the metabolism of protein, fat, and carbohydrates (Su et al. 2009).

Fig. 8.1 Pawpaw (*Carica papaya*) tree and its fruits

8.3 Administration Methods in Aquaculture

Depending on the purpose of administration, herbal extracts are administered via three methods: oral, immersion, and injection. Oral administration is the most common method for incorporating extracts into diets, and animals can access the extracts through feeding. This method is commonly used when farmers want to improve fish growth, reverse sex, or improve the overall health of culture fish (Gabriel 2019). The immersion method is also helpful in aquaculture, where it is used for sex reversal, parasites treatment, and anaesthesia (Mukherjee et al. 2015; de Oliveira Hashimoto et al. 2016; Hoseini et al. 2019). Injection, on the other hand, is thought to be an effective method of administration; however, it can cause a high level of stress in fish, is labour intensive, expensive, and may require high-level technology that may not be available in other parts of the world (Mastan 2015).

8.3.1 Potential Health Benefits of Pawpaw Crude Extracts in Fish

Plant extracts are an essential resource in aquaculture for promoting growth, increasing stress resistance, and combating severe and infectious diseases. It is estimated that 80% of the world's population relies on traditional medicine, and a significant portion of traditional therapies involve using plant extracts or active ingredients (Ekor 2014; World Health Organization 2004). Furthermore, studies have shown that pawpaw products in their crude form contain a high concentration of bioactive compounds (such as saponins, flavonoids, phenols, alkaloids, terpenoids, glycosides, steroids, and cardenolides (Lohiya et al. 2000; Ezike et al. 2009; Oloyede 2005), which have antioxidant, antifungal, antifertility, anti-inflammatory, antimicrobial, and antifungal (Mansura et al. 2009). According to Awad and Awaad (2017), the presence of compounds with antibacterial, antifungal, and antiviral

Table 8.1 Health benefits response of fish-fed diet enriched with pawpaw crude extracts

Type of plant extract	Type of phytochemicals	Function	References
Root	Benzyl iso-thiocyanate, glucosinolatescarposide	Pawpaw root extracts were used to treat wound infections and gastroenteritis diseases in fish caused by pathogenic bacteria	Doughari et al. (2007)
Seed	Phenolics compounds, vanillic acid, vitamin C, caricain, alkaloids, steroids, flavonoids, saponins, and tannins	Pawpaw seed powder credited with molluscicidal activities against freshwater snail (*Lymnaea acuminata*) Pawpaw seeds exhibited significant inhibitory activity against cowpea weevil (*Callobruchus macalatus*)	Jaiswal and Singh (2008) Farias et al. (2007)
Fruit	Ferulic, p-coumaric, vitamin C, caffeic acid, carotenoids	Promote wound healing and skin repair	Emeruwa (1982)
Leaves	Folic acid, saponins, glycosides, tannins, flavonoids, vitamin B12, A, and C	Source of antimicrobial agent against fish pathogens	Fakoya et al. (2019)
Unripe pulp	Saponins, alkaloids, terpenoids, flavonoids, glycoside, stereoids, cardenolides	Responsible for medicinal properties in fish	Oloyede (2005); Ezike et al. (2009)

properties in the fish system may directly inhibit pathogen growth. Several studies have shown that compounds extracted from the pawpaw plant can inhibit pathogen growth in fish (Table 8.1). Emeruwa (1982), for example, discovered that pawpaw fruit and seed extracts have antibacterial properties. Furthermore, Doughari et al. (2007) reported that bioactive compounds in pawpaw root extracts were used to treat pathogenic bacteria-caused diseases in fish, such as wound infections and gastroenteritis. According to Jaiswal and Singh (2008), pawpaw seed powder has molluscicidal properties against the freshwater snail *Lymnaea acuminata*. Similarly, Farias et al. (2007) discovered that pawpaw seed crude extract had significant inhibitory activity against the cowpea weevil *Callosobruchus maculatus*.

Furthermore, studies have shown that mature unripe pawpaw pulp contains phytochemicals such as saponins, alkaloids, terpenoids, flavonoids, glycosides, steroids, and cardenolides, all of which are responsible for medicinal properties (Oloyede 2005; Ezike et al. 2009). According to Emeruwa (1982), whole fruit extracts contain ferulic, p-coumaric, vitamin C, caffeic acid, and carotenoids, all of which promote wound healing and skin repair. Folic acid, saponins, glycosides, tannins, flavonoids, vitamin B12, A, and C have been reported to be present in leaf extracts, and they serve as a source of an antimicrobial agent against fish pathogens (Fakoya et al. 2019). Pawpaw seeds have been found to contain anti-oxidants, anticancer, and antibacterial active ingredients such as phenolic compounds, vanillic acid, vitamin C, caricain, alkaloids, steroids, flavonoids, saponins, and tannins.

Ampofo-Yeboah (2013) reported that benzyl iso-thiocyanate in the crushed pawpaw seeds is thought to have activity against helminthic intestinal parasites.

8.3.2 *Sex Reversal Effects of Pawpaw Crude Extracts in Fish*

The adoption of natural plant extract practices that produce fish that are environmentally sound and free of pollutants has been prompted by a rise in consumer demand for safe and high-quality fish products (Chakraborty et al. 2014). This has led to the promotion of fish to satisfy new market demands. In tilapia culture systems, pawpaw crude extracts like seed meal have been used to reduce prolific spawning. According to reports (Udoh and Kehinde 1999; Verma et al. 2006), pawpaw seeds contain essential bioactive substances like saponins and oleanolic acid 3-glucoside with antifertility properties. Additionally, pawpaw seeds have been used to control fertility in a variety of animal models, including fish (Omeje 2016; Ampofo-Yeboah 2013; Iipinge 2019), rabbits (Pathak et al. 2000), rats (Udoh et al. 2005), and langur monkeys (Verma et al. 2006) (Table 8.2). Other studies have shown that the active components in pawpaw seeds, such as oleanolic glycoside and carpasemine (a plant growth inhibitor), caused sterility in male rats (Kobayashi et al. 2008) and were used to control *O. niloticus* breeding by changing the sex of fish in favour of males (Ekanem and Okoronkwo 2003; Ayotunde and Ofem 2008). According to Ampofo-Yeboah (2013), the potential use of pawpaw seed meal in fish feed resulted in a 65% masculinisation rate in *O. mossambicus*. Omeje (2016) found that *O. mossambicus* had a masculinization rate of 77.8%. In the study on the

Table 8.2 The sex ratio response of fish-fed diet incorporated with pawpaw seed powder

Type of plant product	Function	Fish species	References
Seed	Pawpaw seed meal incorporated into fish feed produced 65% masculinization rate	Mozambique tilapia (*Oreochromis mossambicus*)	Ampofo-Yeboah (2013)
	Pawpaw seed meal produced 77.8% masculization rate	Mozambique tilapia (*O. mossambicus*)	Omeje (2016)
	A high percentage of male fish (82%) was produced when fish fed with pawpaw seed powder	Three spotted tilapia (*O. andersonii*)	Iipinge (2019)
	A significant reduction in the sperm parameters in fish fed with pawpaw seed powder	Sharp-tooth catfish (*Clarias gariepinus*)	Ekpo et al. (2018)
	Pawpaw seeds at high dosage disintegrated the testes and ovaries leading to the devoid of spermatids and oocytes	Nile tilapia (*O. niloticus*)	Ekanem and Okoronkwo (2003); Jegede and Fagbenro (2008)

impact of pawpaw seed powder on the growth performance, feed utilisation, and masculinisation of sexually undifferentiated *O. andersonii* fry, a high proportion of male fish (82%) was noted (Iipinge 2019).

Furthermore, pawpaw seeds have been linked to a decrease in the quantity and quality of male rats' sperm (Nkeiruka and Chinaka 2013). Ekpo et al. (2018) discovered that C. *papaya* seed powder significantly reduced the sperm parameters of sharp-tooth catfish. A historical observation of gonads in *O. niloticus*-fed diets containing pawpaw seed powder revealed that glucoside in the seeds showed antifertility properties at high dosage as they disintegrate the testes and ovaries, respectively, devoid of spermatids and oocytes (Ekanem and Okoronkwo 2003; Jegede and Fagbenro 2008). The phytochemicals in pawpaw seed meal may contribute to tilapia masculinisation by lowering 17 estradiol levels in female fish while increasing testosterone levels (Ampofo-Yeboah 2013).

8.3.3 Growth Benefits of Pawpaw Crude Extracts in Fish

Pawpaw crude extracts are predominantly used in aquaculture to improve fish growth, boost innate immune response, and control a variety of diseases (Logambal et al. 2000). Pawpaw crude extracts have been used as feed additives in aquaculture to improve fish survival rates, feed utilisation efficiency, and productive performance of fish (Lević et al. 2008) (Table 8.3). Numerous studies on applying pawpaw products in crude form in various fish species have been reported, with impressive results. A study by Farrag et al. (2013) found that feeding *O. niloticus* a diet containing pawpaw seed meal at 6 g/PSP/kg diet for 45 days improved growth performance. Irabor et al. (2016) discovered that feeding *Clarias gariepinus* fingerlings 80% pawpaw seed powder meal improved their growth performance. According to studies, an increase in growth performance and feed utilisation in fish is attributed to a wide range of immune-nutritional constituents, including complex sugars such as polysaccharides (Zahran et al. 2014), which are believed to contain prebiotic properties (Kumar et al. 2016), which can increase an animal's nutrient digestibility, absorption, and assimilation capacity through improved

Table 8.3 Growth performance and feed utilisation response of different fish species-fed diet containing pawpaw seed powder

Types of plant extract	Function	Fish species	References
Seed	An improved growth performance was observed in fish-fed pawpaw seed meal incorporated at the level of 6 g/PSP/kg diet for 45 days	Nile tilapia (*Oreochromis niloticus*)	Farrag et al. (2013)
	An increased in growth performance was reported in fish fed with 80% of pawpaw seed powder meal	Sharp-tooth catfish (*Clarias gariepinus*)	Irabor et al. (2016)

gastrointestinal morphology or digestive system (Heidarieh et al. 2013; Gabriel et al. 2015).

8.4 Conclusion

The potential benefits of pawpaw crude extracts as alternatives to pharmaceutical drugs in boosting fish growth, preventing infectious diseases, and controlling undesirable reproduction in tilapia production systems were revealed in this chapter. Pawpaw crude extracts contain phytochemicals that are used to treat bacterial, viral, and parasitic diseases, as well as to control fish breeding in growing ponds. Because pawpaw is locally available, accessible, biodegradable, cheap, and diverse in nature, it could be used as a medicinal and economically beneficial plant by poor small-scale fish farmers and aquaculture scientists in tropical, subtropical, and sub-Saharan Africa. Even though the number of studies on the application of pawpaw crude extracts in aquaculture is increasing, more research is still needed to collect adequate information, particularly immune parameters, sex reversal effects, and toxicological effects in different fish species for better aquaculture optimisation.

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Chapter 9
Microbial-Based Systems and Single-Cell Ingredients: Exploring Their Role in Sustainable Aquaculture Production

Benjamin U. Akpoilih

Abstract Nearly 20% of all animal protein comes from seafood, which is often a good source of vitamins, minerals, and omega-3 fatty acids. Since the beginning of the 1990s, the production of marine fisheries has stayed the same. This is because of the massive fishing pressure on wild fish stocks and human activities. The increasing scarcity of fish meal (FM), the most expensive feed ingredient in aqua feed, may pose a future threat to aquaculture expansion. This chapter examines the role of single-cell ingredients (SCI) and microbes (microbial-based systems, MBS) in circular economy-based sustainable aquaculture production of farmed fish and shellfish. Single-cell organisms (e.g. bacteria, yeasts, and microalgae) and microbial-based systems (MBS) such as biofloc and periphyton play critical roles in reducing nitrogen (N) and phosphorus (P) loss from fish diets to the environment by volarising aquaculture wastes. Single-cell protein (SCP) and single-cell oil (SCO) are derived from microbial biomass that contains a high concentration of antioxidants and other bio-active components such as amino acids, long-chain polyunsaturated fatty acids (LC-PUFA), carotenoids, glucan, mannan, pullulan, xylitol, polyhydroxy butyrate (PHB), and polyhydroxyalkanoate (PHA). These dietary compounds stimulate the immune system, improve reproductive performance, and increase disease resistance in farmed fish species. With zero-water exchange and a low ecological footprint, biofloc technology can support intensive fish or shrimp production at a lower cost. To ensure that the aquaculture industry takes advantage of SCP and MBS, advanced but affordable technology to produce these agents must be developed to improve production, reduce feed costs, and minimise the harmful effects of SCP anti-nutritional factors.

Keywords Aquaculture · Biofloc · Single-cell protein · Microalgal oil · Periphyton · Biofilm

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9.1 Introduction

Fish contributes essentially to human nutrition, providing various health benefits in terms of protein, essential fatty acids (EFA), long-chain polyunsaturated fatty acids (LC-PUFA), and eicosapentaenoic acid (EPA) and minerals (Gephart et al. 2020; Kok et al. 2020). Fish and other aquatic foods from marine environments are central to meeting food and nutrition security goals, providing more than 3.3 billion people with 20% of their animal protein intake (FAO 2020; Gephart et al. 2020). However, fish production from the marine environment has been static since the late 1980s (Tacon and Metian 2018; FAO 2020). In contrast, aquaculture production has increased, with inland and fin fish aquaculture accounting for 51.3 Mt and 54.3 Mt, respectively, of the total fish production from all sectors (FAO 2020). In 2018, fed aquaculture represented more than 70% of global aquaculture production (Hua et al. 2019; Naylor et al. 2021), with carp, shrimp, tilapia, catfish, and salmon accounting for about 75–80% of farmed fish and shellfish combined (FAO 2020; Naylor et al. 2021). Freshwater fish species represented about 75–83.6% of total global edible farmed fish production, mainly under intensive net cage systems, including lakes, reservoirs, and rivers (FAO 2020; Naylor et al. 2021). The rapid growth of aquaculture makes it one of the fastest food-producing sectors globally (FAO 2020). According to Waite et al. (2014), fish production from the sector will increase to 140 Mt in 2050 and provide a source of high-quality protein in the future. Engle et al. (2017) estimated that aquaculture could close roughly 14% of the “gap” between global animal protein consumption today and the animal protein requirement in 2050.

However, aquaculture is heavily reliant on fish meal (FM) to fuel growth, particularly for major farmed species such as catfish, shrimp, and salmon (Cottrell et al. 2020), which accounted for 18% (15 Mt) of total aquaculture production in 2018 (FAO 2020). According to Boyd et al. (2022), formulated feed containing FM and fish oil (FO) accounts for roughly two thirds of fin fish and crustacean production. Concerns about the sustainability of aquaculture have recently arisen because of a decline in FM and FO production from capture fisheries (Costello et al. 2020). This decline may impact global aquaculture production of carnivorous fish such as salmon, trout, sea bream, sea bass, and shrimp, which rely on FM and FO to meet stringent requirements (Chatvijitkul et al. 2016; Kok et al. 2020). The shift from reliance on marine products to crop-based aquaculture increases competition for land and water (Fry et al. 2016; Chatvijitkul et al. 2016; Hua et al. 2019) via crop production (maize, rapeseed, wheat, soya bean) (Fry et al. 2016). Despite the declining use of FM and FO in aqua feed, feed accounts for 50–70% of the production cost of fish farming operations (Waite et al. 2014); it is also responsible for approximately 90% of the cumulative environmental impact of aquaculture supply chains (Kok et al. 2020; Naylor et al. 2021). The rapid growth rate of human populations (Engle et al. 2017; Hua et al. 2019) will increase aquaculture competition for natural resources and their ecological limits (Engle et al. 2017; Costello et al. 2020; Naylor et al. 2021) through habitat loss or degradation, mainly for shrimp farming (Carvalho Pereira et al. 2021), and through discharge of waste and nutrient-rich sludge (Carvalho Pereira et al. 2021).

The rapid expansion of the aquaculture sector is also associated with environmental issues such as greenhouse gas (GHG), carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (NO_2) emissions, which contribute to climate change (Boyd and McNevin 2015; Boyd et al. 2022; Fang et al. 2022; Luo et al. 2018). Other aspects of aquaculture production's environmental impacts include toxic and ecotoxic effects (Camargo and Alonso 2006); toxic residue in fish and antimicrobial resistance due to chemical use (antibiotics, hormones, pesticides, fertilisers Kawsar et al. 2022); increasing land, water, and energy requirements for feed production (Chatvijitkul et al. 2016; Fry et al. 2016); and global incidences of disease outbreaks in aquaculture systems (FAO 2020; Gephart et al. 2020; Kok et al. 2020). The impressive growth rate of aquaculture (11%, 2000–2019) in Sub-Saharan Africa is hampered by fish disease (e.g. Ghana), high production costs, and prohibitive feed prices, combined with the impact of the COVID-19 pandemic (Ragasa et al. 2022a, b), and the unavoidable threat to food security posed by Ukraine's ongoing war.

Chemical treatment and recirculating aquaculture systems (RAS) are two methods for reducing the environmental impact of aquaculture (Badiola et al. 2018). However, the risks of chemical contamination of water and fish, the high cost of RAS operation, and the discharge of nutrient-rich sludge have significant environmental consequences (Badiola et al. 2018; Carvalho Pereira et al. 2021). Practices that improve environmental performance include reducing feed conversion ratio (FCR) and increasing productivity with fewer inputs (water, land, and energy) required per tonne of production to reduce aquaculture's impact on resource use and the environment (Chatvijitkul et al. 2016; Costello et al. 2020). To achieve the goal of sustainable aquaculture, researchers tested several novel protein sources: Food and feed-processing wastes (Boyd et al. 2019; Jones et al. 2020); microbial-based food systems (Martínez-Córdova et al. 2017; Viau et al. 2020; Muthoka et al. 2021); and single-cell organisms (Martínez-Córdova et al. 2017; Viau et al. 2020; Muthoka et al. 2021). (Maizatul et al. 2017; Shah et al. 2018; Boyd et al. 2019; Costello et al. 2020; Carter and Codabaccus 2022). Single-cell organisms (e.g. bacteria, yeasts, and microalgae) and microbial-based systems (MBS) such as biofloc and periphyton play critical roles in reducing nutrient loss to the environment by recycling nutrients and volatilising waste from aquaculture (Chavan and Mutnuri 2019). The process can produce protein-rich biomass (SCP) and microalgae biomass (MAB) with an excellent nutritional profile (Azim and Little 2008; Goncalves et al. 2017; Gullian-Klanian et al. 2020; Pacheco et al. 2020; Adeoye et al. 2021; Ahmad et al. 2022; Maizatul et al. 2017; Han et al. 2019; Ansari et al. 2021; Muthoka et al. 2021; Tinh et al. 2021, Liao et al. 2022). This chapter reviewed the contributions of single-cell ingredients (SCI) to circular economy-based sustainable aquaculture production of farmed fish and shellfish. The current literature on the nutritive and feeding value of microbial-based systems and single-cell ingredients in aquaculture was reviewed.

9.2 Overview of Sustainable Alternative Protein Sources

Several researchers have reviewed some nutritional approaches in the literature to improve the sustainability of aquaculture and reduce its associated environmental impact (reduced P and N) (Gasco et al. 2019; Costello et al. 2020; Naylor et al. 2021; Albrektsen et al. 2022); namely, plant protein (PP), and plant by-product derived from the fermentation industry (e.g. distillers dried grains and solubles—DDGS) (El-Husseiny et al. 2018; Amer et al. 2019). These innovative approaches can help create a circular economy by making better use of food waste and natural resources (Ragasa et al. 2022a, b). Nonetheless, several factors limit their use in aquaculture: high anti-nutritional factors (for example, phytic acid in PP, Krogdahl et al. 2010), low essential amino acids (EAA) (Makkar et al. 2014), deficiencies of EFA and LC-PUFAs (Fry et al. 2016; Malcorps et al. 2019), low nutritional quality (Hua et al. 2019), and sustainability issues related to aquaculture.

9.3 Microbial-Based Food Systems and Single-Cell Proteins as Novel Ingredients in Aquaculture

For sustainable aquaculture production, MBS and single-cell organisms (e.g. bacteria, yeasts, and microalgae) represent a valuable feed protein (SCP) and lipid or single-cell oil (SCO) (Crab et al. 2007; Azim and Little 2008; Tibbetts et al. 2017; Sillman et al. 2019). They can also reduce the environmental impact of intensive aquaculture production through nutrient cycling (Martınez-Cordova et al. 2014; Martínez-Córdova et al. 2017; Huang 2020; Campanati et al. 2022) and waste removal (e.g. bacteria and microalgae Goncalves et al. 2017; Jung et al. 2017; Spalvins et al. 2019; Huang 2020). SCP and MBS (for example, biofloc) may also offer an alternative to antibiotics in aquaculture production by reducing the negative impact of disease on fish health and increasing fish immunity (Durigon et al. 2019; Wang et al. 2019; Agboola et al. 2020; Wang et al. 2022a, b). Dietary SCP can also reduce global feed demand, closing the gap between fish production and demand in aquaculture (Shah et al. 2018; Ahmad et al. 2022; Campanati et al. 2022).

9.3.1 Microbial-Based Food Systems in Aquaculture: Nutritional Composition and Feeding Value

Microbial-based food systems are a collection of microscopic organisms that live in a matrix (bacteria, fungi, rotifer, zooplankton, and microalgae). A biofloc is an aggregation of microorganisms such as algae, fungi, ciliates, flagellates, rotifers, and detritus that contain essential amino acid (EAA) comparable to commercial

Table 9.1 Overview of the nutritional composition of some microbial-based systems in aquaculture

Microbial systems	Culture system	Proximate composition (g/kg DM)	References
Periphyton	Mixed-sex tilapia farming in earthen ponds	CP: 272.6; L: 35.9; CF: 5.5; Ash: 359	Muthoka et al. (2021)
Biofloc	BFT using indoor tanks for Pacific white shrimp (*Litopenaeus vannamei*)	CP:292–303; E: 12.7–14.4; Ash: 361–401; TN: 47–49	Tinh et al. (2021)
Biofilm	Enclosures of shrimp with artificial substrates	CP: 4.30; biomass: 1.76–4.23 mg cm^{-2}; L: 12.1	Martiınez-Cordova et al. (2014)
Biofilm	Enclosures of shrimp with artificial substrates in zero-water system	CP: 3.4–6.90; L: 6.0–9.10; CHO: 8.8–14.1; Biomass: 2.9–15.6 g cm^{-2}	Viau et al. (2016)
Biofloc	Indoor internal minimum water exchange BFT internal tanks given with restricted protein	CP: 293.4–297.6, L: 250–500	Gullian-Klanian et al. (2020)

CP Crude protein (g/kg), *L* lipid, *CF* Crude fibre (g/kg), *E* Energy (kJ/g), *DW* dry weight, *CHO* Carbohydrates, *DM* Dry matter

shrimp feed (Najdegerami et al. 2015; Ju et al. 2008). Reportedly, biofloc enhances growth in fish species (Ekasari et al. 2015; Dauda et al. 2017, 2018a, b; Aboseif et al. 2022). Microbial floc and MBSs provide essential nutrients and increase digestive enzymes in fish (Najdegerami et al. 2015; Viau et al. 2016); however, the nutritional composition of these food sources is dependent on several factors, including the type of microbial system (Table 9.1, periphyton, biofilms, and bioflocs), their association with organic and inorganic materials (detritus, sludge) and the carbon (C) source ((Nevejan et al. 2016). Protein concentration in bioflocs, for example, can range from 140 to 500 g/kg of dry matter (DM), with greater levels observed for bioflocs created in shrimp tanks utilising aquaculture wastewater (Martiınez-Cordova et al. 2014). Ekasari et al. (2014a, b) found that the >100 m biofloc group had more protein and fat content than the other size categories. In contrast, the 0.48 m biofloc group had the most excellent amino acid (AA) content. According to Dauda et al. (2017), the crude protein (CP) of biofloc generated from various C sources ranged from 113.9 g/kg DM (rice bran) to 312.7 g/kg DM (sucrose).

9.3.2 Biofloc Systems

Increasing the abundance of heterotrophic bacteria in the biofloc system reduces the toxic inorganic N species and P in the system (Tinh et al. 2021; Aboseif et al. 2022). It also increases biomass yield compared to that of C added by algae (Avnimelech et al. 2014) and in tanks without C (Tinh et al. 2021). The addition of a carbon source lowers the concentrations of potentially toxic total ammonia nitrogen (TAN) and nitrate–nitrogen (NO_2–N) in biofloc systems (Debbarma et al. 2022), allowing for greater reuse of biofloc-derived aquaculture wastewater (up to 100%) (Figueroa-Espinoza et al. 2022). Crab et al. (2007) reported that the inclusion of carbohydrate (CHO) reduced CP from 400 to 250 g/kg of dry matter (DM) without compromising shrimp production. Biofloc replaced 500–1000 g/kg of DM of the FM in fish and crustacean diets, according to Martínez-Córdova et al. (2017). According to Kumar et al. (2015), rice flour added to a culture tank of black tiger shrimp *Penaeus monodon* (Fabricius, 1978) in a biofloc technology (BFT) system resulted in better growth in shrimp fed a 32% CP diet than in shrimp fed a 40% CP diet. Debbarma et al. (2022) found that adding C at 0 mL/L, 1.7 mL/L (C/N 10), 6 mL/L (C/N 15), 13 mL/L (C/N 20), and 14.6 mL/L (C/N 25) increased floc volume and improved fish growth performance when comparing the potential of biofloc in the production of panda (*Ompok bimaculatus*, 0.082 g). The authors also observed increases in digestive enzymes (lipase, amylase, and protease) in the gut, liver, and muscle in the biofloc group, with a C/N of 20, showing overall improvement in production performance and water quality compared to other groups.

These observations show that applying a C source in an aquaculture system stimulates microbial growth and improves access to nutrient-rich microbial floc, effectively enhancing growth performance (Wang et al. 2015). The magnitude of growth response depends on the type of C source with biofloc produced from glycerol (Dauda et al. 2017) and tapioca resulting in better growth and feed utilisation (Ekasari et al. 2014a, b). The daily feeding rate (e.g. common carp fed up with 75% biofloc (Najdegerami et al. 2015), fish stocking density (Table 9.2, Fauji et al. 2018), and the amount of biofloc used (Wang et al. 2015) are all factors that influence fish growth. Biofloc technology (BFT) enables a decrease in the amount of feed applied for fish feeding (Kaya et al. 2019). A study carried out by Aboseif et al. (2022) showed that in addition to increased growth and feed utilisation, biofloc enhanced carcass protein content and increased the population of lactic acid bacteria (LABs) in the gut, demonstrating the probiotic effect of biofloc; the authors concluded that increasing the C/N facilitated higher assimilation of nutrients (EAA, LC-PUFA, and protein) and decreased total N discharge in the water.

9.3.3 Periphyton Systems

Periphyton is a type of MBS that serves as an important natural food source for aquatic animals due to its high concentration of essential dietary nutrients (Martiınez-Cordova et al. 2014). Bacteria, fungi, protozoa, snails, chironomids, oligochaetes, and crustaceans comprise periphyton which is attached to submerged substrates (Azim et al. 2002). These organisms provide live food for cultured fish (Azim et al. 2002; Miao et al. 2021;Muthoka et al. 2021; Saikia and Das 2014), reduce feed input in the system (Garcia et al. 2016), and improve water quality (Garcia et al. 2016). (Li et al. 2019; Muthoka et al. 2021; Saikia and Das 2014).

Table 9.2 Overview of some factors that influence growth performance, feed utilisation, and physiology of fish that are raised in BFT system

Parameters	Treatments	Experimental diet	Chemical composition (g/kg dry matter)	Feeding strategy	Culture system	Fish/shrimp species	Size (g)	Duration (days)	Response (best diet)	References
C/N	9.5:1 (control), 15:1, 20:1, 25:1	Control (basic feed); Exp diet (Basic feed + added glucose)	Comm diet: CP, 300; L, L, 120; CF, 120; Ash, 15%	Fixd ration (3–5% body weight)	Zero-water exchange	Crucian carp, *Carassius auratus*	5.01 ± 0.13	56	Improved WG, SGR; reduced FCR compared to control (20:1 and 25:1)	Wang et al. (2015)
	0 (control), 10:1, 15:1, 20:1	Control (comm..feed); Exp diet: (comm. feed + added glycerol)	Comm diet: CP, 430; L, 60	Fixed ration (3% body weight)	Zero-water exchange	African catfish (*Clarias gariepinus*)	11.77 ± 0.01	42	Higher WG, body protein, chymotrypsin, and lower muscle cholesterol, lipid peroxidation compared to control (15:1)	Dauda et al. (2018a, b)
Feeding rate	100% DFR, BFT+ 75% DFR, BFT + 50% DFR and BFT + 25% DFR	Control (comm.. diet); Exp diet (BFT+ comm. diet). C source: Beet molasse (24% C; CP,	Comm. Diet: CP, 350; L, 70; Ash, 90	Fixed ration Control: 3.5% body weight (100% DFR), BFT(+75%, 50%, 25% DFR)	Zero-water exchange	Common carp (*Cyprinus carpio* L.) fingerlings	58.6 ± 0.2	30	Improved WG, SGR, and digestive enzymes (pepsin, lipase activities (BFT + 75%)	Najdegerami et al. (2015)

(continued)

Table 9.2 (continued)

Parameters	Treatments	Experimental diet	Chemical composition (g/kg dry matter)	Feeding strategy	Culture system	Fish/shrimp species	Size (g)	Duration (days)	Response (best diet)	References
C source	Control, Sucrose, glycerol, rice bran	Control (Comm diet); Exp diet (biofloc with sucrose, glycerol and rice bran)	Comm diet; CP, 430	Apparent satiation	Zero-water exchange	African catfish *C. gariepinus* fingerlings	5.06	42	Improved WG, SGR, biomass gain, biofloc volume, survival and plasma glucose and triglycerides (glycerol)	Dauda et al. (2017)
	Control, molasses, tapioca, tapioca by-products, and rice bran	Control (comm. Diet), exp. diet: control with C sources added to the system	Comm diet: 300 CP	Fixed ration (7% body weight)	Zero-water exchange	Pacific white shrimp (*Litopenaeus vannamei*) juveniles	2.02 ± 0.05	49	Improved SGR, FCR, survival, yield, and protein assimilation, and immunity in C sources (Tapioca)	Ekasari et al. (2014a, b)
Biofloc level	0, 50 g/kg, 100 g/kg, 150 g/kg, and 200 g/kg diet	Control (comm.. diet); Exp. Diet (comm.. diet with biofloc)	Comm. Diet: CP, 350; L, 54.5; Exp. Diet: CP, 351–357; L, 52.2–56.3	Fixed ration (3.5–5% body weight)	Zero-water exchange	Crucian carp, *C. auratus*	3.24 ± 0.27	56	Improved WG, WGR, SGR and reduced FCR compared to control (10 g/kg)	Wang et al. (2015)

Biofloc size	Un-sieved, <48 μm, 48–100 μm, >100 μm	Control (comm.. diet); Exp. diet (comm.. diet with biofloc sizes)	Comm diet: 400 CP	Fixed ration (8% body weight)	Zero-water exchange	White shrimp (*Litopenaeus vannamei*), red tilapia (*O. niloticus*) and mussels (*Perna viridis*)	5	4	Nitrogen uptake, recovery were in higher in >100 μm, while biofloc consumption as well as amino acid was higher in <48 μm than un-sieved (<48 μm)	Ekasari et al. 2014a, b
Dietary protein level	Control (32C and 40C), 32R, 32 M, 40R, 40 M	32C (practical diets with 32% CP) and 40C (practical diets with 40% CP); Exp diets 32R and 32 M (32C + rice flour (R) and molasse (M); 40R and 40 M (40C + R and 40C + M)	32R/32M: CP, 318; L, 58; CF,121; Ash, 137 40R/40M: CP: 405; L, 6%; CF, 121; Ash, 152	Fixed ration (4–6% body weight)	Partial (30%) water exchange	black tiger shrimp *Penaeus monodon* (Fabricius, 1978)	3.37 ± 0.04	75	Higher FW, SGR and lower FCR, catalase, serum protein and glucose in 40R, 40M and 32 R than 32 C and 40C (32 R)	Kumar et al. (2015)

(continued)

Table 9.2 (continued)

Parameters	Treatments	Experimental diet	Chemical composition (g/kg dry matter)	Feeding strategy	Culture system	Fish/shrimp species	Size (g)	Duration (days)	Response (best diet)	References
Stocking density	Control, low (LD), medium (MD), and high density (HD)	Control, 333 fish m^{-3}; Exp.: 166 fish m^{-3} (LD), 333 fish m^{-3} (MD), and 600 fish m^{-3} (HD)	Control had no glucose in water, while exp. groups all had glucose	Apparent satiation	Zero-water exchange	Nile tilapia (*O. niloticus*) fingerlings	0.51 ± 0.05	120	Higher FBW, DWG, SGR, and lower FCR; higher immunity in LD and MD than control (LD&MD)	Liu et al. (2018)
Feeding habit	BFT + LFBH, BFT + ACF	Triplicate group of each fish (20) were fed Comm. diet in 25 L BFT	Comm. diet: CP, 400; L, 60	Fixed ration (3% body weight)	Zero-water exchange	Lemon fin barb hybrid (LFBH) & African catfish (ACF)	1.77 ± 0.02 (LFBH) 0.98 ± 0.05 (ACF)	56	Higher WG, SGR, and PER as well as higher biofloc volume and protein for LBFT than ACF	Dauda et al. (2018a, b)

C/N carbon/nitrogen ratio, *Comm* commercial diet, *Exp Diet* experimental diet, *WG* weight gain (g), *FCR* feed conversion ratio, *SGR (% /day)* specific growth rate, *FBW* Final body weight, *CP* crude protein, *L* lipid, *CF* crude fibre, *BFT* biofloc technology

When compared to a control without periphyton, a source of C is added to the system to maintain an optimum C/N of 10–20, which increases the growth of the microbial community and improves fish growth performance and yield (Guo et al. 2020; Tinh et al. 2021). (Asaduzzaman et al. 2008; Garcia et al. 2017). Muthoka et al. (2021) reported that Nile tilapia (12 g) raised in the periphyton technology (PPT) system in a fertilised pond (1 m deep) and fed at 3% body weight for 3 months exhibited higher WG, SGR, and lower FCR than non-PPT systems; the abundance of diatom and zooplankton communities was higher with reduced cyanobacteria and decreased ammonia (NH3), Fish raised in PPT-based systems in cages grew faster than fish raised in periphyton-based systems (Garcia et al. 2016; Tammam et al. 2020). However, David et al. (2021) reported that PPT in a cage system did not benefit from feed restriction when compared to a system with full feeding but no periphyton; this was due to the study's low N/P ratio when compared to previous research with PPT (27:1, Garcia et al. 2017).

9.3.4 Biofilm Systems

A biofilm is a microbial consortium consisting of microalgae, bacteria, protozoans, fungi, and metazoans that are attached to a submerged substrate. It is critical for fish species whose diet does not consist of plant matter (Martiınez-Cordova et al. 2014). Dar and Bhat 2020; Dar et al. 2020). Biofilms are made up of microorganisms from various domains held together by EPS on surfaces (Dar et al. 2020), whereas biofloc is made up of heterotrophic bacteria (HB), phytoplankton, zooplankton, and protozoa attached to a floating surface (Porchas-Cornejo et al. 2017). Biofilms are high in protein, lipids, and LC-PUFA, which are beneficial to fish, particularly tilapia (Martínez-Córdova et al. 2017). Biofilms are critical to the live food sources of many farmed fish species (Garibay-Valdez et al. 2019; Ortiz-Estrada et al. 2019).

Viau et al. (2016, 2020) reported improved growth and reproductive success of pink shrimp in a zero-water system with biofilm as a single feed source, as well as reduced N loss. According to Lara et al. (2017), biofilm reduced feed input by 35% compared to the group reared in biofloc without artificial feed or biofilm. Wang et al. (2022a, b) found that augmentation of microalgae–bacteria with biofilm carriers increased fish production in recirculating ponds; bacteria–microalgae–biofilm decreased total ammonia-N (TAN) and nitrite–N by 51.28% and 33.48%, respectively. FM can be replaced in a fish diet by a biofilm-based single-cell protein (SCP) derived from purple phototrophic bacteria (PPB) (Delamare-Deboutteville et al. 2019). MBS is a powerful bioremediation tool for heavy metals and other contaminants in aquatic environments (Dar et al. 2020; Dar and Bhat 2020).

9.3.5 Microbial-Based Systems as Immunostimulants in Aquaculture

In addition to enhancing growth, the incorporation of MBS, such as biofloc, in aquaculture production systems improves water quality (Crab et al. 2007; Ekasari et al. 2014a, 2015; Dauda et al. 2018b); controls harmful pathogens (Crab et al. 2007; Martínez-Córdova et al. 2017); and increases beneficial gut microbiota (Crab et al. 2007). (Clenfuegos-Martinez et al. 2022). Biofloc minimises the environmental effect of aquaculture when compared to other aquaculture production technologies (Dauda et al. 2018a, b). Biofloc includes beneficial components such as EFA, carotenoids, chlorophylls (Ju et al. 2008), poly-hydroxybutyrate (PHB), Gulian-Klanian et al. 2020), and polyhydroxyalkanoate (PHA). These chemicals have been shown to promote immunological response and reproductive performance in farmed fish species (Ekasari et al. 2014a, b, 2015; Bossier and Ekasari 2017), as well as suppress pathogenic microorganisms (Supono et al. 2014; Matassa et al. 2015). Biofloc has several value-added components, such as antioxidants that boost aquatic animal immunity (Ekasari et al. 2014a, b; Yu et al. 2020). (Liu et al. 2018). Simultaneously, biofloc stimulates fish immune systems (Ekasari et al. 2014a, b; Liu et al. 2018; Karimi et al. 2019; Yu et al. 2020), effectively overcoming the problem of antibiotic abuse in aquaculture (Martínez-Córdova et al. 2017; Durigon et al. 2019; Wang et al. 2019) by enhancing disease resistance (Dauda et al. (Bentzon-Tilia et al. 2016). Biofloc promoted innate immunity (phenoloxidase and respiratory burst activity) and improved resistance to infectious myonecrosis virus (IMNV) in Pacific white shrimp (*L. vannamei*) juveniles, according to Ekasari et al. (2014a, b).

9.4 Single-Cell Protein and Their Application in Aquaculture

9.4.1 Production of Single-Cell Protein (SCP)

Several researches have shown that SCP and microbial consortia might be used in biomass and feed production (Overland et al. 2013; Bakhshi et al. 2018; Vidakovic et al. 2019). Protein obtained from yeast, fungus, microalgae, and bacteria may be used to make SCP or microbial protein (MP) (Nasseri et al. 2011; Bharti et al. 2014; Glencross et al. 2020). These microbes are grown on agricultural and industrial wastes (cassava waste, bran, bagasse, paper pulp, sucrose, ethanol, polysaccharides, industrial by-products, dairy waste, Jach et al. 2022) via solid/semi-solid state fermentation (SSF, Sharif et al. 2021) or submerged fermentation (SMF) using free-flowing liquid substrates (molasses, broth) (Bharti et al. 2014; Upadhyaya et al. 2016; Kuzniar et al. 2019). The following steps are involved in SCP production, depending on the culture technique and microorganism used (Ritala et al.

2017): preparation of nutrient media, possibly from waste; enzymatic hydrolysis (for yeast production, Overland and Skrede 2016); cultivation, including SSF; separation and concentration of SCP, in some cases drying; and final processing of SCP into ingredients and products (Ritala et al. 2017; Jach et al. 2022). In contrast to yeast SCP, bacterial SCP (Spirulina, Methylococcus, or Methylophilus) undergoes a secondary drying process (Overland et al. 2010). The drying phase in SCP processing allows for incorporation in extruded/pelleted feeds (Glencross et al. 2020). Microalgae, a high-protein source (510–740 g/kg), may be cultivated in various conditions and organic substrates (Han et al. 2019; Acquah et al. 2021). Microalgae farming yields more biomass (4–15 tonnes per acre per year) than traditional protein sources (0.6–2 hectare per year, Acquah et al. 2021). Microalgal extraction produces biopeptides, animal feed, and feed additives (Ahmad et al. 2022; Campanati et al. 2022). However, depending on the species, microalgae's solid cell wall composition limits its usage as feed (Raji et al. 2020). As a result, multiple techniques (for example, mechanical disruption) that assist in protein extraction, concentration, isolation, or purification of various products, including feed, are used to improve protein extraction efficiency (Amorim et al. 2021). SCP-manufacturing techniques for many microorganisms have been examined by Anupama and Ravindra (2000), Nasseri et al. (2011), Upadhyaya et al. (2016), Sharif et al. (2021), Albrektsen et al. (2022), and Jach et al. (2022) (yeast, bacteria, and fungi).

A recent trend in SCP production has seen an increase in the usage of different by-products (off-gas biogas and syngas) (Teixeira et al. 2018) derived from a variety of sources such as dairy wastes (whey, biogas, biohydrogen, bioethanol, protease, and bio-active substances, Sar et al. 2022); fruit and potato-processing wastewater (Sharif et al. 2021); and alkane wastewater (Sharif et al. 2021), agro-industrial waste, and industrial residue (Jones et al. 2020; Overland and Skrede 2016; Ritala et al. 2017; Jach et al. 2022; Leeper et al. 2022). Recent improvements in microbial technology have resulted in better and enhanced MB production using gas bioreactor fermentation technology (Matassa et al. 2016; Sillman et al. 2019; Albrektsen et al. 2022). Many new businesses are manufacturing MP from natural gas, primarily CH4)-using methanotrophic bacteria (Ritala et al. 2017; Teixeira et al. 2018; Kuzniar et al. 2019; Jones et al. 2020). Banks et al. (2022) predicted a $24 billion growth in alternative proteins by 2024, thus, lowering operational costs in the future owing to economies of scale. Compared to FM, SCP has a higher production volume and market value (Table 9.3). Industries that use current microbial biotechnology and better downstream processes have a bright future (Matassa et al. 2016; Ritala et al. 2017).

9.4.2 Nutritional Composition of SCP

SCP derived from bacteria has a high-protein content that ranges from 500 to 800 g protein kg^{-1} dry weight (DW) (Table 9.4). In comparison to yeast and microalgae SCP, bacterial meals (BM) have the most methionine (Overland et al. 2010).Protein

Table 9.3 Overview of production volumes and market sizes for different MPs

SCP	Production by volume (tonne/y)	Production costs (Euro/kg DM)	Economic value (Billion Euro)	Growth rate (% per year)
Yeast[a]	3,000,000 (Frost and Sullivan 2018)	–	9.2 (Jach et al. 2022)	8 (Jach et al. 2022)
Microalgae[b]	9000 (Frost and Sullivan 2018), 40,000 (Hua et al. 2019)	4–25 (Matassa et al. 2016)	1.6–2.4 (Matassa et al. 2016), 4.4–6.2 (Chang et al. 2017)	
Microalgae (Spirulina)[c]	10000 (Upadhyaya et al. 2016)		1.49 (Ahmad et al. 2022)	7.9 (Ahmad et al. 2022)
Bacteria (FeedKind)[d]	80,000, 200000 (Frost and Sullivan 2018)	–	–	–
ValProMic[e]	5000 (Matassa et al. 2016)			
Mycoprotein (Quorn)[f]	25000 (Matassa et al. 2016)	–	0.214 (Matassa et al. 2016)	20 (Matassa et al. 2016)
Bacteria (ProFloc™)[g]	5000	1–1.1 (Matassa et al. 2016)	–	–
Fish meal	171Mt (FAO 2018)	0.81–0.98[h], 1.303BC (Alloul et al. 2021)		

[a] Produced by LeSaffre® in France under different product names such as Lynside®Nutri, Lynside®ProteYn and related products (Lesaffre Human Care products), as well as yeast-based flavour ingredients (Biospringer products), with a turnover of 1.6 billion Euro in 2013

[b] Produced and marketed by E.I.D Parry Ltd., Parry Nutraceuticals Division, which is part of the 4.4 billion US$ Murugappa Group that produce Chlorella and Spirulina (Ritala et al. 2017)

[c] Produced and marketed by Cyanotech Corporation, USA;, with turnover of almost 32 million US$ and a GRAS status by FDA (Ritala et al. 2017)

[d] Produced by Calysta Inc, Menlo Park, Canada

[e] ValProMic is an MP grown on wastewater from the potato- processing industry (Ritala et al., 2017)

[f] Produced by Marlow Foods Ltd, and sold to Monde Nissin Corporation

[g] Nutrinsic, based in USA with subsidiaries in China, it used waste water for SCP

[h] Based of 2018 market price and a CP of 65%, according to Delamare-Deboutteville et al. (2019)

levels in dietary microalgae range from 500 g/kg (*Nannochloropsis oculata*, Sarker et al. 2020) to 600 g/kg (Pavlova sp., Wei et al. 2022) and 700–710 g/kg (*Spirulina maxima*), depending on the species (Maizatul et al. 2017; Shah et al. 2018; Hua et al. 2019). The nutritional profile of microalgae meal (MAM) was superior to that of fish meal (FM) (Bharti et al. 2014; Shah et al. 2018). Microalgae are rich sources of docosahexanoic acid DHA (300 g/kg, Schizochytrium sp., Sarker et al. 2020), with high ADC of protein (83%), lipids (91%), omega-6 6-PUFA (94%), omega-3 PUFA

Table 9.4 Nutrient composition of SCP source used in aquaculture production

Composition (g/kg DW)	Microorganisms			
	Fungi	Microalgae	Yeasts	Bacteria
Crude protein	300–450[k], 300–700[a], 400–500,[f] [h]300–500 350–500[i]	400–600[a], 550–700[b], [e]710, [h]600–700, 400–600[i], 540[q]	450–550,396–539*,462–598[¶], 544[#]	500–650, 500–830[a],800[b], [c]500–830, [d]500–650,[g]780,[h]500–800, 600–800[i]
Crude lipid	20–80, 200–250[f], 50–130[i], 560[o], 501[p]	70–200[a], [e]400, 50–100[i], 110[q]	20–60, 5–80*, 3.2–24[¶],9[#], 580[l], 650[m], 720[n]	10–30, [g]25–90, 80–100[i]
Ash	90–140	80–100, 100[q]	50–100, 45–103*, 58–95[¶], 81	30–70
Nucleic acid	70–100, 97[i]	30–80[h], 40–60[i]	6–120, 48–90*, 15–99[¶], 109[#]	80–120, 150–160[i]
Bioactive compounds[a]	Carbohydrates	Microbial oil	Amino acids, glucan & mannan[r]	PHB Ectoine
	Pullulan	Carbohydrates	Alcohols (1-butanol and isobutanol)[£]	Lipids Coenzyme Q8[j]
	Xylitol	Vitamins	Sesquiterpenes (farnesene and bisabolene) [£]	Extracellular polysaccharides

[a] Matassa et al. (2016)
[b] Upadhyaya et al. (2016)
[c] Sillman et al. (2019)
[d] Delamare-Deboutteville et al. (2019)
[e] Hua et al. (2019)
[f] Karimi et al. (2019)
[g] Nevejan et al. (2016)
[h] Ritala et al. (2017)
[i] Anupama and Ravindra (2000)
[j] Overland et al. (2010)
[k] Bharti et al. (2014)
[l] *Candida curvata*
[m] *Cryptococcus albidus*
[n] *Cryptococcus albidus*
[o] *Fusarium equiseti*
[p] *Mortierella isabellina* (Szczepańska et al. 2022)
[q] *Pavlova sp.* 459 (Tibbetts and Patelaskis, 2022)
[r] Agboola et al. (2020)
[*] *S. cerevisiae*
[¶] *Candida utilis*
[#] *Kluyveromyces marxianus* (Overland and Skrede 2016)
[£] Ekpeni et al. (2015). *PHB* poly-hydroxybutyrate

(99%), and (EPA + DHA, 99%) recorded for marine microalgae (Pavlova sp. 459, Tibbetts and Patelakis 2022).

The nutritional content of yeast SCP is affected by the fermentation technique, species, and downstreaming procedure (Hansen et al. 2021). Yeast SCP protein content varied between 380 and 600 g/kg (Albrektsen et al. 2022). C. utilis and Kluyveromyces marxianus have lately sparked attention as possible protein sources in aqua feed (Overland and Skrede 2016; Jones et al. 2020). These yeasts have been granted "generally recognized as safe" (GRAS) classification by the US Food and Drug Administration (FDA), which is given to drugs that are not detrimental to health (Overland and Skrede 2016). Despite higher contents of non-protein N in the form of nucleic acids in yeast (10–15%, Overland and Skrede 2016; Ritala et al. 2017; Albrektsen et al. 2022), the analysis of nutrients in yeast protein and FM reveals similar contents of most indispensable AA on a CP basis (Glencross et al. 2020; Albrektsen et al. 2022). Yeast protein has more lysine, leucine, and isoleucine than FM, but less methionine, tryptophan, arginine, and lysine (Glencross et al. 2020). Yeast, on the other hand, has a better FAO protein scoring pattern than FM (Anupama 2000; Glencross et al. 2020), based on human EAA needs to quantitatively assess protein quality (Matassa et al. 2016). The CP and lipid of five yeast S. cerevisiae, *Cyberlindnera jadinii*, *Kluyveromyces marxianus*, *Blastobotrys adeninivorans*, and *Wickerhamomyces anomalous* are 380–520 g/kg and 7–89 g/kg, respectively (Agboola et al. 2020), with a comparable chemical score (a ratio of the individual digestible AA in each yeast product and the (Agboola et al. 2020). *S. cerevisiae*, on the other hand, contains more methionine and cysteine but less lysine than other yeast species (Agboola et al. 2020).

9.4.3 Nutritional Feeding Value of SCP in Aquaculture

The potential of SCP as a future feed ingredient in aqua feed production for larval and adult fish/shellfish with opportunities for future expansion and commercialisation has recently been realised (Carter and Codabaccus 2022). Beal et al. (2018) reported that it is possible to substitute 30% of world FM and FO with microalgae MP, which can improve the sustainability of fisheries and aquaculture. On the other hand, while performing a 10-year FM and FO replacement meta-analysis, Cottrell et al. (2020) reported that dietary SCP can reduce forage fish demand to 8–10 Mt based on projected aquaculture growth scenarios of faster growth rate and global shifts in consumer preferences in 2030, which is below the ecosystem-based fisheries management limit of fish supply (8.65–10.27Mt). Studies with marine and freshwater fish species show that dietary MP is essential for the growth and physiology of aquatic species (Crab et al. 2007; Azim and Little 2008; Vidakovic et al. 2019; Gullian-Klanian et al. 2020; Mahmoud et al. 2020).

9.4.4 Yeast SCP

Yeasts and many co-products of ethanol-fermented yeast, such as dry distiller grains with solubles, DDGS (Overland et al. 2013; Overland and Skrede 2016; Shurson 2018; Glencross et al. 2020; Rimoldi et al. 2020) improve fish growth (Overland et al. 2013; Goda et al. 2019) and protein availability (88–98%, Overland et al. 2013; Langeland et al. 2016). Fayeofori and Bob-Manuel (2014) reported good growth and FCR for Nile tilapia fed up to 500 g/kg YM compared to the FM diet. In contrast, including 328 g/kg YM in the diet was ideal for African catfish (*Clarias gariepinus*). The replacement of FM with YM (200–300 g/kg) improved protein digestibility (80%) in *O. niloticus* fry (Olvera-Novoa et al. 2002), and rainbow trout fed a practical diet (Martin et al. 1993). According to Olvera-Novoa et al. (2002), it is possible to replace up to 650 g/kg of animal protein with a mixture of SBM (200 g/kg), alfalfa leaf protein concentrate (150 g/kg), and torula yeast *C. jadinii* (300 g/kg) in tilapia fry diets without adverse effects on fish performance. Gumus et al. (2016) reported good growth and improved feed utilisation in the goldfish-fed diet supplemented with brewer's YM (350 g/kg diet) than in other yeast diets (0, 150, 250, and 450 g/kg). Compared to FM, dietary supplementation of non-saccharomyces enhanced growth in Nile tilapia (*Rhodotorula mucilaginosa*, Chen et al. 2019), rainbow trout (*Wickerhamomyces anomalous*, Vidakovic et al. 2019), shrimp (*C. aquaetextoris*, Babu et al. 2013), and Atlantic salmon (*Kluyveromyces marxianus*, Overland et al. 2013; *C. utilise*, Overland et al. 2013; Sahlmann et al. 2019).

A recent study by Leeper et al. (2022) showed that torula yeast (*C. jadinii*) cultivated on wood hydrolysates can replace 200 g/kg FM without affecting the growth performance of Atlantic salmon. However, the authors reported that while dietary yeast (100 g/kg) supplementation promoted growth by enhancing LAB associated with host fish, the population of *Staphylococcus* increased in the gut as the dietary yeasts increased in the diet to 200 g/kg, suggesting that a plant-based diet could alter the gut microbiome and reduce intestinal function. Differences between the single and combined yeast substitution levels in the mix might be due to dietary composition and CP level, which for Atlantic salmon, is met mainly by FM supply (Costello et al. 2020; Naylor et al. 2021). Current research has shown that a protein-rich solid fermentation culture method is suitable for yeast production, which can be a source of feed in aquaculture. After 8 weeks of culture, Wang et al. (2022a, b) discovered that supplementing the hybrid grouper (*Epinephelus fuscoguttatus* × *Ephelus lanceolatus*) diet with dietary yeast culture (YC, ESTAQUA®) (20 and 40 g/kg) stimulated growth and improved antioxidant and immune (immunoglobulin) response parameters. The post-challenge test against *Vibrio harveyi* infection revealed that YC enhanced disease resistance and improved fish survival. The authors found higher intestinal microflora (*Blautia* and *Lactobacillus*) than in the control group without YC. After 12 weeks, Hao et al. (2022) discovered that replacing dietary FM with *S. cerevisiae*-derived YC (200 g/kg diet) increased WG and decreased FCR in channel catfish (*Ictalurus punctatus*). The expression of the intestinal HIF1 gene increased while intestinal Nf-kB gene expression was down-regulated in the group that fed on YC. The authors reported a higher relative abundance of *Firmicutes* and *Turicibacter* in fish with YC than in control fish. Fish survival improved in fish challenged with *Aeromonas veronii* Hm091 and *A. hydrophila* NJ2.

The high nucleic acid and indigestible cell wall contents (Rimoldi et al. 2020) in yeast protein products constrain their use as a dietary protein source in aqua feed because they limit digestive enzymes and nutrient digestibility in fish (Nasseri et al. 2011; Glencross et al. 2020). Homogenisation (centrifugation), cell wall crushing and spray drying (Hansen et al. 2021), enzymatic treatment (Rimoldi et al. 2020), and extrusion (Overland et al. 2013) are applied to reduce the high cell wall content (Glencross et al. 2020) and enhance protein solubility and digestibility in fish (Atlantic salmon, Hansen et al. 2021). Fish can tolerate nucleic acid due to their efficient hepatic uricase activity that degrades plasma uric acid (Karimi et al. 2019).

9.4.5 Bacterial SCP

Protein derived from BM in aquaculture is gaining popularity due to its high nutritive value and palatability in aqua feed with the potential to improve the growth and welfare of several fish species (Biswas et al. 2020; Adeoye et al. 2021), and reduce plant-induced enteritis in the intestine (Romarheim et al. 2013). Table 9.5 presents the results from various studies that evaluated the use of BM in fish production. The response varied with the type of bacteria and fish species used. For example, FM substitution (100–200 g/kg diet) by the bacteria *Corynebacterium ammoniagenes* SCP in the diet of white leg shrimp resulted in good growth, nutrient utilisation and whole-body protein compared to FM control (Hamidoghli et al. 2018). The use of *C. autoethanogenum* in the diet of largemouth bass (*Micropterus salmoides*) indicated that dietary levels up to 156–204 g/kg could replace FM without affecting fish growth, haemato-biochemistry, digestive capacity, as well as protein digestibility and intestinal morphology (Zhu et al. 2022). A similar response in black sea bream (*Acanthopagrus schlegelii*) fed a diet with *C. autoethanogenum* has been reported previously (Chen et al. 2019a, b).

A study with an Atlantic salmon-fed diet supplemented with *Methylococcus* BM improved growth performance and reduced soybean-induced distal enteritis and intestinal inflammation (Romarheim et al. 2013; Vasanth et al. 2015), suggesting the potential of *Methylococcus* bacteria in enhancing gut health and immune protection as well as replacing SBM in the fish diet. Chen et al. (2022), while evaluating the performance of Pacific white shrimp (*L. vannamei*) fed a diet supplemented with methanotroph (*M. capsulatus*, Bath), observed no significant impact on growth performance and feed utilisation. Similarly, a recent study with Pacific white shrimp (*L. vannamei*) showed that dietary substitution of FM (25%) with *M. capsulatus* Bath (15, 30, and 45%) did not affect the growth performance and feed utilisation of shrimp compared to the FM reference control group, which indicated the possibility

Table 9.5 Overview of the effect of dietary SCP supplementation on growth performance and nutrient utilisation/ digestibility in fish and shrimp

MP source	Treatments	FM/ SBM replacement (g/kg)	Chemical composition	Feeding strategy (bw)	Culture system	Fish/shrimp species	Size (g)	Duration (days)	Response (Optimum requirement)	Reference
Bacteria *Corynebacterium ammoniagenes*	0%, 10%, 20%, 30%, and 40%	0 g/kg, 20 g/kg, 40 g/kg, 60 g/kg, and 80 g/kg FM (200 g/kg)	All diets contained 45% CP, 7% L, and 16KJ/g GE The PROC contained 63% CP, 8.77% L	Fixed ration (7% body weight)	RAS	Whiteleg shrimp (*L. vannamei)*	0.15 ± 0.02	63	WG, SGR, and FCR were improved for PRO 0 and PRO2 than for other diets (10% and 20%)	Hamidoghli et al. (2018)
Rhodopseudomonas palustris and mix culture *Rhodobacter capsulatus*	0, *Rps. palustris* (50 g/kg and 110 g/kg), *Rb. capsulatus* (50 g/kg and 110 g/kg), and mix culture *Rb. capsulatus* (110 g/kg)	50 and 110 g/kg, 50 and 110 g/kg, and 110 g/kg protein, respectively, from SBM and FM	Practical diets contained 35% CP and 7% L	Fixed ration (based on FCR of 1.6 and SGR of 15% / day	RAS	*L. vannamei* postlarvae	9.33 g	28	WG, SGR, and FCR were significantly improved in fish fed 50 g/kg *Rps. Palustris*, 110 g/kg *capsulatus* and 50 g/kg *Rb. capsulatus* (50 g/kg *Rps. Palustris*) diet	Alloul et al. (2021)
Purple phototrophic bacteria (PPB)	0%, 33%, 66%, and 100%	100, 200, and 300 g/kg PPB grown in synthetic wastewater	Practical diet contained 56.3% CP, 12.5% L. PPB contained 58% CP, 3.4% L	Restrictive pair fed	RAS	Asian sea bass (*Lates calcarifer)*	6.11 ± 0.10* g (4 tanks)–4.23 ± 0.21 (8 tanks)	47	WG, SGR, and FCR were not affected by PPB substitution (33% and 66% PPB)	Delamare-Deboutteville et al. (2019)
Marichromatium sp. & *Rhodopseudomonas sp.*	*Rhodopseudomonas sp* + control (diet 1), *Marichromatium sp.* + control (diet 2), Control (comm.. diet) diet 1	Exp diets were mixed with control diet at 2:1	Commercial diet contain 39.55–42.7% CP, 4.77–8.13% L	Apparent satiation	RAS	Malaysian Mahseer or Kelah (*Tor tambroides*)	12.27 ± 0.25 g	70	Higher WG, SGR, and lower FCR in diet 2 than diet 2 and diet 1 (*Marichromatium sp)*	Chowdhury et al. (2016)
Microalgae *Chlorella*	0% (RCM0), 25% (RCM25), 50% (RCM50), 75% (RCM75), and 100% (RCM100)	Control (520 g/g FM), RCM 25 (390 g/kg FM +99.6 g/kg RCM), RCM50 (260 g/kg FM + 199.2 g /kg RCM), RCM 75 (130 g/kg + 298.8 g/kg RCM), RCM100 398.4 g/kg RCM).	The diets were equal for CL = 38%, L = 9%	4%–7% body weight	Static renewal (30% daily)	Crucian carp (*C. auratus gibelio*)	1.77 ± 0.04 g	42	WG, SGR, FCR and ADC of protein, lipid, and energy as well as digestive enzyme activities (amylase, trypsin, and lipase) in intestine were unaffected by RCM inclusion (100% RCM)	Shi et al. (2017)

(continued)

Table 9.5 (continued)

MP source	Treatments	FM/ SBM replacement (g/kg)	Chemical composition	Feeding strategy (bw)	Culture system	Fish/shrimp species	Size (g)	Duration (days)	Response (Optimum requirement)	Reference
Chlorella	0, 60, 120, 180, 240, and 300 g/kg of whole-cell or cell-ruptured *C. vulgaris* meals	The practical diet (100: 0, reference diet) was blended (w/w) with test diets containing *C. vulgaris* at 94:6, 88: 12, 82:18, 76:24, and 70:30 for whole-cell or cell-ruptured *C. vulgaris* meals	Reference diet: CP = 50.2, L = 17.8 Test diet: CP = 43.5–49.3%, L = 18–18.6%	Apparent satiation	Flow through	Atlantic salmon (*Salmo salar L*	40.4 ± 2.7 g	25	Lower ADC of lipid and protein at >60 g/kg for whole cell. Protein ADC was unaffected by cell-ruptured *C. vulgaris* (60–240 g/kg). Levels (>120 g/kg) reduced ADC of leucine whole cell. Cell ruptured *C. vulgaris* did not affect ADC of all 10 AA (240–300 g/kg	Tibbetts et al. (2017)
Scenedesmus obliquus	Standard diet (control), whole *S. obliquus* biomass and control) + whole microalgal biomass (50:50) diets	Half the diet (FM and peanut based) was mixed with microalgae at equal ratio (diet2); whole microalgae was used as diet 3	Control: CP = 30%, L = 3.5%, 40% + CHO *S. obliquus* biomass 53.2%CP, 12.5% L, and 22% CHO	Fixed ration (2% body weight)	Static renewal (80% daily)	Rohu (*Labeo rohita*), mrigal (*Cirrhinus mrigala*) and catla (*Catla catla*)	4.5–4.9 g	90	Higher WG and SGR in 50:50 diet than control and *S. obliquus*biomass (50:50)	Patnaik et al. (2019)
Nannochloropsis oceanic	Control (0%), 25%, 50%, 75%, and 100% algae biomass	57.5 g/kg (25%), 115 g/kg (50%), 175 g/kg (75%), and 230 g/kg (100%) of SBM (230 g/kg diet)	All diets were equal for CP (30%), L (6%) and CHO (55%)	n.a	n.a	Red tilapia larvae	0.32 ± 0.1 g	30	FI, WG, SR increased while FCR declined in fish-fed diet up to 75% replacement (75% algae biomass)	Abugrara et al. (2019)
Chlorella	Control, CL-25, CL-50, CL-75, CL-100	62.5, 125, 187.5, and 250 g/kg of FM (250 g/kg diet)	The diets were equal for CP (40%) and L (20%)	Fixed ration (10% bw)	Static renewal	*M. rosenbergii* postlarvae	2.20 ± 0.39 g	90	Higher WG, SGR, and lower FCR in PL fed 75% CL (CL-50) than control diet	Radhakrishnan et al. (2015)

Yeast *Saccharomyces cerevisiae* and *Wickerhamomyces anomalus*	FM control, S20, S40, S60, S60 (meth), W20, W40, W60	*S. cerevisiae* replaced 107 g /kg (20%, S20), 214 g/kg (40%, S40), and 321 g/kg (60% (S60) of FM (300 g/kg) and a 70:30 biomass ratio of the yeasts *W. anomalus* and *S. cerevisiae* replaced 118 g/kg (20%, W20), 239 g/kg (40%, W40), and 355 g/kg (60%, W60) of FM. No methionine in S60meth	The diets were equal for CP (42.5–46.3%); L (18.6–20.8%)	Near-satiation fixed rations of 1.5% body weight	Flow through	Rainbow trout (*O. mykiss*)	144.7 ± 25 g	70	Replacement of FM with W60 and S60 produced lower SGR and abnormal (oedematous mucosal fold) than other diets, respectively. ADC of AA and P were similar for FM and W20 (.S40)	Vidakovic et al. (2019)
S. cerevisiae	0% (control), 15%, 25%, 35%, and 45% yeast	88.7 g/kg (15%), 147.8 g/kg (25%), 207.1 g/kg (35%), and 266.3 g/kg (45%) of FM (400 g/kg)	All diets had similar CP (37%) and L (8%)	Apparent satiation	Static renewal (50% daily)	Goldfish (*C. auratus*)	0.56 ± 0.01 g	84	WG, SGR, FCR and PER of fish fed 35% of yeast diet were better than other diets (35% yeast)	Gumus et al. (2016)
Candida utilis	FW and SW (Control), FW and yeast-based diet in SW (Control/Yeast), yeast-based diet in FW and SW (Yeast/yeast), and yeast-based FW and control SW (Yeast/ Control)	Two diets (a plant-based control diet and an experimental diet with 25% or 106.5 g/kg *C. utilis* (replaced 29% FM (150 g/kg) in control were given to fish in two periods: FW (0–28 days) and SW (28–56 days)	Both diets contained equal CP (50%), L (16%)	Fixed ration 2% (FW) and 0.5–1% (SW)	Flow through	Atlantic salmon (*Salmo salar* L.	80–85 g (FW) 115–129 g (after 56 days)	56	Higher WG and RWG was found for yeast diet than control (Yeast)	Sahlmann et al. (2019)

FI feed intake, *WG* weight gain, *SR* survival rate, *FCR* feed conversion ratio, *SGR* specific growth rate, *PER* protein efficiency ratio, *PPB* purple phototrophic bacteria, *VFA* volatile fatty acid, *CL* Chlorella, *RAS* recirculation aquaculture system, *SBM* soya bean meal, *FM* fish meal, *CP* crude protein, *L* lipid, *Exp diet.* experimental diet, *comm diet* commercial diet, *ADC* apparent digestibility coefficient, *FW* fresh water, *SW* salt water, *n.a* not available of incorporating BM as an alternative protein source in fish diets (Chen et al. 2022). Recent studies have revealed that PPB, a novel protein-rich MP source (670–737 g/kg CP), grows exclusively on wastewater under anaerobic conditions in light (Alloul et al. 2021). Delamare-Deboutteville et al. (2019) reported that PPB replaced 660 g FM/kg in the diet of Asian sea bass (*Lates calcarifer*), a high-value carnivorous fish, without affecting growth and feed utilisation. A recent study by Alloul et al. (2021) reported that white leg shrimp (*P. vannamei*) fed a diet supplemented with purple non-sulphur bacteria (a PPB): The shrimp fed with *Rhodobacter capsulatus* (110 g/kg feed protein) and *Rhodopseudomonas palustris* (50 g/kg feed protein) displayed higher WG (5–25% and 26%), respectively, compared to commercial feed. The authors also found that dietary inclusion of PPB enhanced resistance against *Vibrio* infection and reduced NH_3 stress compared to the control diet, indicating the suitability of PPB in sustainable fish production.

9.4.6 Microalgae SCP

9.4.6.1 Effect on Fish Growth

Several kinds of literature have reported the aquaculture potential of microalgae meal (MAM) as a replacement for FM in the fish diet with a positive impact on growth and feed utilisation in fish (Mahmoud et al. 2020; Raji et al. 2020). In several pieces of literature on aqua feed formulations, the most commonly used microalgae are *Chlorella spp*. (Tibbetts et al. 2017; Raji et al. 2020), *Scenedesmus sp.* (Skalli et al. 2020), and *Spirulina* (Olvera-Novoa et al. 1998). It is possible to incorporate 300 or 600 g/kg of MAM into the diet without affecting growth performance (Sørensen et al. 2016). However, the effect of dietary supplementation of MAM varies with the source of microalgae species used, the composition of the diet, as well as fish species and fish size. While Hajiahmadian et al. (2012) reported significantly higher growth in Golden Barb (*Puntius gelius*) fed a diet with *Spirulina* meal (200 g/kg diet) as a replacement for FM, the dietary inclusion of 500 g/kg *Spirulina* meal produced comparable FCR and WG in silver seabream (*Rhabdosargus sarba*) fed an FM-based diet. Cardinaletti et al. (2018) evaluated the performance of European sea bass, *Dicentrarchus labrax*, fed a diet with a blend of 18% of freeze-dried microalgae (*Tisochysis lutea* and *Tetraselmis suecica*) meal and 15% FM and found no difference in growth performance with fish fed the control diet (27.5% FM). Radhakrishna et al. (2015) showed that *C. vulgaris* meal substituted about 500 g FM/kg in the diet of postlarvae freshwater prawns. *Macrobrachium rosenbergii* without affecting growth and survival.

Olvera-Novoa et al. (1998) reported improved growth and feed utilisation of 20–40% *Spirulina* meal (104.7–314.1 g/kg) substituted FM in the diet of *O. mossambicus* (Peters) fry, whereas the supplementation of the diet with de-fatted biomass of *N. oculata* (80 g/kg) or whole cells of *Schizochytrium sp.* (32 g/kg) enhanced WG and SGR of Nile tilapia (34.5 g). The economic conversion ratio ($0.95/kg of fish) of Nile tilapia was reduced relative to fish that fed on the reference diet with FM and FO ($1.03/kg) (Sarker et al. 2020). However, Tibberts et al. (2017) found that feeding Atlantic salmon with whole-cell *C. vulgaris*-enriched diets reduced WG and increased FCR compared to a reference diet with FM. However, MAB combined with PP (e.g. rapeseed and *Chlorella*) replaced FM in the diet without affecting growth and feed utilisation (Shi et al. 2017).

9.4.6.2 Effect on Nutrient Digestibility in Fish

Dietary microalgae supplementation improves growth by enhancing nutrient availability in fish (Gamble et al. 2021). Gamble et al. (2021) reported that dietary *Schizochytrium sp, Chlorella and Spirulina* had a significantly higher apparent digestibility coefficient (ADC, 74.02–81.53%) of phosphorus (P) in Nile tilapia than FM control group (71.7%). Shah et al. (2018) reported that the high ADC of nutrients in *Sprirulina* (*Arthrospira,* 86.1% of CP) and *Chlorella* (80.0% of EAA) compared well with conventional feed stuff. Feeding European sea bass (*D. labrax*) and rainbow trout (*Oncorhynchus mykiss*) with freeze-dried *Isochrysis sp.* (14%, Tibaldi et al. 2015) and whole cells of *Schizochytrium sp.* (30%, Bélanger et al. 2021) improved the ADC of CP (92.6% and 90.8%), lipid (87.6% and 85.9%), and energy (85% and 84.3%). Similarly, Nile tilapia and African catfish-fed dietary *Schizochytrium sp* meal (Sarker et al. 2016; Teuling et al. 2017) and *C. vulgaris* and *S. maxima* meal (Teuling et al. 2017), respectively, showed high lipid ADC of 80–98% and >80%, respectively. Raji et al. (2020) evaluated the performance of *C. gariepinus* fed diet supplemented with *Chlorella* and *Spirulina* for 42 days. The study showed that higher ADC of protein (98.64–98.66% vs 97.71%), lipid (96.51–96.67% vs 92.77%), energy (93.2–94.66% vs 86.04%, lysine (99.05–99.34% vs 98.59%), and PUFA (98.92–99.01% vs 97.51%) were higher than the fish that fed on FM diet.

Some studies showed that dietary microalgae supplementation did not improve ADC of essential nutrients in some species (Shi et al. 2017; Roy et al. 2011). For example, while dietary *Nannochloropsis, Phaeodactylum, and Isochrysis* up to 240 g/kg in the diet did not affect feed intake, nutrient digestibility of *Nannochloropsis* and *Isochrysis* was reduced compared to control (Skrede et al. 2011). These findings are consistent with a study which showed that the combination of dried *Nannochloropsis sp.* and *Isochrysis sp.* reduced feed intake, nutrient utilisation, and somatic indices in algae-fed (15–30%) Atlantic cod as compared to the control group. The reduced feed utilisation could be attributed to palatability issues related to the rigid cell wall content of microalgae.(Shah et al. 2018; Acquah et al. 2021). A recent study with Atlantic salmon-fed whole-cell *Pavlova* 459 meal (20 g/kg) showed that ADC of protein (90.1% vs 92.3%) and lipid (91% vs 94.4%) were lower than that of the FM-based reference diet (Tibbetts and Patelakis 2022). The reduced ADC of nutrients observed in these findings might be related to microalgae cell composition, microalgae source, diet composition, processing techniques used, and fish species and experimental conditions.

Homogenisation (Tibbetts et al. 2017), acid hydrolysis (Patnaik et al. 2019), pasteurisation (Agboola et al. 2019), bead milling (Agboola et al. 2019), and spray drying (Raji et al. 2020) can reduce the cell wall content and improve the feeding value of MAM. Tibbetts et al. (2017) found that dietary inclusion of cell-ruptured *C. vulgaris* biomass did not affect protein ADC at 60, 120, 240, and 300 g/kg diet (Table 9.5). However, dietary whole-cell MAB significantly reduced protein ADC at >60 g/kg diet. Similarly, ADC of all AA was unaffected by cell-ruptured MAB compared to reduced ADC of whole-cell biomass. Teuling et al. (2019) observed that cell wall ruptured *N. gaditana* meal improved the availability of nutrients in the diet of juvenile Nile tilapia, *O. niloticus*. Agboola et al. (2019) reported higher ADC of protein (83.8% vs 77.4%) and lipid (81.8% vs 65.4%) of *C. gariepinus* fed the diet supplemented with bead-milled *N. gaditana* meal (300 g/kg) compared to untreated microalgae. A blend of MAB with PP can enhance microalgae utilisation. In this instance, Shi et al. (2017) fed crucian carp (*C. auratus gibelio*) a diet based on a mixture of rapeseed meal and *Chlorella* meal (0, 25%, 50%, 75%, and 100%) as a replacement for FM for 6 weeks. In contrast, dietary de-fatted *N. oculata* and DHA-rich *Schizochytrium sp* improved the ADC of protein, lipid, and AA in Nile tilapia (34.5 g). The enhanced digestive enzyme activities in the fish-fed *Schizochytrium sp* meal diet may have improved nutrient availability in the fish (Sarker et al. 2020).

9.4.6.3 Effect on Fish Carcass Quality and Reproductive Performance

Studies show that dietary microalgae improve the carcass quality of aquatic animals (Roy and Pal 2014; Chang et al. 2017) through enrichment with LC-PUFAs (Stoneham et al. 2019). Dietary MAM in fish diets can replace or supplement FO (Haas et al. 2015; Allen et al. 2019; Guimaraes et al. 2019; Stoneham et al. 2019) and FM in aqua feed (Adel et al. 2017; Shi et al. 2017; Abugrara et al. 2019; Patnaik et al. 2019) without affecting growth performance, suggesting that microalgae contribute to nutrient-sensitive fish production in aquaculture. Stoneham et al. (2019) evaluated the effect of FO (10, 30, 50 g/kg diet) replacement with *Schizochytrium sp* meal (17.5, 52.6, 87.7 g/kg diet). They observed no significant difference in WG and carcass FA amongst the diets after 8 weeks of feeding juvenile Nile tilapia (160 g). However, compared to the group fed the 50 g/kg FO diet (165% and 232%), the diet supplemented with 87.7 g/kg *Schizochytrium sp* showed higher fillet n-3 (189%) and LC-PUFA (298%) (Stoneham et al. 2019). Dietary supplementation with 10–20% *Pav* 459 meal (2.86% EPA and 1.45% DHA) exhibited no significant differences in carcass DHA, EPA, and most FAs compared to Atlantic salmon fed the control diet based on FM after 12 weeks of culture, which indicates that MAM from *Pav* 459 is a good source of protein and n-3 LC-PUFA in farmed fish species (Wei et al. 2022). For 21 days, Carvalho et al. (2022) studied the performance of gilthead sea bream (*Sparus aurata*, 0.48 mg) fed dietary marine heterotroph *Schizochytrium limacinum* (19% DHA), alga fermentation-derived *Crypthecodinium cohnii* (39.5% DHA), and *S. limacinum* (49% DHA). The authors found that it is possible to replace FO with microalgae oil in the diet with increased DHA in the fillet of gilthead sea bream (*S. aurata*, 0.48 mg).

Cardona et al. (2022) showed that the carcass quality of female rainbow trout (*O. mykiss*) fed a plant-based diet containing *Schizochytrium sp.* meal (69 g/kg diet) or *Schizochytrium sp*. oil (26 g/kg) as a replacement for FM or FO in commercial feed, respectively, for 8 weeks, showed high PUFA n-6 and n-3 levels compared to the control group that had no MAM in the diet. The authors, however, reported that the reproductive success of females, as measured by egg weight, absolute fecundity, and relative fecundity, was similar to that of brood stock females fed a commercial diet. Kohal et al. (2018) and Zhang et al. (2020) also reported improved reproductive performance and survival of red cherry shrimp (*Neocaridina davidi*) and yellow tail cichlids (*Pseudotropheus acei*) fed a diet containing *Spirulina* meal when compared with a control diet without microalgae.

9.4.6.4 Effect on Immunomodulation in Fish

Studies reveal that dietary microalgae plays a positive role in fish immunomodulation. For example, Zhang et al. (2014) reported improved physiology and enhanced innate immunity of gibel carp (*C. auratus gibelio*) fed a diet containing *Chlorella* meal. Similarly dietary supplementation of *C. Vulgaris* (60–80 g/kg diet) enhanced immune response and improved resistance of *M. rosenbergii* postlarvae against *A. hydrophila* infection (Maliwat et al. 2017). A recent study with pacu (*Piaractus mesopotamicus*) exposed to 2.5 mg/L NH_3 for one hour after a 45-day feeding with dietary *Spirulina* (*A. platensis*, 40–60 g/kg diet) in place of FM indicated that microalgae stimulated the immune system and enhanced antioxidant enzymes as compared to control fish that did not feed on *Spirulina* (Carneiro et al. 2022). According to the authors, these effects seem to be attributable to antioxidant compounds present in *Arthrospira*, which mitigated NH_3 toxicity. Ma et al. (2022) found that dietary supplementation with microalgae (*Schizochytrium sp*., *A. platensis*, *C. sorokiniana, Chromochloris zofingiensis, Dunaliella salina*) enhanced the immune status and intestinal health of zebrafish (*Danio rerio*), comparing groups fed non-microalgae supplemented diets.

9.5 Application of Single-Cell Oil (SCO) in Aqua Feed: Effect on Fish Growth and Nutrient Digestibility

Single-cell oils (lipids derived from microorganisms) are a potential nutrient source in aqua feed, providing fish with a cheap source of lipid and EFA (Glencross et al. 2020; Lee et al. 2022). Oleaginous microbes can be grown on organic wastes with high lipid biomass recovery, ranging from 560 g/kg DW (*Fusarium exquisite,* Yang and Hu 2019) to 750 g/kg DW of lipid (*Schizochytrium sp*, Spalvins et al. 2019). Compared to dietary FM, SCO is more efficient at reducing FO inclusion in the diet, which reduces aquaculture demand for forage fish (Cottrell et al. 2020). According to Cottrell et al. (2020), dietary microalgae oil can replace 100% FO without affecting carcass quality (DHA + EPA) compared to 20%, 10%, and 25% soy oil or soy oil blend replacement for salmonids, shrimps, and marine fishes, respectively.

The majority of research has focused on *Schizochytrium* SCO products, which have a high protein (91.4%) and lipid digestibility (94.2%) for rainbow trout (Lee et al. 2022). A study conducted by Sarker et al. (2020) revealed that whole-cell *Schizochytrium* (6.2%) and de-fatted *N. oculata* (8% without FM) completely replaced FO in Nile tilapia after 184 days of feeding. The study concluded that the microalgae blend enhanced fillet macro-minerals and DHA deposition in the fillet of the group that fed on FM- and FO-free feed (5.15 mg/g) compared to the reference diet (2.47 mg/g). In contrast, Carvalho et al. (2020) reported that a dietary blend of microalgae oil, poultry oil, and rapeseed oil enhanced the EPA/DHA profile and fillet quality of gilthead seabream (*S. aurata*) when compared with fish fed with poultry oil or rapeseed oil. The authors concluded that microalgae oil replaced 52.8 g/kg of FO and 150 g/kg of FM in a PP-based diet of gilthead seabream. Sarker et al. (2016) reported that dietary *Schizochytrium* enhanced growth performance, fillet DHA and LC-PUFA of Nile tilapia, compared to fish fed with an FO diet. Lee et al. (2022) found that *Schizochytrium* (80%) replaced FO in rainbow trout without affecting growth, fillet quality, or lysozyme activity. In a post-challenge test against bacteria (*Lactococcus garvieae* 1×10^8 CFU/mL), microalgae outperformed FM in terms of fish survival. Katerina et al. (2020) evaluated the lifelong performance and fillet quality of Atlantic salmon reared from tank phase (18 g in freshwater to 800 g in salt water) on FO, *or S. limacinum* biomass (SLB) or a mix (FO + SLB) to slaughter stage (3 kg) in sea cages on FO or SCL for 11 months. At the end of the trial, the fish fed on SCB had higher body weight (3.3 kg vs 2.8 kg), fillet DHA + EPA, and higher ADC of LC-PUFA and DHA when compared to the FO and FO + SLB groups. There was no difference in fillet colour or odour between the FO and SCB groups, even though the SCB group had more astaxanthin than the FO group. Hossain et al. (2022) reported that the feeding of sobaity sea bream (*Sparidentex hasta*) with a high DHA algae meal diet containing 9.34% DHA improved fish growth, fillet DHA, serum lysozyme activities, and superoxide dismutase when compared with commercial finisher feed and basal diet (no added DHA). However, the fish fed the high DHA algae diet were similar to FO with similar DHA as the algal meal, suggesting the possibility of replacing FO in the diet.

9.6 Sustainability and Environmental Performance of SCP and Microbial-Based Systems

Dietary SCP can enhance aquaculture sustainability (Overland et al. 2010; Hua et al. 2019; Sillman et al. 2019). Compared to conventional agriculture, Pikaar et al. (2017) claim that MP or SCP can increase overall nutrient efficiency by 2.5 times, with 3 to 10 times lower nitrogen loss (43% improved protein efficiency). This significant ecological function makes MB, a sustainable third-generation protein source after FM and soy protein (Matassa et al. 2015, 2016; De Vrieze et al. 2019; Sillman et al. 2019). A recent study that linked the absolute planetary boundary to the sustainable environmental performance of MP showed that aerobic HB grown on potato-processing waste in a bioreactor emitted lesser N and P and caused reduced land-use change than FM and SBM, which suggests the sustainability of MP as an alternative to conventional protein sources (Owsianiak et al. 2022). Linder (2019) estimates that by 2050, replacing 10–19% of conventional crop-based protein feed with MP can reduce global cropland area, N loss, and greenhouse gas emissions.

Unlike terrestrial crops (Schlechtriem et al. 2016), microorganisms do not require pesticides or insecticides (Sillman et al. 2019) for cultivation. They demand less space, water, and land than conventional agriculture (Swain et al. 2018) and terrestrial PP production (Matassa et al. 2015; Sillman et al. 2019). In comparison to conventional proteins such as SBM, MP requires 128 times less land and five times less water to produce 1 kg of protein (Matassa et al. 2016; Sillman et al. 2019). Sakarika et al. (2022) reported that MP requires 40,000 less land (0.05 m^2/kg protein vs 2279 m^2/kg protein) and 20 times less water (282 L/kg protein vs 5516 L/kg protein), and higher N efficiency (430 g N consumed/kg N supplied vs 40 g N consumed/kg N supplied) than meat.

Several studies have reported significantly reduced GHG, water, and land requirements with MP from renewable energy sources like the wind (Sillman et al. 2019), electricity (Jourdin et al. 2018), and solar (Matassa et al. 2016; De Vrieze et al. 2019).The production of MP through innovative continuous fermentation culture processes allows high volumetric productivities (3–4 kg MP/m^3 per hour, Matassa et al. 2016), with a physical footprint that is a factor of 1000 smaller than any conventional vegetable protein production system (Matassa et al. 2015). Despite the small amount of land required for FM processing (Matassa et al. 2016), the C footprint analysis shows that MP emits less CO_2 (1.7-tonne CO_2eq/tonne MP) than FM (CO_2 eq/tonne protein). Besides achieving feasible industrial-scale production and cost competitiveness with FM, the final MP product is comparable to FM in terms of EAA profile and overall nutritive value (Overland et al. 2010; Kuzniar et al. 2019). Durigon et al. (2019) found that MBSs require little or no water exchange and have a low environmental impact (Dauda et al. 2018a, b; Liu et al. 2018). While conventional aquaculture ponds require approximately 20,000 L of water per kg of fish or shrimp produced, Martínez-Córdova et al. (2017) reported that the water demand in biofloc systems could be as low as 200 L per kg and that the cost of raising fish in biofloc systems is lower than in conventional RAS systems (Crab et al. 2007).

9.7 Conclusion, Future Perspectives, and Opportunities

Given that future farming systems will have to be increasingly more self-contained, not only in terms of farm biosecurity and potential disease exclusion/impacts but also in terms of water reuse and minimising nutrient discharge, improving the functionality of aqua feeds will be of paramount importance in guiding the long-term sustainable development of the fed fin fish and crustacean aquaculture sector toward the development of a more environmentally friendly and nutrient-sensitive production system. Novel techniques (for example, aerobic/anaerobic fermentation technology, gas bioreactor fermentation, and microbial electrosynthesis, Jourdin et al. 2018; Jones et al. 2020) will be required to up-scale production and improve the nutritional value of SCP feed ingredients. Using anaerobic digestion to exploit the C content of microalgae from high organic load wastewater for MP without dewatering (drying) can reduce the high cost and environmental footprint of microalgae production. Harvesting, dewatering, and lipid extraction from MAB pose challenges due to the high energy requirements. Batch, fed-batch, continuous bioreactors, and semi-continuous cultivation are all examples of anaerobic fermentation (AnF) that can improve the production performance of microalgae, particularly in relation to high-rate sludge systems. Co-cultivation of bacteria and microalgae in bioreactors can reduce energy demand associated with the production process, which could reduce the climate change and ozone depletion impact potential of MP and support the United Nations' sustainable development goals (Owsianiak et al. 2022). Novel approaches like heat shock treatment and alkaline hydrolysis (Sakarika et al. 2022) can mitigate ANF (trypsin inhibitors, heavy metals, nucleic acid, and cell wall contents) associated with low nutritional value and acceptance of SCP (Ahmad et al. 2022). Bioreactors can also remove suspended solids (95–99.5%) and nutrients (>90% for NO_3-, NO_2-, and NH_3) from aquaculture wastewater (Avnimelech et al. 2014). Large-scale biofloc production in external bioreactors (ex situ biofloc) can ensure MP availability and reduce aquaculture's environmental impact.

A good selection of microbes with improved nutritional quality or growth characteristics could improve their efficiencies and reduce the cost of production through metagenomics (Diwan et al. 2021). Metagenomics can be applied to evaluate the potential for isolation and culture of aquaculture-relevant microbial species. Post-genomic and cutting-edge technologies like transcriptomics and shotgun proteomics can provide insights into microbial cellular processes and function (Kumar et al. 2016; Diwan et al. 2021). The application of proteomic techniques, including the gel-based techniques like two-dimensional gel electrophoresis (2-DE or 2D PAGE, Schrama et al. 2018), sequential window acquisition of all theoretical spectra (SWATH) technology (for quantifying and distinguishing strains of MP, Kumar et al. 2016), electrospray ionisation mass spectrophotometry (ESI-MS, Graham et al. 2007), gel-free nano liquid chromatography electrospray ionisation (LC-ESI, Kumar et al. 2016), liquid chromatography coupled to tandem mass spectrophotometry (LC-MS/MS, Timmins-Schifman et al. 2018), label-based isobaric tag for relative and absolute quantitation (iTRAQ, Rodrigues et al. 2017), stable isotope labelling by/with amino acids in cell culture (SILAC, Rodrigues et al. 2017), quantitative real-time polymerase chain reaction (qRT-PCR, for detecting, identifying, and quantifying pathogens, (Kumar et al. 2016), and matrix-assisted laser desorption ionisation time of flight mass spectrophotometry (MALDI-TOF MS, Singhal et al. 2015), will advance knowledge about the physiology and metabolism of microorganisms in aquaculture through changes in proteome (complete set of protein expressed by a genome, tissue, or organism. These methods will also facilitate the rapid identification of mass microbial samples consisting of diverse microorganisms of different strains, species, and genera.

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Chapter 10
Ferulic Acid as Feed Additives in Aquaculture: A Review on Growth, Immune Response, and Antioxidant Status of Finfish

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Abstract Producing protein through aquaculture is the solution to the world's protein needs. Aquaculture feed additives boost fish growth, immunology, and antioxidant status and prevent diseases. Among these feed additives, phytochemicals draw the most attention. Phytochemicals are considered harmless for humans, fish, and the environment because they are natural products. Ferulic acid (FA) is a phenolic substance with numerous advantages linked to its antioxidant, cytoprotective, antibacterial, and anabolic activities, generating particular interest in aquaculture. The stimulation and favouring of these systems lead to the stimulation of physiological and metabolic processes, promoting aquatic animals' development and reproduction. Therefore, the administration of FA could enhance the growth of muscle fibres, immunological response, inflammatory response, and antioxidant capacity in fish. This is a product that African aquaculture farmers can incorporate into their fish feed formulas; however, more research is required to fully understand the dietary potential of FA application, particularly in Africa. Therefore, this chapter reviewed recent studies that utilize ferulic acid (FA) as feed additives in cultured fish species.

Keywords Ferulic acid · Phytochemicals · Phenolic substance · Growth performance · Feed additives · Metabolic processes

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10.1 Introduction

Aquaculture has grown into a large industry and the world's fastest-growing agricultural and commercial sector, generating significant economic activity in several countries (Kumari and Sahoo 2010; Villa-Cruz et al. 2009; Karga et al. 2020). In the last year, global aquaculture production has increased massively for the protein requirement of humans (Özçelik et al. 2020; Salem et al. 2021). However, aquaculture practices have intensified to meet demand as wild fish sources become scarcer by the day. With this intensification, problems and threats associated with high production costs, diseases, stress, environmental impact, animal welfare issues, and organic production demand are increasing to inhibit sustainable aquaculture production (Sönmez 2017; Arslan et al. 2018; Elbesthi et al. 2020). Due to this perspective, chemical additives and drugs from veterinary medicines such as antibiotics have been the only effective way to enhance growth, prevent and treat the occurrence of diseases in animals. However, these drugs are often considered expensive and unhealthy to improve growth and treat an infection. Secondly, these drugs are generally associated with considerable public health hazards by encouraging bacterial-resistant strains' selection, multiplication, and survival in the host (Dawood et al. 2020). Indeed, antibiotic resistance can be acquired through chromosomal mutation or plasmid acquisition. Resistance plasmids can be moved very rapidly, producing a high percentage of pathogenic bacteria that develop mediated plasmid resistance in a short period (Lazdins et al. 2015). At the same time, chromosomal mutations are non-transferable to other bacteria. For instance, multidrug resistance was transferred during the cholera epidemic in Ecuador between 1991 and 1992, spread by shrimp farmworkers. Although the original epidemic strain, *Vibrio cholerae* 01, was susceptible to all 12 antimicrobial medications tested, it gained multidrug resistance along the Ecuadorian coast due to resistance genes transferred from other *Vibrio* species that are fatal to shrimp (Faruque and Albert 1992).

Also, the scrutiny for high-performance alternative feedstuffs has gained much attention. For instance, Soy protein has been a primary source of fishmeal replacement in the plant protein field, providing a high protein alternative at a reasonable price (Sales 2009). The administration of diets based on soybean meal has received attention for its connection to intestinal enteritis, particularly in fish. The distal intestine is most susceptible to enteric inflammation due to the inclusive antinutritional factors (ANFs) and alcohol-soluble components of the feed ingredients (Romarheim et al. 2008), thus resulting in immune dysfunction. The immune system function is closely related to fish health and is usually associated with nutrition. Immune dysfunction causes a wide range of unanticipated effects. Intestinal mucosal immune dysfunction, for instance, can impair the equilibrium of the intestinal microbiota and cause the host to contract several diseases (Williams et al. 2017), causing death in fish species. As a result, immunological dysfunction is a component of many fish disease pathogens. So, instead of using growth promoters, synthetic antimicrobials, or hormones as a natural technique to boost animal production output or to enhance immunity in aquaculture, it is of significance to explore additives suitable for improving feed utilization by fish as use of these additives aims to increase feed digestion rates as well as immunity and resilience to oxidative stress and inflammation (Kothari et al. 2019). Recently, the benefits of phytochemicals in boosting immunological activation and promoting growth through diet and feed have received more attention (Hashem et al. 2020; Macías-Cruz et al. 2018; Marquardt and Li 2018). Phytochemicals are plant-derived bioactive molecules with a wide range of therapeutic effects, including antiviral, growth-promoting, antioxidant, immune-stimulating, and anti-inflammatory activities (Mani et al. 2020; Choudhari et al. 2020; Terzi et al. 2021).

Ferulic acid (FA) is presently a phytochemicals phenol compound with antioxidant, antibacterial, and anabolic qualities, potentially enhancing farm animals' health, productivity, and reproduction (González-Ríos et al. 2016; Macías-Cruz et al. 2018; Wang et al. 2019). Ferulic acid, also known as hydroxyl cinnamic acid, is the most prevalent phenolic acid found in plants, including grains, fruits, vegetables, herbs, and spices (Zhang et al. 2018). FA exists as esters attached covalently to monosaccharides, disaccharides, and polysaccharides and is broadly used in food, industry, and medicine as a natural antioxidant (Yildiztugay et al. 2018). In addition, FA aids in scavenging reactive molecules like hydroxyl, superoxide radicals, nitric oxide, and peroxynitrite and suppressing lipid peroxidation (Dulong et al. 2018). In this regard, some researchers have explored utilizing FA as a nutritional supplement used in domestic animal feed to increase productive qualities. These were reported in livestock species such as beef cattle, pigs, and ewe lamb (Kroon and Williams 1999; González-Ríos et al. 2016; Macías-Cruz et al. 2014). Hence, this chapter aims to summarize current knowledge of FA's modes of action and its advantages on animal production. Also, the potential regulatory impacts of FA as an additive on growth performance, immune stimulation, and antioxidant capacities in aquaculture were discussed.

10.2 Ferulic Acid: Structural Properties and Importance as a Functional Ingredient

Ferulic acid ([E]-3-[4-hydroxy-3-methoxy-phenyl] prop-2-enoic acid) (Fig. 10.1) belongs to the family of phenolic acids that are frequently present in plant tissues (Mattila and Kumpulainen 2002). Ferulic acids are secondary metabolites of varying chemical structures and biological properties. The plants are mainly bound as ester or glycosides, lignin components, and hydrolysis tannins (Bezerra et al. 2017), as shown in Table 10.2. They can be separated into cinnamic and benzoic acid derivatives, which differ in the amount and substitution of hydroxyl and methoxy groups, and phenolic acids of a peculiar character, based on their chemical structure. Ferulic acid is the most frequent cinnamic acid derivative, alongside caffeic, p-coumaric, synapine, syryte, and vanillin (Bezerra et al. 2017). The physical properties of FA are listed in Table 10.1.

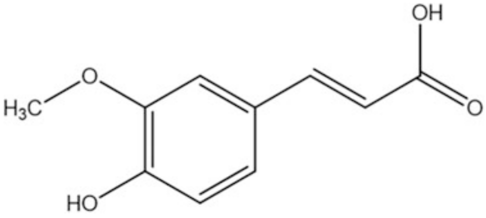

Fig. 10.1 Chemical structure of ferulic acid

Table 10.1 Chemical properties of ferulic acid

Properties	Value/nature
Common name	Ferulic acid
Synonym	trans-4-Hydroxy-3-methoxycinnamic acid
Molecular formula	$C_{10}H_{10}O_4$
Chemical family	Phenolic acids
Molecular weight	194.18
Physical status	Amber coloured solid
Odour	Nil
Melting temperature	174 °C1 λmax: 234 nm, 322 nm^2
Vapour pressure	0.00000269 [mmHg]
Melting Point	168–172 °C (L)
Density	1.3 ± 0.1 g/cm^3
Boiling Point	372.3 ± 27.0 °C at 760 mmHg
Decomposition temperature	~55 °C
Solubility	Soluble in water 0.78 g/L
pH stability	3–4.5
Relative sweetness	Nil
Molar mass	194.18 g/mol
Appearance	Crystalline powder
Carcinogenicity	Nil
Flavour enhancer	Monosodium glutamate (MSG)
Absorbability in the gastro-intestinal tract	FA can be absorbed along the entire gastrointestinal tract and metabolized mainly by the liver

The antioxidant activity of phenolic acids, particularly cinnamic acid derivatives, is determined by the quantity of hydroxyl and methoxy groups connected to the phenyl ring (Bezerra et al. 2017; Aguilar-Hernández et al. 2017). The absorption capacities of ferulic acid are significantly higher in the body and could remain in the bloodstream longer than other phenolic acids. Compared to other phenolic compounds, ferulic acid is an effective antioxidant (Tee-Ngam et al. 2013). Ferulic acid is low in toxicity and has many physiological effects, including anti-inflammatory, antibacterial, nerve-cell damaging properties and the potential to restore broken cells. It is also a sports supplement since it can neutralize free radicals in muscle tissue (alleviating muscle fatigue). It has been utilized in pharmaceutics and food for a long time. Additionally, research in mouse models indicates that FA may aid in treating obesity and infertility in humans (Kuppusamy et al. 2019; Salazar-Lopez et al. 2017). In addition, research in mouse models suggests that FA could effectively treat obesity and infertility in humans (Kuppusamy et al. 2019; Salazar-Lopez et al. 2017). It has also been used to produce pharmaceuticals, cosmetics, and nutraceuticals. Using FA as a nutraceutical supplement, numerous research teams have been researching this phenolic molecule to increase animal production in the past ten years (Macías-Cruz et al. 2018; Wang et al. 2021).The chemical properties of ferulic acid are shown in Table 10.1.

FA is a secondary metabolite produced by plants in the shikimate and phenylpropanoid pathways that provides stiffness and protection to the host (de Oliveira Silva and Batista 2017). As a result, it is found unbound, dimerized, and coupled by ester and ether linkages with lipids, carbohydrates, and lignin in the cell wall's structural composition (de Paiva et al. 2013). Different extraction methods release free and bound FA from natural sources (Mancuso and Santangelo 2014). While free FA can be extracted using aqueous or organic solvents (e.g. methanol), bound FA requires chemical alkalinity or enzymatic hydrolysis to break covalent connections with the other cell wall components. Free FA or other bioactive derivatives can be released depending on the extraction process and operational parameters (such as room temperature, pH, and time) (Bento-Silva et al. 2018). The levels of ferulic acid in grains, fruits, and vegetable sources are presented in Table 10.2.

Due to its widespread use as a component in pharmaceuticals, functional foods, and nutraceuticals, FA extraction offers accessible business opportunities as well as significant environmental and economic support for enterprises. In the literature, various alkaline, acidic, and enzymatic techniques for extracting FA from various sources have been proposed (Buranov and Mazza 2009; Kim et al. 2006; Mathew and Abraham 2005; Feng et al. 2005), as shown in Table 10.3. However, optimizing important parameters for FA isolation, such as extraction duration, pH, and temperature, for a high yield is necessary. The study was conducted with the help of response surface methodology, which showed 1.3-fold increases in the production of FA compared to the unoptimized conventional extraction technique (Tilay et al. 2008). At room temperature, FA is insoluble in water. However, it is soluble in hot water, ethyl acetate, ethanol, and ethyl ether, and it has been discovered that ethanol (60%) is ideal for FA extraction (Guo et al. 2003). Although FA is abundant in the cell walls of hardwoods, grasses, and maize husks, it is difficult to obtain from these natural sources because it is covalently attached to various carbohydrates as a glycosidic conjugate, ester, or amide. As a result, alkaline hydrolysis is the only way to get it out of these natural products (Tilay et al. 2008). FA created through a chemical technique cannot be regarded as natural; therefore, numerous efforts have been made to release FA from natural sources enzymatically. However, most FA contents in plants are covalently bonded with lignin and other biopolymers, isolating

Table 10.2 The levels of ferulic acid in grains, fruits, and vegetable sources

Sources	FA contents (%)	References
Carbohydrate		
Refined maize bran	2.61–3.3	Zhao and Moghadasian (2008); Zhao et al. (2005)
Maize, dehulled kernels	0.174	Adom and Liu (2002)
Whole grain rye flour	0.086	Zhao and Moghadasian (2008); Mattila et al. (2005)
Whole brown rice	0.042	Zhao and Moghadasian (2008); Adom and Liu (2002)
Maize flour	0.038	Mattila et al. (2005)
Whole grain barley flour	0.025–0.034	Mattila et al. (2005)
Oat bran	0.033	Zhao and Moghadasian (2008); Mattila et al. (2005)
Rye bran	0.28	Zhao and Moghadasian 2008; Mattila et al. (2005)
Fruits		
Grapefruit	0.0107–0.0116	Mattila and Hellström (2007)
Rhubarb	0.00147	Mattila and Hellström (2007)
Apples	0.00027–0.00085	Mattila and Hellström (2007)
Banana	0.0054	Mattila and Hellström (2007)
Orange	0.0092–0.0099	Mattila and Hellström (2007)
Berries	0.00025–0.0027	Mattila and Hellström (2007)
Vegetables		
Eggplant	0.0073–0.035	Mattila and Hellström (2007)
Tomato	0.00029–0.006	Bourne and Rice-Evans (1998); Mattila and Hellström (2007)
Carrot	0.0012–0.0028	Mattila and Hellström 2007
Chinese cabbage	0.0014	Mattila and Hellström (2007)
Broccoli	0.00409	Mattila and Hellström (2007)
Red cabbages	0.0063–0.0065	Mattila and Hellström (2007)
soybeans	0.012	Mattila and Hellström (2007)
Green bean/fresh	0.0012	Mattila and Hellström (2007)

Source: Zhao and Moghadasian 2008; Boz 2015; Kumar and Pruthi 2014

FA for commercial production by enzymatic techniques seems challenging. Extraction of ferulic acid from various by-products are presented in Table 10.3.

10.3 Absorption and Metabolism Effect of FA in Animal

Compared with other phenolic compounds, ferulic acid is quickly absorbed from the stomach (Zhao and Moghadasian 2008). Following absorption, ferulic acid quickly transforms into a conjugation product in the liver when combined with glucuronides,

Table 10.3 Extraction of ferulic acid from various by-products

Name of raw materials	Method of Extraction	Yield	Reference
Sugar beet pulp	Three extraction solvents, sodium hydroxide (0.5, 1, 2 M), methanol, and their mixture (alkaline methanolic solvent)	957.4 mg/L	Aarabi (2016)
The root of Angelica sinensis	Ethanol with supercritical CO_2	0.35–0.37%	Sun et al. (2006)
Palm pressed fibre	Deep eutectic solvent (DES) of choline chloride-acetic acid (ChCl-AA) and choline chloride-citric acid (ChCl-CA)	41,155 ± 940 mg/kg	Mei and Hadi (2022)
Sweet corn cob (SCC)	Chemical or enzymatic hydrolysis	1.69 ± 0.02 g kg^{-1}	
Flax shives, wheat bran, and corn bran	Non-pressurized alkaline hydrolysis (0.5 M NaOH) and pressurized solvents (0.5 M NaOH, water, ethanol, and ammonia)	Flax shives 25 mg/100 g FA Wheat 391 mg/100 FA Corn bran 2510 mg/100 g FA	Buranov and Mazza (2009)
Wheat-bran	Enzymatic hydrolysate	2000–3000 mg/L	Liu et al. (2004)
Corn fibre	Alkaline	2.10 ± 0.09 g. L^{-1} and 11.14 ± 1.00 kg Ton^{-1}	Valério et al. (2021)
Rice Bran oil	Ultrasonic method	10–20%	Arumsari et al. (2019)
Sweet potato stem	Enzymatic treatment	>2.0%/g dry weight	Min et al. (2006)
A recombinant strain of Saccharomyces cerevisiae	Eugenol and coniferyl alcohol	90%	Lambert et al. (2013)
Defatted rice bran	Enzymatic production	22%	Uraji et al. (2013)
A recombinant strain of *Ralstonia eutropha* H16	Eugenol hydroxylase	93.8 mol%	Overhage et al. (2002)

sulfate, and sulfoglucuronide (Zhao and Moghadasian 2008). FA can be quickly absorbed from the stomach and is likely metabolized mainly in the liver. Ferulic acid taken orally was distributed at 4% in gastric mucosa and 10% in the blood pool and liver, kidney, and 53% in other tissues (Zhao and Moghadasian 2008). However, free ferulic acid bioavailability is very low due to the rapid conjugation process in the liver (Zhao and Moghadasian 2008). It is more bioavailable than other dietary flavonoids and phenolics studied. Furthermore, the intestinal microflora metabolizes FA into hydroxyphenyl propionic acid through reduction, demethylation, and dihydroxylation at C4 (Chesson et al. 1999). FA's absorption and metabolism effect in the animal has been demonstrated, owing to its cytoprotective effects. Studies have shown that FA could improve animal carbohydrate utilization; this was observed in several studies. Extensive research in sheep shows that FA could increase cellular glucose absorption while preserving euglycemia (Macías-Cruz et al. 2018; Wang et al. 2019). A similar result was also observed in mice fed FA diet (de Oliveira Silva and Batista 2017; Ramar et al. 2012; Roy et al. 2014). However, the authors attributed the improved glucose metabolism to the increase in the circulation of insulin concentration and translocation of gluco-transporters (GLUT4) towards the cell membrane (Kumar and Goel 2019; Naowaboot et al. 2018). This positively affects glucose metabolism fed FA diet, which promotes energy metabolism in tissues such as skeletal muscle (Chen et al. 2019; Chodkowska et al. 2018). Macías-Cruz et al. (2018) discovered alterations in the glucose–insulin system, including lower serum glucose levels and enhanced insulin secretion in pre-pubertal lambs fed free FA diet. Notably, this is a crucial response for animal reproduction and growth because glucose is the primary energy source used by gonads and muscles

The anti-hyperlipidemic effects of FA were observed in obese farm animals as it decreases the biosynthesis of fatty acids, triglycerides, and cholesterol esters. This study was carried out with mouse C2C12 myoblasts exposed to hydrogen peroxide (Chodkowska et al. 2018) and rats fed a high-fat diet (Melo et al. 2017; Salazar-Lopez et al. 2017). Lipid synthesis was significantly improved in obese rats fed a high-fat diet supplemented with FA. This suggests that dietary FA could stimulate lipolysis to hinder dyslipidemia by exerting an anti-insulin resistance effect in rats administered a high diet (Naowaboot et al. 2018). In contrast, no change was observed in serum TG and TC concentrations when fattening lambs received free FA supplementation (Macías-Cruz et al. 2014; Wang et al. 2019). At the same time, FA-fed pigs (Li et al. 2015) and steers (González-Ríos et al. 2016) ´show decreased meat lipid peroxidation rates. These findings suggest that FA modulates lipid metabolism only in dyslipidemia. Overall, FA seems to act as a modulator of energy metabolism in animals with carbohydrate and lipid metabolic disorders.

However, studies have shown that FA did not affect serum total protein and urea concentrations in hair ewe lambs under heat stress or thermoneutral settings (Macías-Cruz et al. 2014; Macías-Cruz et al. 2018). However, an increase in serum total protein concentrations in cold-stressed male lambs (Wang et al. 2019). Increased blood total protein concentrations have also been seen in lambs fed feruloyl oligosaccharides (Wang et al. 2019). According to both studies, FA raises total protein in the blood because it enhances microbial protein production and/or enzymatic antioxidant activity, preventing protein oxidation (Wang et al. 2019). FA may enhance protein metabolism in ruminants by increasing protein synthesis while lowering catabolism (cytoprotective effect). The mechanism of action for FA's beneficial effect on protein metabolism in ruminants and other producing animals needs further investigation.

Therefore, with the findings above, it can be inferred that FA affects metabolic routes of the major nutrients and consequently favours both animal reproduction and growth than those present in fish species

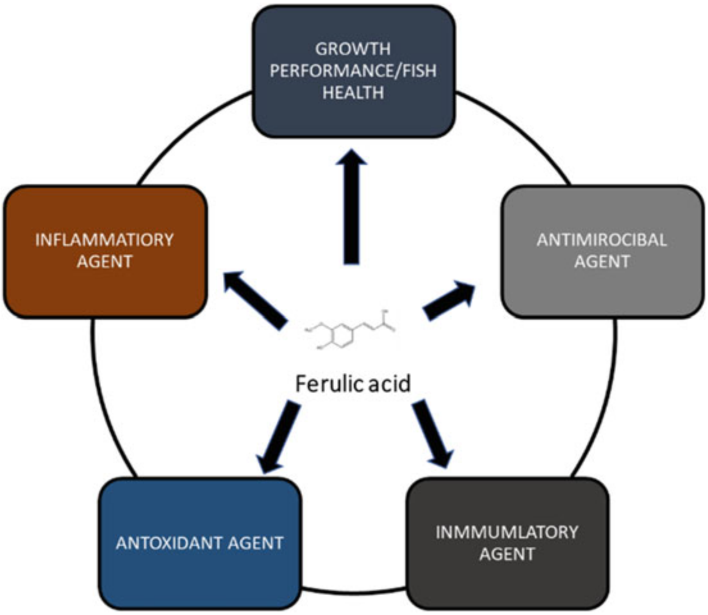

Fig. 10.2 The role of ferulic acid in fish

10.4 Overview of the Use of Ferulic Acid in Aquaculture

Providing sustainable seafood for human consumption is best accomplished through aquaculture. Several criteria, like environmental considerations, dietary practices, and disease control, are necessary for aquaculture to succeed (Abdel-Tawwab et al. 2020; Dawood and Koshio 2019). Ferulic acid (FA) is one of the most crucial additions to increase immunity and enhance an animal's physiological state (Ahmadifar et al. 2019; Kroon and Williams 1999; Nomura et al. 2003). Therefore, the role of ferulic acid in improving growth, fish health, antioxidant capacities, and anti-inflammatory and immune response has thoroughly been investigated and reported in fish, as shown in Fig. 10.2.

10.4.1 Ferulic Acid Improves Growth Performances and Biochemical Parameters

The change in length and weight of a fish or any organism due to nutrition metabolism is called growth. As a result, growth is the ability to provide healthy food. The cost of aquaculture has led business owners to desire to harvest the maximum yield per unit area. In contrast, the scarcity of natural resources has driven scientists to do the same. Both situations have the same objective: faster fish growth with fewer costs. Hence, growth promotion is among the essential purposes of recent studies.

FA is successfully demonstrated to promote growth in various fish species. For instance, studies in fish have shown that weight gain in genetically improved farmed tilapias fed FA derivative diet at 0.52 mmol kg^1 was much higher than those fed the control diet. In contrast, the opposite pattern was observed in feed conversion ratio, hepatosomatic and viscerosomatic index (Yu et al. 2017, 2018). This was accompanied by significantly lower TCHO, LDLC and TG, LDL, AST, ALT, and higher HDL contents than the control. Similarly, Yu et al. (2017) noted a significantly higher WGR with lower FCR, VSI and HSI in GIFT (*Oreochromis niloticus*) fed dietary FA at a 100 mg/kg in diet. This was connected with a substantial reduction in serum TG, TC, LDL contents, AST and ALT activities, whereas serum HDL content was significantly higher. The growth performance was significantly affected by the inclusion of FA, and the highest rates were reported in an 80 mg/kg diet after 60 days of feeding in Nile tilapia (Dawood et al. 2020). Also, weight gain rate (WGR) and specific growth rate (SGR) of oriental river prawn (*Macrobrachium nipponense*) fed FA diet for 10 weeks were significantly higher with the opposite trend seen in FCR than those of the control group (Liu et al. 2022). After 8 weeks of feeding, common carp fed with an FA diet registered a significantly higher SGR, FBW, WGR, white blood cells (WBCs), red blood cells (RBCs), haematocrit (HCT), and haemoglobin (Hb), compared to those in control. Yu et al. (2020) noted a considerable improvement in serum ALB, TP and ALP, BUN, AST and LDH in genetically improved farmed tilapia (*Oreochromis niloticus*) administered with an oxidized fish oil diet supplemented with FA for 12 weeks as compared to the control. At 10 weeks of feeding, FA inclusion level at 80 mg/kg obtained noticeable growth performance and feed utilization compared to the control. However, serum TC, TG, LDL, ALT, AST, and AKP were significantly decreased, and HDL levels increased following the FA-containing (80–160 mg/kg) diets. Additionally, it was shown that the expression of genes involved in growth (GH, IGF-1, GHR1, GHR2) was significantly increased in the liver. Dietary FA at 20 g/g enhanced growth and feed absorption and increased PPAR-α, a gene linked to fat metabolism, and lowered the expression of PPAR-β and PPAR-γ in male adult zebrafish (Yin et al. 2002). These alterations in gene expression improved fatty acid production and metabolism and decreased fat deposition. This suggests that FA may be necessary for lipid metabolism.

10.4.2 Ferulic Acid Improves Molecular Mechanisms Associated with Muscle Hypertrophy

Skeletal muscle is a flexible tissue that aids movement and energy metabolism (King et al. 2004). Muscle hypertrophy, defined by a rise in muscle mass and an expanded cross-sectional area due to the proliferation of myofibers, is the most common pattern of skeletal muscle growth in adults (Hernandez and Kravitz 2003). The myofiber is the skeletal muscle's basic unit, consisting of bundles of myofibrils, each of sarcomeric units (Sanger et al. 2004). FA, like β-AA, can regulate signaling pathways and myogenic gene expression, which may promote muscle hypertrophy in obese animals. Due to the activation of the Sirt1/AMPK/PGC-1 pathway and improved mitochondrial function, supplemental FA increases the proportion of slow-twitch fibres in the animal's Longissimus thoracic muscle (LTM) (Wang et al. 2021). FA also activates the 3 kinase/protein B kinase (PI3K/PKB or Akt) pathway in a manner comparable to insulin-like growth factor I (IGF-I), resulting in increased muscle fibre diameter (Kuppusamy et al. 2019; Yeh et al. 2014). In zebrafish, a diet supplemented with FA increased transcription of myogenic regulatory factors (i.e. MyoD, Myogenin, and SRF), resulting in improved hypertrophic growth of rapid skeletal muscle for increased body weight (Wen and Ushio 2017).

On the other hand, FA has been shown to increase sarcomeric unit proteins in zebrafish by increasing the expression of sarcomeric unit proteins, which are the primary components of the myofiber. FA dramatically boosted the expression of genes involved in myogenic development (myod1, myog, and myf5) and increased the breadth of skeletal muscle fibres (Yin et al. 2002). However, because these findings are still preliminary, more research with fish species is required to confirm the efficiency of FA on transcription, translation, and expression of sarcomeric proteins, and hence on muscle hypertrophy.

10.4.3 Ferulic Acid as an Antimicrobial Agent

A substance known as an antimicrobial prevents the growth or kills germs (Citarasu 2012). By functioning as a fermentation substrate, FA, whether in free form or bound to oligosaccharides, promotes the population expansion of the intestinal beneficial family *Bifidobacteriaceae*. Due to this alteration in the microbiota, FA also reduces the number of bacteria from the Enterobacteriaceae family, which are linked to GIT disorders and the breakdown of amino acids. FA was demonstrated to improve GIT health, increase microbial protein production, and provide a natural option for treating common bacterial and viral illnesses in animal models (Wang et al. 2019). According to Yin et al. (2002), zebrafish fed 20 g/g FA exhibited a higher number of goblet cells in intestinal tissue, and the makeup of the gut microbiota also changed. Also, the authors updated that the 16s rRNA gene sequences showed that 20 g/g FA increased *Bacteroides* and decreased *Firmicutes*, indicating that FA had an antibacterial effect. However, further research will be needed to fully comprehend the intricate connections between the FA and GIT microbiota and how these affect the well-being and output of aquatic animals.

10.4.4 Ferulic Acid as an Anti-apoptotic Agent

Cells have a built-in cell death program, apoptosis (programmed cell death), which protects the organism by removing potentially damaged cells and unnecessary cells after differentiation. Apoptosis occurs when internal monitors recognize damage or malfunction and initiate signaling cascades that eventually activate caspases and endonucleases that kill the cell (Gao et al. 2013). Apoptosis is induced in a wide range of physiological settings regulated by cell growth and differentiation in normal biological processes and pathogenesis in vertebrates (Ellis et al. 1991; Steller 1995; Jacobson et al. 1997). The two primary forms of apoptosis pathways are "extrinsic pathways", where a cell receives a signal to begin apoptosis from other cells in the organism, and "intrinsic pathways", where a cell receives a signal to start apoptosis from one of its genes or proteins owing to the detection of DNA damage (Elmore 2007). A thorough understanding of the mechanism between apoptosis and diseases has excellent potential for treating diseases. Additionally, studies have connected stress and diet to be associated with apoptosis. For instance, common carp fed a high-fat diet exhibited higher Caspase-8 and Caspase-9 than the control (Abasubong et al. 2022). A similar result was also observed in blunt snout bream (Dai et al. 2018). Recent studies have found that FA can take an anti-apoptotic part by mediating different targets. Fu et al. (2022) noted the ameliorating effect of hepatic morphology coupled with the downregulated gene expression of apoptosis (Caspase-3 and p53) and keap1bin juvenile hybrid grouper (*Epinephelus fuscoguttatus*♀ × *Epinephelus polyphekadion*♂) fed FA 80–160 mg/g.

10.4.5 Ferulic Acid as an Anti-inflammatory Agent

Inflammation, which involves the recruitment of phagocytes (macrophages and neutrophils) and the release of numerous cytokines, is essential to defend against tissue damage, infection, or toxic substances (Medzhitov 2008). Macrophages are one of the most significant phagocytes during an inflammatory process and can contribute to the emergence of a range of diseases by secreting a massive number of cytokines, such as TNF-, IL-6, and IL-1. Such inflammatory mediators can influence immune and non-immune cells to activate an immunological response that defends the body against pathogens and toxic chemicals (Medzhitov 2008). The inflammation process is usually tightly regulated, comprising signals that initiate and sustain inflammation and those that impede it. When the two signals are out of balance, inflammation can develop unchecked and cause damage to cells and tissue. The mononuclear phagocyte system strongly depends on macrophages as one of its essential components and is composed of closely related bone marrow-derived cells, including blood monocytes and tissue macrophages. The three primary functions of macrophages in inflammation are antigen presentation, phagocytosis, and immunomodulation by producing various cytokines and growth factors.

Macrophages have a vital role in initiating, continuing, and resolving inflammation. During the inflammatory process, they are both activated and deactivated. Some activation signals include interferon-gamma, granulocyte-monocyte colony-stimulating factor, tumor necrosis factor-alpha, bacterial lipopolysaccharide, extracellular matrix proteins, and other chemical mediators. The host can repair damaged tissues when inflammation is suppressed by removing or inactivating mediators and inflammatory effector cells. Anti-inflammatory cytokines (such as interleukin 10 and transforming growth factor-beta) and cytokine antagonists, primarily produced by macrophages, deactivate active macrophages.

Numerous studies have demonstrated that FA has a potent anti-inflammatory effect in many disorders. In order to reduce and combat inflammation, FA primarily suppresses the production and expression of associated inflammatory components via numerous molecular pathways, and multiple types of mediators (cytokines, chemokines, and eicosanoids) are released by strengthened immune cells, (Rinaldi et al. 2011). These inflammation-related mediators are in charge of removing the pathogen that has invaded and establishing the recovery procedures. Therefore, in response to infection, ferulic acid inhibited the synthesis of macrophage inflammatory protein-2 (Sakai et al. 1999). The control of inflammation depends on preventing the synthesis or activity of inflammatory cytokines and mediators (Vinegar et al. 1969). As a result, a requirement for an anti-inflammatory substance may be the capacity to control inflammatory mediators.

Several studies have been conducted to prove these in fish species. For instance, compared to controls, juvenile hybrid grouper (*Epinephelus fuscoguttatus, Epinephelus polyphekadion*) fed diets containing 80–160 mg/kg FA had significantly higher transcriptional levels of immune-related genes (IL-1, IL-8, TNF-, and IFN-) in the liver, head, kidney, and spleen (Fu et al. 2022). Additionally, following FA administration of LPS, the contents of pro-inflammatory cytokines gene expression, including TNF- and IL-1, under LPS stimulation at 96 hpi in Megalobrama amblycephala were considerably decreased (Chen et al. 2021). Additionally, Fish fed diets containing 80–160 mg/kg FA had significantly higher transcriptional levels of immune-related genes in their liver, head kidney, and spleen. These genes include IL-1, IL-8, TNF-, and IFN-. Fish offered dietary FA upregulated the HSP70 gene before and after high stress while upregulating the INF-, TNF-, and IL-1 gene expression (Dawood et al. 2020).

10.4.6 Ferulic Acid Immunostimulatory Agent

The mucosal layer, epithelium, and lamina propria are the three defence lines of the gut's innate immune system. The mucosal layer is the initial line of defence against foreign infections in the host digestive tract (Xu et al. 2014). The immune system comprises various humoural and cellular components that protect the body from foreign invaders (Biller-Takahashi and Urbinati 2014). Immunostimulation is a phenomenon in which an organism's immune response is stimulated beforehand so that it must face a strengthened immune system when an extraneous substance enters the body. Immune responses are the main controlling elements for the emergence and spread of numerous chronic diseases. In studies, numerous compounds, besides ferulic acid, have successfully activated the immune response in finfish (Mohamed et al. 2018; Bilen et al. 2020). Ferulic acid is a bioactive compound class that enhances intestinal health through various processes, including mucosal immunity and inflammatory modulation. Many investigations on the regulatory effects of ferulic acid on intestinal immune function have produced compelling evidence, necessitating more research.

Present studies in aquatic animals show that FA supplemented with 163.99–183.33 mg/kg level significantly improves albumin/globulin ratio (A/G), the complement 3 (C3)) with down-regulated *Toll* and *Dorsal*, immune deficiency (*IMD*), and heat shock protein (*HSP70*) and disease resistance against non-O1 *Vibrio* cholera GXFL1-X infection of *M. nipponense* (Liu et al. 2022). Similarly, higher lysozyme was observed in improved farm tilapia (Yu et al. 2017). After 8 weeks of feeding, lysozyme activity and the serum respiratory burst were enhanced in common carp given a 100 mg/kg FA diet. However, after the challenge with pathogenic *A. hydrophila,* fish fed FA added diet had a higher survival rate than those in the control group (Ahmadifar et al. 2019). According to the results, FA could be employed as a valuable feed supplement to enhance immune responses and disease resistance in common carp culture's initial phases. The serum nitric oxide (NO), complement 3 (C3), complement 4 (C4), and lysozyme (LSZ) were all significantly increased in tilapia (*Oreochromis niloticus*) fed oxidized fish oil supplemented with 400 mg/kg FA for 12 weeks (Yu et al. 2020). Fu et al. (2022) noted that fish fed dietary 80–160 mg/kg FA increased the contents of complement 3, immunoglobulin M, and lysozyme compared to the control.

10.4.7 Ferulic Acid as Antioxidant Agents

When oxidation and antioxidation in the body are out of balance, this is referred to as oxidative stress (OS) (Mustafa et al. 2020), and it causes the body's general state to lean toward oxidation. When the body's antioxidant mechanism and ROS generation are imbalanced, they promote a significant amount of ROS (Kikuzaki et al. 2002; Birben et al. 2012). This ROS results in neutrophil infiltration, an increase in protease secretion, and the development of many oxidation intermediates (Halliwell 1994), which ultimately cause tissue degeneration, steatosis, cell transformation, apoptosis, and host death (Abasubong et al. 2022). Additionally, the synthesis of NO and nuclear factor kappa B (NFkB), along with other mediators, control the expression of cyclooxygenase (COX)-2 and induced nitric oxide synthase when ROS levels rise above physiological levels (iNOS). Oxidative stress is associated with improper dietary formation. In the body, there are two types of antioxidant systems: non-enzyme antioxidants (lipoic acid (LA), glutathione, vitamin C, vitamin E); and enzyme antioxidants (catalase (CAT), superoxide dismutase (SOD), glutathione peroxidase (GPx) (Mustafa et al. 2020). ROS, an oxygen-containing material, is constantly created in the body because the body continually obtains oxygen for a long time Williams (Williams et al. 2004)(Mustafa et al. 2020). With this, the body's antioxidation mechanism can resist oxidation, limiting the body's production of reactive oxygen species (ROS) and repairing the harm they produce.

An antioxidant is a substance that inhibits oxidation. Oxidation, a chemical reaction, results in the production of free radicals (Williams et al. 2004). Atoms or clusters of atoms containing an unpaired electron are referred to as free radicals. Since unpaired electrons are likely to form pairs with other electrons, they are typically unstable and reactive. The occurrence of metabolism in a living organism causes oxygen molecule (O_2) to undergo reduction by four electrons. In this process, reactive oxygen metabolites are produced, which interact with transition elements, the excitation of electrons, or the input of energy. These oxygen-reactive metabolites are called active oxygen species because they are far more reactive than oxygen molecules. Active oxygen species include hydroxyl radicals (OH*), hydrogen peroxide (H_2O_2), superoxide (O_{2-}), and singlet oxygen ($_1O^2$) (Bors et al. 1990). Free radicals are formed in live cells due to photolysis, homolysis, chemical bond fission, radiolysis, and redox processes. In a live organism, free radicals start a chain reaction that damages cells and causes disease. Antioxidants are chemicals that stop a chain reaction in a live organism that free radicals have formed (Rizzo et al. 2010). In other words, antioxidants prevent the detrimental effects of reactive oxygen species (free radicals) by neutralizing or deactivating their impact. Oxidative stress is a term that describes the distinction between the creation of antioxidant defenses and very reactive oxygen groups.

Ferulic acid's antioxidant effect is multifaceted, involving both the prevention of the production of reactive oxygen species (ROS) or nitrogen as well as the neutralization ("sweeping") of free radicals. This acid also chelates protonated metal ions, including copper and iron ions (Rice-Evans et al. 1996, 1997). Ferulic acid is a free radical scavenger, an inhibitor of free radical generating enzymes, and increases the activity of scavenging enzymes (Kumar and Pruthi 2014). The mechanism of antioxidative activity is the capacity of ferulic acid to create persistent phenoxyl radicals due to the radical molecule reacting with the antioxidant molecule. It is therefore inhibiting the occurrence of chemical chain reaction that generates free radicals. This chemical could also operate as a hydrogen donor, supplying atoms to radicals directly. This is crucial for protecting lipid acids in cell membranes from unwanted autoxidation reactions. This reduces the generation of harmful hydroxyl radicals, which cause the peroxidation of cell membranes.

According to studies, oxidized fish oil was shown to induce oxidative stress, destroy the liver, and dysregulate the lipid metabolism of tilapia fed for 12 weeks. However, a diet supplemented with 400 mg/kg of ferulic acid offsets these adverse effects by increasing SOD, CAT, and GPx activities and reducing malondialdehyde (MDA) content (Yu et al. 2020). Chen et al. (2021) reported that FA gavage (50 mg/kg BW and 100 mg/kg BW) significantly increased GSH, GST, SOD, GR, and GPx activity. This was associated with increased SOD, CAT, and GPX mRNA expression, suggesting that FA administration could inhibit the LPS-induced oxidative stress in *Megalobrama amblycephala*. Ahmadifar et al. (2019) reported a noticeable increase in serum antioxidant enzymes (CAT, GPX SOD) activity in common carp (*Cyprinus carpio*) fed FA for 8 weeks as compared to the control. Nile tilapia (*O. niloticus*) fed 80 mg kg^{-1} for 60 days significantly increased SOD, CAT, and GPx activity and reduced MDA levels before and after heat stress (Dawood et al. 2020). The antioxidant-related parameters of SOD, CAT, GPx, and total antioxidant capacity were elevated. At the same time, MDA content was significantly reduced in 80–160 mg/kg FA treatment with a significant antioxidant gene expression Nrf2, Cu/ZnSOD, and MnSOD) as compared with control (Fu et al. 2022). Studies have also shown that European sea brass fed XOS diet obtained higher SOD, CAT, and GPX activities than the control (Guerreiro et al. 2015). The authors attributed this improvement to their composition of ester-linked phenolic acids such as ferulic in XOS. Abasubong et al. (2022) also obtained a similar result when an XOS was given to common carp fed the high-fat diet for 8 weeks. Finally, iNOS, NO, SOD, GPx, and MDA were dramatically decreased in the FA groups fed oriental river prawn (*Macrobrachium nipponense*) compared to the control group after ten weeks of feeding (Liu et al. 2022).

10.5 Conclusion

Current research indicates that FA can boost growth, anti-inflammation, immunological response, and antioxidant capacity in fish. However, knowledge is lacking, which has resulted in the opening of a vast field of research into the application of this phytochemical. Future research should examine environmental variables, species, the animal's oxidative status, bioavailability, modes of action, and product dosage. The information acquired thus far and findings from future studies will allow management methods to be developed to make this natural material viable for ensuring food safety while protecting animal welfare and human health.

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Chapter 11
The Importance and Utilization of Palm Oil as a Fish Oil Replacement in Aquaculture

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Abstract The oil palm tree is a centuries-old tropical plant native to West Africa. Palm oil has been used as a food and medicine for centuries. Crude palm oil (CPO) is extracted from the oil palm tree's fruit (*Elaeis guineensis*). Palmitic acid, carotene, and vitamin E are abundant in the oil. This chapter reviewed the progress made in using palm oil as an alternative lipid source in aquafeeds. This section discusses the most recent significant materials discovered in the literature on palm oil processing, refining, and distribution compared to other vegetable oils. Furthermore, palm oil in aquafeeds may or may not compromise fish growth and feed utilization composition. Finally, the effect of replacing fish oil with palm oil on immune and antioxidant capacity was discussed. This could be an additional good source of aquafeed oil for African aquaculture. More research in the African setting, however, is required to optimize this ingredient in different culture species.

Keywords Oil palm · Growth performance · Fatty acid profile: body composition: inflammation: antioxidant capacity

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11.1 Introduction

The world's fastest expanding industry for producing food is aquaculture. It makes up almost half of the world's fish consumption. According to estimates, aquaculture presently provides 50% of the food fish need, and by 2030, this percentage is expected to increase to 60–70% (Subsinghe et al. 2009). Over the past few decades, aquaculture has expanded, and farmed fish consumption has increased globally (FAO 2018). Global fisheries production increased by 174.0 Mt in total, of which 83.6 Mt came from aquaculture and 90.4 Mt from capture (Hodar et al. 2020). The demand for aqua feeds rises as worldwide aquaculture production expands. Fish feeds to give them the nutrients they need for rapid growth, survival, and maintaining a healthy existence. It accounts for between 30 and 70% of the overall operating expenses in an aquaculture production system. Overall, aquaculture feed output increased by around 4% from the previous year to 40.1 million tons in 2018. The primary research areas in recent years have concentrated on identifying substitute raw materials due to the rising expense of fishmeal and marine oils and their restricted availability. Since feed can account for 50% or more of the production costs of most aquaculture systems, artificially designed diets (also known as aquafeed) are essential to maintaining the ongoing expansion of aquaculture production. Fish oil, which provides vital fatty acids and dietary energy, is crucial in aquafeed formulation.

Fish oil (FO) is a crucial source of omega-3 long-chain polyunsaturated fatty acids (n-3 LC-PUFA), particularly docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) (Fukada et al. 2020). They are estimated to give 8.5 kcal of metabolizable energy (ME) per gram, making them the biological product with the highest energy density per unit weight. Fish oil is a great provider of lipids, specifically HUFAs and PUFAs (Rice 2009). Triacylglycerols (TAGs), most stored fats and typically make up more than 90% of the total fatty acid makeup, are abundant in fish oil. Particularly in aquaculture diets, the fatty acid profile of fish oils determines a significant portion of their nutritional content.

Additionally, FO includes several lipid-soluble additives, flavorings, and additives that improve palatability and essential nutrients for fish (Turchini et al. 2009). FO has thus emerged as the top lipid source for fish feed (Nasopoulou and Zabetakis 2012). However, the global supply of FO is constrained due to declining marine catches and cannot keep up with the fast-increasing demand for aquafeed production (Turchini et al. 2011). As a result, there is a significant shortage of FO, which drives up FO prices. After fish meal replacement, fish oil replacement in aquafeeds is a top international research focus (Torstensen et al. 2005). Although using vegetable oils in commercial feed formulations for farmed fish has mixed results, this alternative method for creating aquafeeds offers promising results. This is generally attributed to the inconsistent nutritional quality and types of oils (Benedito-Palos et al. 2008; Fountoulaki et al. 2009; Abbasi et al. 2020; Alvarez et al. 2020; Tseng and Lin 2020). Therefore, adequate lipid sources must be found to replace FO to support the sustainable development of aquaculture.

With the global production of roughly 66 million tons in 2017, palm oil (PO) is one of the most widely used vegetable oils. It is found in between 34 and 50% of frequently used food and consumer products (Kushairi et al. 2019). The nutritional and health benefits of PO have been determined for human ingestion and are well established (Sun et al. 2015). The oil is rich in C16:0 and C18:1n-9 FA but has comparatively low levels of C18:2n-6, despite having a higher level of saturated fatty acids (SFA) than other edible vegetable oils (Balbuena-Pecino et al. 2021). PO has stronger resistance to rancid because of its high SFA level, which could produce long-lasting fish meals (Ng et al. 2007; Riera-Heredia et al. 2020). As a result, significant efforts have been made to utilize PO as a viable FO substitute in aquafeeds (Bell et al. 2002), and numerous studies have demonstrated that PO can replace FO in diets at a range between 40 and 100% without negatively impacting fish growth performance (Ng et al. 2004; Fonseca-Madrigal et al. 2015; Balbuena-Pecino et al. 2021). However, when fish were fed a high PO diet, the fatty acids (FA) profile of the muscle was significantly different from that of the FO treatment in various fish species (Fonseca-Madrigal et al. 2015; Aliyu-Paiko and Hashim 2012; Ahmad et al. 2013; Ma et al. 2019). This could have an impact on the quality of fish meat. As a result, while considering whether to include PO in the fish diet, the evaluation of the quality of the flesh may be crucial (Mock et al. 2019; Gudid et al. 2020; Balbuena-Pecino et al. 2021; Guo et al. 2021). In this chapter, we review the use of palm oil in aqua feeds, considering its availability, distribution, significance, growth performance, fatty acid and body composition, and antioxidant and inflammatory and immune response in fish.

11.2 Palm Oil

The ripening mesocarp of the oil palm tree's fruits is where palm oil is obtained (*Elaeis guineensis*). The fruit of the oil palm is a drupe that develops in spikey, compact bunches (Fig. 11.2). The oil palm tree is a member of the Palmae family and has an unbranched stem. The tree has a 25-to-30-year economic life span and can reach a height of 20–30 m. The female bunch can weigh up to 30–40 kg and contain up to 2000 fruits, which are initially black before becoming orange-red when they are ripe (Vincent et al. 2014). After germination, which takes about 3 months, the seedlings are planted in plastic bags, moved into the field at almost a year old, and begin to bear fruit in less than 2 years (Abdullah and Sulaiman 2013). At 5–6 years, the number of leaves in an oil palm plant increases from 30 to 40 per year. After that, just 20–25 leaves each year are produced on average (Abdullah and Sulaiman 2013). Palm oil is one of the top 17 oils and fats now produced and traded worldwide. The fastest-growing oil in the world during the last 40 years has been palm oil. Despite presently ranking second behind soybean oil, palm oil is predicted to become the most produced oil in the world (Carter et al. 2007). Compared to three million tons of soybean oil, only 1.5 million tons were produced in 1961. However, in 2006, palm oil production overtook soybean oil for the first time, and by 2011, there were 48.6

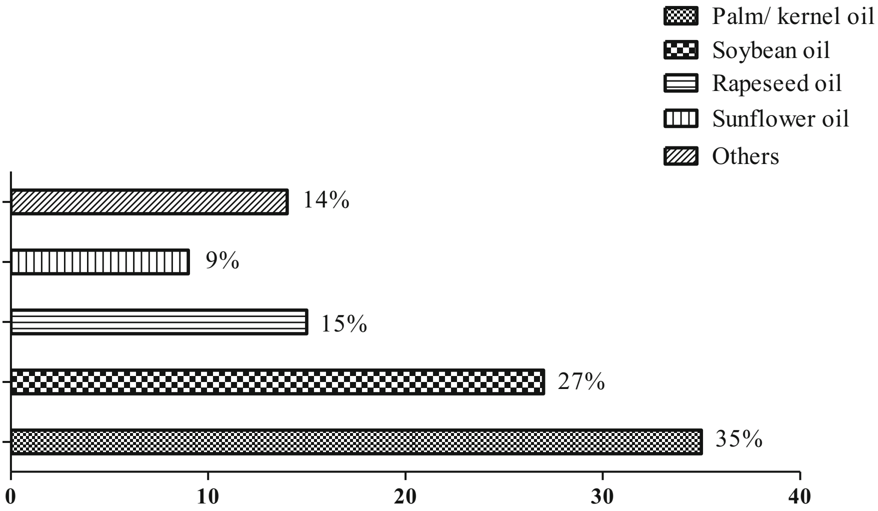

Fig. 11.1 Global vegetable production in 2011. (Adopted from Koushki et al. 2015)

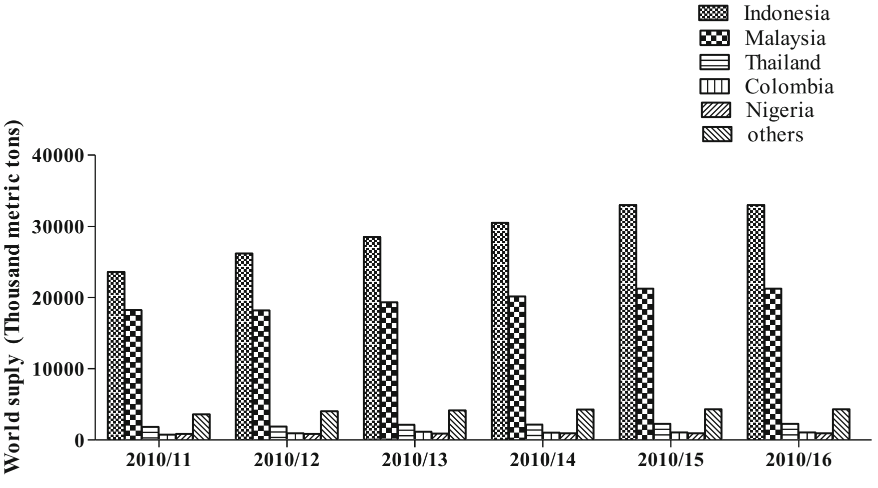

Fig. 11.2 World supply and distribution (Thousand Metric Tons). (Source: Adopted from Koushki et al. 2015)

million tons of palm oil produced globally, compared to 41.6 million tons of soybean oil, as shown in Fig. 11.1. Also, a detailed summary of the physiochemical analysis of palm oil is shown in Table 11.1.

A single hectare of an oil palm plantation can yield up to ten times as much oil as other essential oilseed crops. The mesocarp of the palm fruit yields crude palm oil (CPO), and the kernel yields palm kernel oil (PKO) (Röbbelen 1990). In global trade, CPO and PKO are both significant (Schroeder et al. 2006). CPO and PKO

Table 11.1 Physiochemical analysis of palm oil

Characteristics	Range
Apparent density at 50 1 °C (g/mL)	0.892–0.899
AOM stability (h)	53.0–60.0
Melting point (°C)	33.0–45.0
Oxidative stability index at 110 °C (h)	16.6–19.0
Refractive index at 50 °C	1.449–1.456
Smoke point (°C)	230.0–235.0
Solidification point (°C)	35.0–42.0
Specific gravity at 50 °C	0.888–0.889
Viscosity (cP)	45.0–49.0
Iodine value (g/100 g)	46.0–56.0
Free fatty acid (% FFA as palmitic)	3.17–5.0
Peroxide value (meqO_2/kg)	0.1–10.0
Anisidine value (mg KOH/g)	0.6–4.65
Saponification value (mg KOH/g)	190.0–209.0
Unsaponifiable matter (%)	0.15–0.99
Total polar compounds (%)	9.47–19.50
Total polymer materials (%)	0.4–15.0
Saturated fatty acids SFA (%)	49.9–54.7
Monounsaturated fatty acids MUFA (%)	37.1–39.2
Polyunsaturated fatty acids PUFA (%)	8.1–10.5
Crystal habit	–

Source: adopted from Mba et al. (2015)

produced 32% of the world's fats and oils in 2012. The most significant vegetable oil in the world now is palm oil, which has replaced soybean oil (Oil world 2013). Due to its high carotene concentration, CPO is also known as red palm oil. It contains high levels of sterols (325–365 mg/kg), coenzyme Q10 (ubiquinone) (18–25 mg/kg), and vitamin E (600–1000 ppm) (Tyagi and Vasishtha 1996). About 90% of palm oil is used in the production of edible foods, and the remaining 10% is used in producing soap and oleochemicals (Oil World 2013).

Pisifera, Dura, and Tenera are the three main varieties of oil palm. The dura kinds are distinguished by their thin mesocarp content (35–55% of the fruit weight), thick endocarp shells (2–8 mm), and big kernels. Pisifera kinds are distinguished by thick, 95% mesocarps (with limited oil content), no endocarp, and small kernels (Baryeh 2001). The Tenera is a single-factorial hybrid of Dura and Pisifera (Baryeh 2001). It has a decent kernel size, a 60–95% thick mesocarp, and an endocarp between 0.5 and 3 mm thin. The carotenoids in the CPO are thermally destroyed to generate the appropriate colour for refined, bleached, deodorized (RBD) palm oil during the refining process, in addition to removing any remaining contaminants in the oil (Ping and May 2000). To expand the range of their applications, RBD palm oil can be fractionated by thermomechanical processes to produce RBD palm stearin and RBD palm olein, primarily used as culinary oils (used mainly in margarine and shortenings). Carotenoids, tocopherols, tocotrienols, sterols, phospholipids, triterpene alcohols, squalene, aliphatic alcohols, and aliphatic hydrocarbons are minor constituents in crude palm oil (Hof et al. 2000). The main substances of interest are the carotenes, tocopherols, tocotrienols, sterols, and squalene. Antioxidants that protect the oil from oxidation are carotenoids and tocopherols. During refining, the bleaching and steam deodorization processes partially remove several vital components. The circumstances of refining determine the quantity kept in the refined oils.

11.3 Global Oil Palm Production

Palm oil production has increased rapidly over the past 50 years. In 1970, the world was producing only two million tons. This is now 35 times higher: in 2018, the world produced 71 million tons. The change in global production is shown in the chart (Wahid et al. 2005). The rise of palm oil follows the rapid increase in demand for vegetable oils more broadly. The stacked area chart shows the breakdown of global vegetable oil production by crop. Global production increased ten-fold since the 1960s, from 17 to 170 million tons in 2014. As we will see later in this article, more recent data for 2018 comes to 218 million tons. The story of palm oil is less about it as an isolated commodity but more about the story of the rising demand for vegetable oils. Palm oil is a very productive crop; as we will see later, it produces 36% of the world's oil but uses less than 9% of croplands devoted to oil production. It has therefore been a natural choice to meet this demand.

After being planted, the palm begins to produce fruit in the third year and continues for roughly 25 years. The oil palm fruit yields two different forms of oil: palm oil from the mesocarp and kernel oil from the nut's kernel. Fruit bunches are routinely picked throughout the year following the plantations' established criteria. They are then delivered to the palm oil mills, where raw palm oil and kernels are extracted mechanically and physically. Fruits are carefully picked at their peak of ripeness, handled as little as possible during shipping, and processed under ideal conditions to preserve oil quality.

A tropical plant species is the oil palm. The finest growing regions are located along a confined band around the equator because it thrives in environments with heavy rainfall, sufficient sunlight, and humidity (Wahid et al. (2005). As a result, palm oil is grown in numerous nations throughout Southeast Asia, South America, and Africa. Although several nations have grown some palm oil, only two—Indonesia and Malaysia—dominate the global market. Wahid et al. 2005 reported that 72 million tons of oil palm was produced globally in 2018. Malaysia generated 27% of this, and Indonesia produced 57% (41 million tons) (20 million tons). Indonesia and Malaysia produce 84% of the world's palm oil. Thailand, Colombia, Nigeria, Guatemala, and Ecuador are additional producers as shown in Fig. 11.2.

11.3.1 Oil Palm Processing and Production

The “wet” or “dry” processes are the most popular ways to extract palm oil (Fig. 11.3). The oil from the milled palm fruits is extracted using a liquid, typically

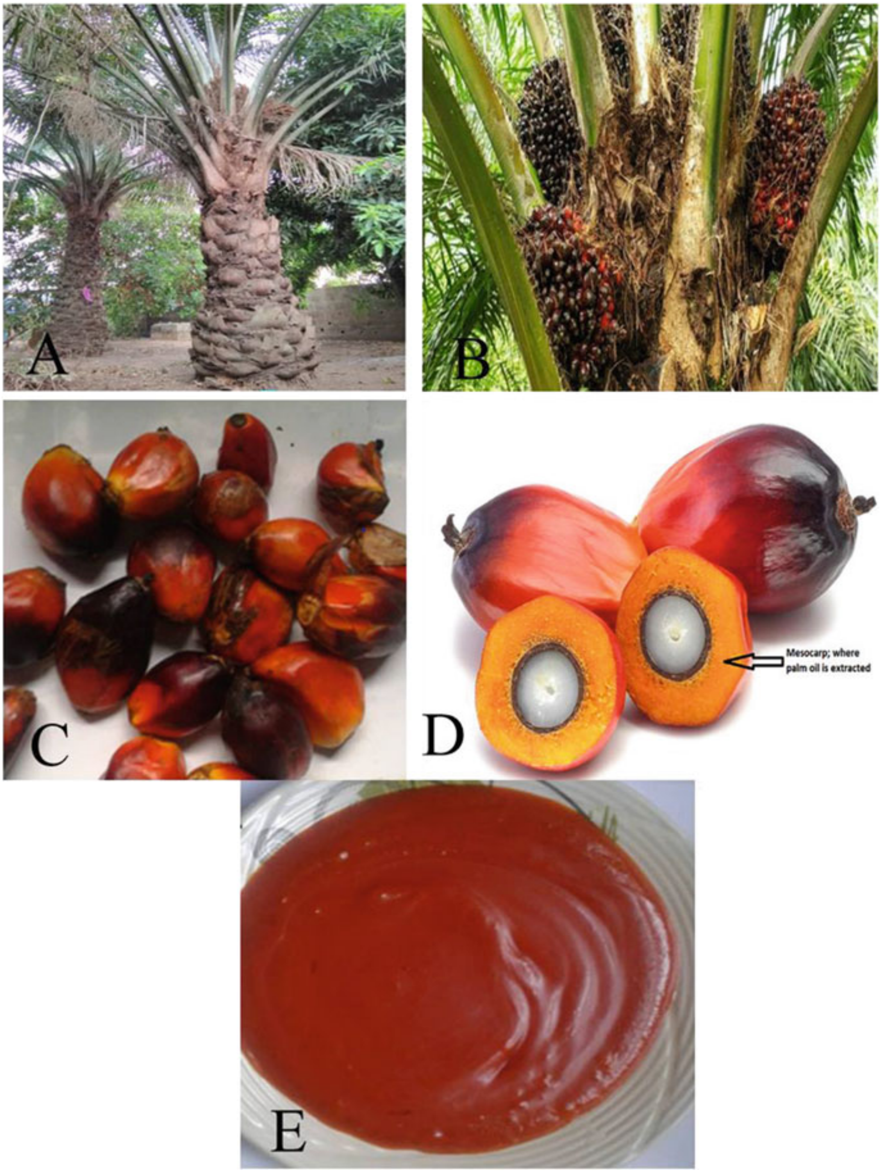

Fig. 11.3 (**a**) Palm tree, (**b**) Palm tree with bunch of fruits, (**c**) Palm friut, (**d**) Sectioned oil palm fruits showing the mesocarp, (e) Palm oil

water, in the so-called "wet" process. Oil is extracted from ruptured oily cells of palm fruits using hot water or steam. In addition to coagulating proteins, the hot water treatment hydrolyses any starch, glue, or gum that may be present. During frying, the gums and resins cause the oil to foam. During oil clarifying, the hydrolyzed and coagulated byproducts are eliminated. After the moisture has been evaporated, the extracted oil is recovered (Obibuzor et al. 2012; Poku 2002). The "dry" approach uses a hydraulic press, a screw press, or centrifugation. Continuous extraction systems are generally more suited for the screw press, while batch or semi-batch extraction systems are more frequently utilized with the hydraulic press (Poku 2002). The fibrous mesocarp is pressed to extract the crude palm oil, leaving behind fiber components containing roughly 5–6% of the oil. The pressure is often decreased, and oil retention rises to 10–12% to prevent the palm kernels' cracking (Corley and Tinker 2003; Obibuzor et al. 2012).

The final press liquor is a blend of various amounts of water, oil, dirt, and fruit fragments. The liquor is further treated to increase oil yield and lower the moisture percentage of the CPO to 10% (Poku 2002). Along with being crucial to the CPO's quality, this process also results in oil loss and environmental contamination. Palm oil mill effluent (POME) is what has left over after the majority of the oil has been extracted. POME can yield more oil when using food-grade solvents for oil extraction, such as hexane and petroleum ether (Obibuzor et al. 2012). Centrifugation and drying are used to purify the CPO stock further. To prevent further deterioration of the oil quality, particularly the FFA concentration, vacuum drying has been recommended. After cooling, the dried oil is poured into storage tanks or other appropriate containers (Bassim et al. 2003; Obibuzor et al. 2012). The viability of using the supercritical carbon dioxide extraction method for the extraction of CPO was reported by Norhuda and Omar in Norhuda and Omar 2009. This is more appropriate when PKO is extracted from crushed kernels. Similar to this, high-capacity mills extract PKO using a solvent extraction technique. Kernel pre-treatment, oil extraction, and solvent recovery from the oil and meal are the three basic unit operations involved. According to Poku (2002) the beginning oil and moisture contents, operation temperature, heating time, and the applied pressure affect the yields and quality of the extracted oil (Fig. 11.4).

11.3.2 Nutritive Component of Palm Oil

11.3.2.1 Sources of Carotenoids and Vitamin

Minor components found in palm oil significantly positively affect nutrition and health. Table 11.2 is a list of the micronutrients. Carotenoids, tocopherols, tocotrienols, sterols, phospholipids, glycerolipids, and squalene are some of these micronutrients (O'Brien (2010). The carotenoids, tocopherols, and tocotrienols operate as biological antioxidants in addition to preserving the stability and quality of palm oil (Wu and Ng 2007). According to Wu et al. (2008), tocopherols and

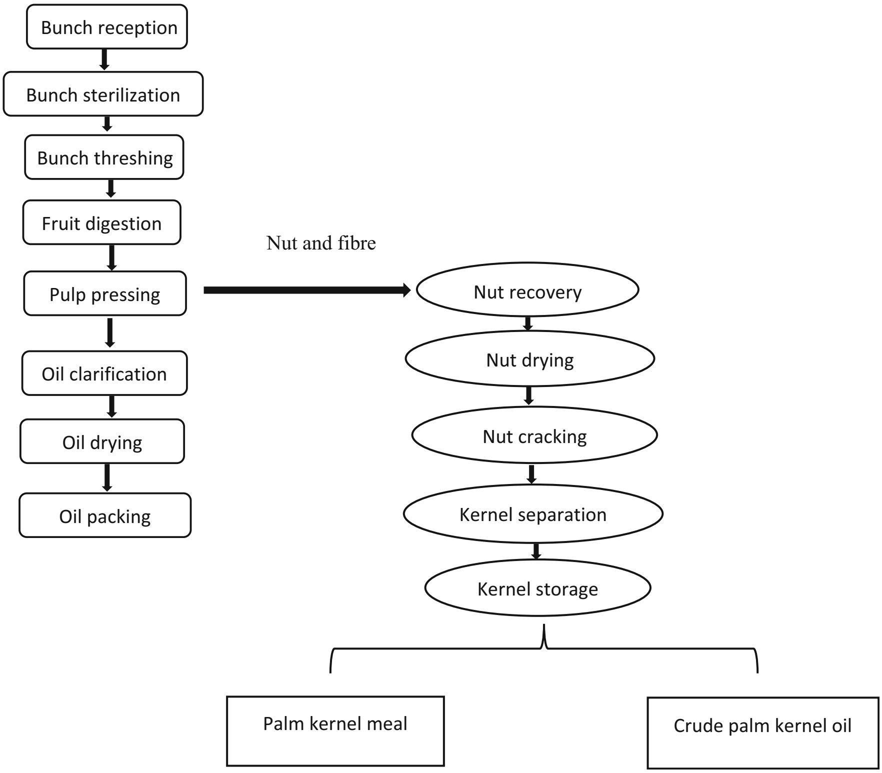

Fig. 11.4 Palm oil processing unit operations. (Source: Koushki et al. 2015)

tocotrienols have anti-cancer, anti-inflammatory, atherosclerosis-controlling, and cholesterol-lowering properties (Das et al. 2007).

The variety of colors found in nature is due to carotenoids. Provitamin A activity has been reported in alpha-, beta-, and cryptoxanthin. The strongest provitamin A carotenoid is beta-carotene. The physiologic processes of cell differentiation, development, and eyesight all require vitamin A (Hof et al. 2000). CPO is the richest natural source of carotenoids since it contains 500–700 ppm of carotenoids. 33%, 65%, and 2% of other carotenoids, such as lycopene and carotene, are found in CPO (Edem et al. 2002). The deep orange-red hue of CPO is a result of the carotenes. Securing free radicals, neutralizing thiyl radicals, chelating peroxy radicals, and quenching singlet oxygen in lipids serve as antioxidants. Carotenoids protect the oil from oxidation by first becoming oxidized themselves before being attacked by oxidants that attack the triacylglycerols (Edem et al. 2002; Gunstone (2011). The use of CPO as a substitute therapy for vitamin A insufficiency has been suggested. The bioavailability of the beta- and gamma-carotene present in CPO is increased by the high digestibility of these compounds (Benadé 2003; Edem et al. 2002).

Lycopene is the pigment that gives fruits and vegetables, including tomatoes, red grapes, watermelon, and pink grapefruit, its red color. Crude oil's deep orange-red

Table 11.2 Micronutrient components of palm oil

Micronutrient/component	Range (ppm)
Carotenoids	
α-Carotene	30.0–35.16
β-Carotene	50.0–56.02
Lycopene	1.0–1.30
Lycopene	500–700
Tocopherol	
α-Tocopherol	129–215
α-Tocopherol	19–32
γ-Tocopherol	19–32
δ-Tocopherol	10–16
Total tocopherol	500–600
Tocotrienols	
α-Tocotrienol	44–73
β-Tocotrienol	44–73
γ-Tocotrienol	262–437
δ-Tocotrienol	70–117
Total tocotrienols	1000–1200
Phytosterols	326–527
Phospholipids	5–130
Squalene	200–500
Ubiquinones	10–80
Aliphatic alcohols	100–200
Triterpene alcohols	40–80
Methyl sterols	40–80
Aliphatic hydrocarbons	50

Source: Mba et al. (2015)

color is from its high carotene content (700–800 ppm) (Sundram et al. 2003). The mechanisms of reactions that the pigment in palm oil goes through inside the plant include antioxidation, photooxidation, and oxidation. Carotene is light and oxygen sensitive. Hydroperoxides produced from lipid oxidation accelerate the oxidation of carotene, causing browning and bleaching (Sambanthamurthi et al. 2000).

Tocopherols and tocotrienols, also known as tocochromanols, are frequently referred to as vitamin E. They can dissolve in fat. The most prevalent form of tocopherol is alpha. The tocopherols and tocotrienols vary depending on the type of vegetable oil and where it comes from (Gunstone 2011). One of the most abundant natural sources of vitamin E is palm oil. Since tocopherols and tocotrienols are both present in palm oil's vitamin E, it is unique. There is 600–1200 ppm of vitamin E in CPO. Tocotrienols make up 78–82%, while tocopherols make up 18–22%. The three main tocotrienols are alpha, beta, and gamma tocotrienols (O'Brien 2010; Ping and May 2000; Zou et al. 2012). Processing and refining CPO causes some vitamin E to be lost. Tocopherols and tocotrienols, which act as antioxidants and free radical quenchers, help keep palm oil stable. Tocopherols can stop lipid oxidation by preventing the chain propagation step's production of peroxide, or they can stop the decomposition process by preventing the production of aldehydes. According to reports, alpha-tocopherol is exceptionally reactive with singlet oxygen and shields the oil from photooxidation (Sundram et al. 2003).

The unsaponifiable fraction of palm oil also contains sterols, higher aliphatic alcohols, and hydrocarbons, which are minor ingredients. Palm oil has very little cholesterol, like all edible oils of vegetable origin. Wax, methyl esters, phytosterols, and ketones are all reduced during refinement (Edem et al. 2002; Sambanthamurthi et al. 2000). Low concentrations of phenolic compounds (100 mg/L) are also present in palm oil. During frying, the phenolic chemicals are to blame for the early darkening of palm oil (Sundram et al. (2003). CPO, palm olein, and their refined derivatives contain a variety of sterols, much like all other vegetable oils. Avenesterols, stigmasterols, campesterols, and sitosterols are among the sterols present in palm oil. Avenesterols have antioxidant properties (Gunstone 2011).

In general, palmitic acid's detrimental effects on health are not demonstrated (Fattore and Fanelli 2013). Palmitic acid is only one of the numerous components of CPO, an intricate alimentary medium. In specific ways, nutritional balance is provided by palm oil's oleic acid content and the presence of several antioxidant chemicals.

11.3.2.2 Source of Fatty Acid

Crude palm oil (CPO) is naturally semi-solid at room temperature due to the almost equal proportion of saturated fatty acids (SFA) and unsaturated fatty acids (UFA). CPO contains much palmitic acid (C16:0), which makes up about 44% of the FAC. Oleic acid (C18:1), linoleic acid (C18:2), and stearic acid (C18:0) are the other three primary fatty acids, making up 40%, 10%, and 5% of the total fat, respectively (Tan and Man 2000). Like other vegetable oils, CPO comprises mixed triacylglycerols (TAGs) and partial acylglycerols such as diacylglycerols (DAGs) and monoacylglycerols as shown in Table 11.3. These fractions include palm olein, palm stearin, and superolein (MAGs). The hydrolysis products of TAGs, known as DAGs and MAGs, can alter the oil's melting point and crystallization behavior (Foster et al. 2009). At concentrations above 10%, partial acylglycerols can produce cloudiness, significantly when temperatures drop below 20 °C (Berger 2007). Table 11.3 displays the fatty acid and glyceride content of palm oil. Its makeup determines the physical and chemical characteristics of the oil. Red palm oil's fatty acid content has been chemically analyzed, and the results show that it comprises roughly 50% saturated fat, 40% monounsaturated fat, and 10% polyunsaturated fat. Palm oil is more stable and less prone to oxidation at high temperatures, while having more saturated fatty acids than soya oil.

Table 11.3 Fatty acid profile of crude palm oil

Compound	Typical	Range
Fatty acid composition (%)		
Lauric acid (C12:0)	0.0	0.1–1.0
Myristic acid (C14:0)	1.1	0.9–1.5
Palmitic acid (C16:0)	44.0	41.8–46.8
Palmitoleic acid (C16:1)	0.1	0.1–0.3
Stearic acid (C18:0)	4.5	4.5–5.1
Oleic acid (C18:1)	39.2	37.3–40.8
Linoleic acid (C18:2)	10.1	9.1–11.0
Linolenic acid (C18:3)	0.4	0.4–0.6
Arachidic acid (C20:0)	0.4	0.2–0.7
Triglyceride composition (%)		
Trisaturated (SSS)	9.8	0.8–9.0
Disaturated (SUS)	48.8	38.5–50.3
Monosaturated (SUU)	36.5	31.8–44.4
Triunsaturated (UUU)	4.8	4.8–9.8
Diglycerides (%)	4.9	3.0–7.6

Source: Mba et al. (2015)

11.4 Uses of Palm Oil

Palm oil, produced from oil palm fruit, has many uses in residential and industrial settings. The debris, which includes palm bunches, trunks, palm fronds, and palm kernel cakes, can be used in home and commercial settings. They make food and non-food products like margarine, shortening, compound cooking fat, soap, detergent manufacture, candles, cosmetics, lubricant grease, confectionery fat, vanaspati (vegetable ghee), and frying fat. In addition to their use in an industry, these oils are also employed locally in antidotes for poisoning, surface protectors for minor wounds, and body treatments and cooking oils (Akpanabiatu et al. 2001).

11.5 Oil Palm Utilization in Aquaculture Nutrition as Fish Oil Replacement

Using palm oil in aquafeeds adds excellent value to the feed produced. It possesses different properties, making it a better oil source concerning its effect on feed quality. Rancidity, the chemical decomposition of fats, oils, and other lipids (this degradation also occurs in mechanical cutting fluids), is a normal phenomenon found in aquafeeds. The level of feed rancidity in aquafeeds made of palm oil is substantially lower in aquafeeds made of palm oil than in other vegetables. This is an advantage of the use of palm oil in aquafeeds over the use of other oils with fish oil inclusive. This is because palm oil contains vitamin E and carotenoids, potent antioxidants in the natural states, and protective values against rancidity.

11.5.1 Effects on Growth Performances and Feed Utilization

Growing performance is one factor that can be used to determine if a particular nutrient or nutrient formulation impacts aquatic animals, such as fish or crustaceans. However, the development of fish is influenced by a variety of favorable and unfavorable influences. According to studies, the quantity and quality of feed play a significant role in how fish species grow. Numerous research has documented the positive effects of palm oil as a good substitute for various fish species.

The findings demonstrated that growth and feed utilization were not compromised when palm oil (PO) was used in place of fish oil (FO) either partially or totally in Nile tilapia (Christain et al. 2018). Weight gain and specific growth rate (SGR) were significantly lower in fish fed 8PO and 10PO diets. The increase in PO levels did not affect fish survival, feed intake, and feed conversion ratio in Juvenile Chu's Croaker, *Nibea coibor* (Huang et al. 2016). Fish fed the diet with 100% PO showed significantly lower growth performance with higher FER and FCR content than those in the control group in large yellow croaker (*Larimichthys crocea*) (Li et al. 2019). Five isonitrogenous diets containing 32% crude protein and increasing amounts of palm oil, 2%, 4%, 6%, and 8% and control (FO) were employed as the primary lipid sources. The findings revealed that at 6% dietary palm oil levels, the animals gained the most weight, had the highest specific growth rate, and had the highest protein efficiency ratio. However, compared to the control group, the feed conversion ratio (FCR) exhibited a reverse pattern (Ayisi et al. 2017). A different study on Japanese catfish found that although there was no discernible difference in the fish's final weight, fish fed with diet PO had numerically higher total weight gain and specific growth rate, as well as higher feed consumption than fish fed with the control diet. While feed efficiency, protein efficiency ratio, apparent protein retention, and apparent lipid retention were comparable across all fish groups. Throughout the 8-week feeding trial, there was no mortality in the diet PO group, and survival rates were reasonable, with at least 96% (Asdari et al. 2014).

Fish fed a 50% PO diet had final weights (FW) and weight gains (WG) that were considerably higher than those of fish fed a 25% PO diet but not significantly higher than those of the control, 75% PO, and 100% PO groups. There was no discernible difference between the groups regarding the condition factor and specific growth rate (SGR). Additionally, in Nile tilapia, feed intake and conversion ratio were comparable across all groups (Ayisi et al. 2017). The growth performance of fish given the crude palmoil (CPO) and palm fatty acid distillate (PFAD) dietary treatments was observed, and both were significantly better than the control (FO). Additionally, feed intake was comparable between the CPO and PFAD treatments and much higher than in the FO treatment. However, it was shown that FCR in the PFAD was superior to that in the other two treatments (Aliyu-Paiko and Hashim 2012). Following 13 weeks of feeding, dietary CPO in rainbow trout had no impact on growth performance or feed efficiency (Fonseca-Madrigal et al. 2015). Fish fed with 10F0P and 8F2P showed no discernible variations in SGR, but both treatments had SGR much higher than 4F6P. Red Sea Bream *Pagrus major* fed 6F4P and 4F6P, after 50 days of feeding, showed significantly lower FI compared to diet groups 10F0P and 8F2P (Komilus et al. 2008). While replacing fish oil with palm oil up to 25%, *C. mrigala* growth performance and survival were unaffected. However, inclusion rates above this threshold significantly slowed the fish's growth. Though, at all levels of dietary PO inclusion, no appreciable improvements in feed efficiency were seen (Singh et al. 2012).

Except for TL and FC, including 3 and 6% of palm oil in the diet resulted in better results than the diet containing only soybean oil. Diets containing 3, 4.5, and 6% of palm oil increased total fish length, while for CF, higher results were observed compared to the control diet for fish fed with a diet containing 100% palm oil in Nile tilapia (*Oreochromis niloticus*) post-larvae (de Souza Alves et al. 2021). FBW, WG, and SGR values were considerably more significant in crabs fed the FO diet than those provided the PO and PO + VA diets. Compared to crabs fed a PO diet alone, adding vitamin A to the diet increased crabs' FBW, WG, and SGR (Huang et al. 2022). African catfish's growth performance significantly improved in response to palm oil additions of up to 8%, while higher levels of palm oil supplementation in the diet had no further effect on growth. RBDPO or CPO was included at the same inclusion level in the diets of African catfish, and neither significantly affected growth or protein utilization efficiency. Compared to catfish fed diets with 4% RBDPO or the control diet, nitrogen retention was considerably higher in catfish fed diets with 8%, 12%, or 16% deodorized palm olein (RBDPO) (Lim et al. 2001). African catfish grew noticeably more when fed a diet containing 25% PFAD than fish fed a control diet with fish oil as the only lipid source. Catfish growth performance did not further increase with higher dietary PFAD supplementation doses (Ng et al. 2003).

Nevertheless, mRNA expression of Capn-3 of fish fed 75% PO was significantly higher than those fed 0% PO, 25% PO, and 100% PO. Also, fish fed 25% PO downregulated Pax-7 mRNA expression, significantly lower than all other groups and the FO group. However, no noticeable differences were observed in the mRNA expression of Psma-5, MyoG, MyoD, IGf-I, IGF-II, and GH (Ayisi et al. 2019).

11.5.2 Effects on Fatty Acid Composition

The body needs triglycerides, a lipid, to store energy, and fatty acids are one of their primary components. A lipid, in the simplest terms, is a type of molecule that includes fatty acids (Lupiañez-Perez et al. 2015). Omega-6 fatty acids linoleic acid and alpha-linolenic acid are complex for many animals to synthesize (an omega-3 fatty acid). On the other hand, those fatty acids are required for cellular processes and synthesizing more critical omega-3 and omega-6 fatty acids. However, studies have shown that palm oil could replace FO without adverse effects on fatty acid profile. For example, in tilapia, after 20 days of feeding, palm oil had considerably higher levels of saturated and monounsaturated fatty acids, but lower levels of polyunsaturated fatty acids (PUFA) than fish fed the FO diet. However, those fed the FO diet had much higher quantities of EPA (eicosapentaenoic acid) and DHA (docosahexaenoic acid) than the PO group. In an 8-week feeding trial, Ng et al. (2001) found that fish fed diets based on palm oil had considerably lower amounts of polyunsaturated fatty acids (PUFA) than those fed the CLO diet. However, their levels of saturated fatty acids did not change. Dietary PUFA concentrations significantly impacted the levels of each PUFA in muscle lipids.

After 8 weeks of feeding, (Asdari et al. 2014) discovered that Japanese Catfish *Silurus asotus* Juveniles fed on PO and MCT diets had significantly greater total levels of saturated and monounsaturated fatty acids in their muscles, notably oleic acid, than fish fed on FO diets, while the inverse was true for total n-3 fatty acids. Additionally, fish fed a PO, and MCT diet had lower n-3/n-6 ratios and total polyunsaturated fatty acid levels than fish fed a control diet. Finally, fish fed the FO diet also had the muscle's highest levels of total n-3 fatty acids. These levels were primarily made up of DHA, with fish on the PO and MCT diets having significantly lower levels of EPA. Similarly, fish treated with crude palm oil (CPO) and palm fatty acid distillate (PFAD) had considerably higher muscle SFA content than fish in control, although muscle MUFA level showed the reverse tendency. Compared to the control diet, fish given the CPO and PFAD diet had considerably lower levels of n-3 PUFA and higher levels of n-6 PUFA in their muscle Channa striatus (Aliyu-Paiko and Hashim 2012).

Additionally, differing quantities of palm oil significantly impacted the total saturates, total n-3 polyunsaturated fatty acids (PUFA), total n-6 PUFA, and DHA/EPA in muscle in Nile tilapia. Docosahexaenoic acid (DHA) levels in the fish fed the 6% palm oil level were the highest and were substantially higher than those in the control group (Ayisiet al. 2017). Liver 18:2n-6, SFAs, MUFAs, SFAs/PUFAs, and n-6 were markedly elevated when PO was substituted for FO. Conversely, PUFAs, n-3: n-6 and n-3 were dramatically reduced with increasing PO levels. These were 20:4n-6, 20:5n-3, and 22:6n-3. Additionally, Nile tilapia liver lipid rose along with dietary PO inclusion levels (Ayisi et al. 2018). Another study also shows that 18:3n-3 (LNA) and 20:4n-3 considerably rose with increasing PO inclusion levels in Nile tilapia, but 20:5n-3 (EPA), 20:4n-6 (ARA), and 22:6n-3 (DHA) dramatically reduced with increasing PO inclusion levels. Additionally, as PO inclusion levels rose compared to the control, n-3 PUFA declined while total saturated fatty acid (SFA) increased (Ayisi et al. 2019).

According to a two-week study by Christain et al. (2018) in Oreochromis niloticus, liver total saturated fatty acids (SFA), monounsaturated fatty acids (MUFA), and 18:2n-6 (LA) increased as PO inclusion levels increased. In contrast, EPA, DHA, and total polyunsaturated fatty acids (PUFA) decreased as PO inclusion levels increased. As opposed to the control, increasing PO levels in the muscle led to an increase in EPA, DHA, total n-3 PUFA, total PUFA, n-3: n-6 ratio, and 20:2n-6. After 56 days of feeding, replacing FO with PO in *Nibea coibor* led to higher levels of saturates and monoene like 16:0, 18:1n-9, 18:2n-6, and C18:3n-3 but lower levels of n-3 HUFA like 20:5n-3, 20:5n-3, 22:6n-3, and n-3/n-6 FA ratio (Huang et al. 2016). The ratios of 18:1n-9 and 18:2n-6 increased with increasing CPO content, while the ratios of n-3HUFA, 20:5n-3, and 22:6n-3 decreased. However, the pyloric ceca and muscle exhibited higher levels of palmitic acid (16:0) but not the liver. Compared to the control, the capacity of HUFA synthesis from 18:3n-3 in the hepatocytes and enterocytes of rainbow trout rose three times when dietary CPO was gradually increased (Fonseca-Madrigal et al. 2015). The amounts of EPA and DHA in the dorsal and ventral muscles both decreased steadily as the amount of dietary palm oil rose. Red sea bream showed no symptoms of EFA shortage throughout the trial, but there was a similar gradient decline in the n-3/n-6 ratio in both the dorsal and ventral muscles compared to the control (Komilus et al. 2008). Concentrations of monounsaturated, polyunsaturated, and saturated fatty acids in palm oil were observed, and the most prominent fatty acids were palmitic (C16: 0), oleic (C18: 1n-7), and linoleic acid (C18: 2n-6) as compared to the control (Alves et al. 2021).

Crabs fed diets of PO and PO + VA showed lower ΣSFA content and SFA, including C14:0, C16:0, C18:0, C20:0, and C22:0, compared to those fed FO and decreased the C12:0 and C16:0) content in hepatopancreas compared to those fed PO diet alone. C14:1n-9, C18:1n-7, C18:1n-9, and C20:1n-9 in the hepatopancreas of crabs fed PO and PO + VA were significantly lower than those fed a diet of FO. Crabs fed diets of PO showed higher C18:1n- 9 content in hepatopancreas than those fed FO, whereas crabs fed PO + VA showed decreased C18:1n-9 content in hepatopancreas. ΣMUFA in the hepatopancreas of crabs fed PO and PO + VA diet was significantly higher than those fed FO, but the opposite was found in Σn-6 PUFA and C18:2n-6 levels in hepatopancreas but showed lower levels of Σn-3 PUFA, C20:4n-6, C20:5n-3, C22:5n-3, and C22:6n-3 in hepatopancreas than that fed FO diet (Huang et al. 2022). PO inclusion showed that the concentrations of 16: 0, 18:1(n-9), 18:2(n-6), total saturated fatty acids, and total monoenoic fatty acids increased linearly with increasing dietary PO. The concentration of eicosapentaenoic acid [20:5(n-3)] was reduced significantly with increasing levels of dietary PO, but the concentration of docosahexaenoic acid [22:6(n-3)] was significantly reduced only in fish fed 100% PO, compared with the other three treatments in Atlantic Salmon (*Salmo salar*) (Bell et al. 2002).

11.5.3 Effects on Hematological Profile

The physiological status and health of fish cultivation can be determined by its hematological profile, so hematology, in conjunction with other standard diagnostic techniques, could be used to identify the effect of dietary nutrition formulation, evaluate stress-causing conditions and/or diseases that have an impact on production performance (Tavares-Dias and Moraes 2006). Based on its nutritional value, palm oil is added to animal feed to replace expensive fish oil and enhance physiological and health-related aspects of animal production. For instance, the highest total serum protein level was seen in fish given 20% palm oil, which was significantly higher than fish fed 60% palm oil, the control, and 40% palm oil. Red blood cells (RBC), hematocrit (Hct), and total bilirubin did not substantially differ across groups. Fish fed with 60% palm oil had the lowest RBC levels compared to the control group (Han et al. 2015). According to the results, glucose, hemoglobin, and red blood cells were all significantly influenced by OF level, whereas Glu and RBC were influenced considerably by factor PO. Despite their interaction, OF and P had no significant impact on the serum level of GOT (glutamic oxaloacetic transaminase). The treatment with the highest RBC was 6F4P, which had a much greater RBC than the oxidized groups (Han et al. 2012). Compared to fish given FO, those fed PO and LO showed a substantial rise in blood levels of TG, NEFA, TNF, ALT, and AST activity. However, there was no discernible difference in the concentration of IL6 in fish serum between treatments (Mu et al. 2019). Elevated dietary PO significantly impacted triglycerides, cholesterol, and total protein levels. The fish fed 8% PO had the most significant mean cholesterol concentrations. At the same time, total protein and triglycerides rose with increasing dietary PO and were considerably higher than those in the control group (Ayisi et al. 2017). Additionally, the plasma levels of the enzymes alanine transaminase (ALT) and aspartate aminotransferase (AST) were also significantly higher in fish fed a meal containing 100% PO than in the control group (Li et al. 2019). Moreover, 8 weeks of feeding by Christain et al. (2018) revealed that Oreochromis niloticus groups fed larger amounts of PO had significantly higher levels of AST, total protein, triacylglycerol (TAG), and low-density lipoprotein cholesterol (LDL-C) than the control group.

11.5.4 Effects on Body Composition

The proximate composition of fish includes the determination of moisture, protein, fat, and ash contents, which constitute about 96–98% of the total constituents of the fish body. Studying these components gives us a clear understanding of assessing the energy value of the fish. The chemical composition of fish flesh is regarded as a reliable predictor of the fish's quality, nutritional value, physiological state, and habitat (Ravichandran et al. 2011). Nowadays, appropriate knowledge about the proximate composition of fish is increasingly finding application in various profound areas. Knowing the chemical composition of fish help nutritionists determine readily available sources of high-protein, low-fat food sources for human food (Foran et al. 2005; Mozaffarian and Rimm 2006).

There were no apparent differences between the groups regarding fish body moisture, crude lipid, ash, or crude protein. Despite this, juvenile Japanese flounders fed the control diet had a slightly greater crude protein content than those feed with different levels of PO (Han et al. 2015). The crude protein of the fish's entire body was significantly impacted by both OF (oxidized fish oil) and P (palm oil), and interactions between the two diets were significant compared to the control. However, crude protein (CP) in the group fed the 10F diet was significantly higher than in oxidized groups (10OF, 6OF4P, and 4OF6P), as well as in the 10P and 4F6P, which were regarded as high substitutions of palm oil (Han et al. 2012). According to Bahurmiz and Ng et al. (2007), there was no discernible impact of the dietary lipid source on the moisture, protein, or ash content of tilapia fillets after 20 weeks of the diet. However, tilapia fed the PFAD diet exhibited statistically lower fillet lipid content than fish fed the CPO or RBDPO diets when compared to control FOs. In comparison to SFO, the CPKO and CLO diets did not significantly differ in terms of whole-body lipid levels after 8 weeks of feeding hybrid tilapia, according to (Ng et al. 2001); however, fish fed the SFO diet had significantly more total muscle lipid than fish fed the CLO-based diets. However, fish fed the CPO and CPKO diets exhibited significantly higher bone ash than fish fed the SFO diet.

During an 8-week feeding trial, it was discovered that the amount of dietary palm oil had a significant impact on the lipid, moisture, ash, and crude protein contents of the fish's muscle, liver, and entire body, with the highest level being obtained at 6–8% in comparison to those fed a control diet (Ayisi et al. 2017). The total body's protein and moisture contents did not significantly alter across dietary regimens. The liver's lipid content increased more with increasing dietary PO than in the control group. However, there were no appreciable differences between the large yellow croaker (*Larimichthys crocea*) fed diets with graduated levels of PO and the control in terms of the moisture content of the liver, the moisture, and lipid contents of muscle (Li et al. 2019). Whole-body lipid deposition in fish fed diet 4F6P was significantly lower than in other dietary groups.

On the other hand, the dorsal lipid contents gradually decreased with increased palm oil levels but there was no significant difference in ventral muscle in red sea bream compared to FO (Komilus et al. 2008). Additionally, due to PO substitution, *Cirrhinus mrigala's* muscle proximate composition did not change dramatically (Singh et al. 2012). However, fish fed 25% PO had a much lower protein content than fish fed 100% PO than FO. In Japanese Catfish *Silurus asotus* Juveniles, there was no appreciable variation in the whole-body moisture, protein, lipid, and proximate ash composition between treatments as compared to the control (Asdari et al. 2014). Fish fed diet 4F6P deposited considerably less total body lipids contents than fish fed other diets. Another study reported that the red sea bream's dorsal lipid levels steadily reduced as the amount of palm oil increased, but there was no discernible variation in the ventral muscle (Komilus et al. 2008). The amounts of dietary palm oil had a substantial impact on the composition of the body's macrominerals, which are calcium (Ca), potassium (K), sodium (Na), phosphorus (P), and magnesium (Mg). Iron (Fe), zinc (Zn), manganese (Mn), and copper (Cu) had similar trends in whole-body micromineral composition when compared to controls in the African Catfish, *Heterobranchus longifilis* (Ble et al. 2018). Compared to crabs fed a diet of FO, those fed diets of PO and PO + VA showed a significant reduction in crude protein and increased total lipid content throughout the body (Huang et al. 2022). The different diets unaffected the moisture and ash content of the crabs. However, when fish were fed with increasing amounts of dietary palm oil compared to the control, the content of lipids whole body and muscles increased (Lim et al. 2001).

Following a 56-day feeding with groupers (*Epinephelus coioides*), noted that the whole-body crude protein content increased in dietary FO replacing level; however, it did not influence the whole-body moisture, crude lipid, and ash content as compared to PO group. Additionally, the incremental dietary PO inclusion levels did not affect the muscles' lipid, protein, or moisture contents. In contrast, the hepatic lipid and moisture contents tended to increase with increasing dietary PO inclusion levels. Hepatic moisture and lipid levels were considerably lower in diets with 75% or more PO substitution than in the control diet. Another study also reported that Africa catfish fed the CLO, CPO, CPKO and CLO + PFAD diets, CLO + SBC diet, and fish fed the RBDPO diet had the lowest quantities of alpha-tocopherol as compared to the highest concentrations in the muscle of fish fed the SFO diet (Ng et al. 2003). After 8 weeks of feeding, Nile tilapia (*Oreochromis niloticus*) fed on CPO displayed the most outstanding level of total carotenes compared to those in control (Wickramanayake et al. 2021). In response to rising dietary levels of alpha-tocopherol derived from RBDPO and CPO, alpha-tocopherol concentrations in muscle and liver tissues increased linearly. At all inclusion levels, African catfish, *Clarias gariepinus*, fed CPO-supplemented meals had approximately three- and five-times higher amounts of alpha-tocopherol in their muscle and liver tissues, respectively, than fish fed RBDPO-supplemented diets as compared to FO (Lim et al. 2001).

11.5.5 Effects on Biological Indices

Fish stocks have been identified using morphological features and biometrical traits, such as morphometric measurement and meristic count. These techniques continue to be the easiest and most accurate ways to identify different species (Turan 2004). In phylogenetics, the analysis of variations and differences in the morphometric and meristic traits of fish populations is crucial because it yields data for further research on the genetic improvement of stocks.

Compared to fish fed the FO diet, the GSI for both male and female tilapia exhibited greater values in fish fed the palm oil-based diets, particularly the CPO diet, than those offer the control diet (Bahurmiz and Ng 2007). Fish fed the CPKO and CLO + PFAD diets had considerably higher HSI scores than fish fed the SFO diet, whereas fish fed the SFO and CLO + SBC diets had significantly lower VSI scores than fish fed the CLO and CPO diet (Ng et al. 2003). The HSI and VSI values for each treatment did not differ. For the same reason, CY did not differ substantially differ between the control and the other two treatments in snakehead (*Channa striatus*, Bloch 1793) fingerlings (Aliyu-Paiko and Hashim 2012). A similar result was also observed in large yellow croaker (*Larimichthys crocea*) (Li et al. 2019) and in Japanese Catfish *Silurus asotus* Juveniles fed a palm oil diet (Asdari et al. 2014). Also, after 8 weeks of feeding, there was no difference between the different groups in the protease activity of the anterior, middle, and posterior intestines (AI, MI, and PI) compared to those fed FO in Nile tilapia. However, there was a trend of increasing lipase activity along with increasing PO levels, with 50% PO recording the highest amylase activity in AI, MI, and DI (Christain et al. 2018).

11.5.6 Effects on Lipid-Related Genes Expression

Crabs fed a PO diet had higher DGAT1 gene expression in the hepatopancreas than crabs fed a FO diet. In contrast, crabs fed diet PO + VA had lower levels of DGAT1 mRNA in the hepatopancreas than crabs fed diet PO. However, the mRNA levels of CPT1a, CPT1B, CAAT, and CPT2 in the hepatopancreas of crabs fed FO were the lowest, whereas the opposite was found in PO diet. Additionally, CPT1a, CPT1B, CAAT, and CPT2 gene expressions were higher in crabs given a PO + VA diet than in crabs on a PO diet alone (Huang et al. 2022). In grouper, the mRNA levels of the FAS, G6PD, LPL, PPARA, and D6FAD genes in the liver showed positive linear and/or quadratic responses, whereas the SCD, HSL, ATGL, FABP, SREBP-1C, and ELOVL5 genes displayed an opposite trend with increasing dietary PO inclusion levels, as compared to FO group. Another study also reported that, except LXR and ELOVL 5, the expression levels of PPAR-α, PPAR-β, ME, LPL, and G6PD genes increased as dietary PO inclusion levels increased. Expression levels of PPAR-α, ME, G6PD, LXR, and LPL were influenced significantly with dietary PO inclusion in *Oreochromis niloticus* as compared to those fed FO diet (Ayisi et al. 2018).

11.5.7 Effects on Antioxidant Capacity

When RO generation exceeds the available antioxidant system, oxidative stress occurs (Adly 2010). The expression of antioxidant enzymes is suppressed by oxidative stress (Wiernsperger 2003). The best natural source of carotenoids is present in crude palm oil (about 15 times more than carrots), which significantly protects cells and tissues from the detrimental effect of free radicals by acting as biological antioxidants. When a higher lipid diet is consumed, a buildup of free radicals is associated with degenerative diseases such as steatosis in fish species (Abasubong et al. 2017). Therefore, it is essential to administer a diet high in antioxidants that can hinder the occurrence of free radicals. Red palm oil is processed palm oil that has been deodorized and acidified and it retains 80% of the natural carotenoids, making it an excellent source of vitamin A. These organic antioxidants are thought to prevent cellular deterioration by acting as free radical buffers and protective barriers.

It has also been demonstrated that consuming PO helps to improve antioxidant status by raising levels of antioxidant enzymes (Ayeleso et al. 2014). However, the liver anti-oxidative enzyme activity in Japanese flounder fed experimental diets for 60 days reveals that the anti-oxidative enzyme activity of fish fed diets containing palm oil was lower than that of the control group. The differences between these two groups were insignificant, despite the control group having the most outstanding levels of SOD and CAT (Han et al. 2015). Compared to fish given FO, fish fed PO and LO was reduced in T-AOC content of the liver, but did not significantly differ from fish fed FO. However, fish fed LO showed significantly greater liver MDA levels than fish fed FO or PO, whereas fish fed PO had significantly lower values than the FO group in giant yellow croaker *Larimichthys crocea* (Mu et al. 2019). According to Li et al. (2019) research, fish fed diets containing 100% PO had significantly lower plasma levels of total antioxidant capacity (T-AOC) and catalase activity (CAT) than fish fed diets containing up to 66.7% PO in large yellow croaker. However, these differences were not statistically significant compared to the control (*Larimichthys crocea*). There were no appreciable variations in the CAT, SOD, or LYZ treatments. However, serum malondialdehyde (MDA) was significantly lower in fish fed 100% PO compared to all other groups, whereas total antioxidant capacity (TAC) was significantly higher in fish fed FO diet compared to all other groups. Nevertheless, Nile tilapia fed FO, 25% PO, and 50% PO exhibited considerably greater glutathione reductase (GR) levels than fish fed 75% and 100% PO (Christain et al. 2018). Another study shows that, fish fed a 10PO diet had considerably higher SOD and CAT activity than fish fed a FO diet, whereas Fish fed 2PO, 4PO, 6PO, and 8PO diets did not significantly differ in SOD and CAT activities in juvenile Chu's Croaker, *Nibea coibor* (Huang et al. 2016). The MDA concentration, SOD and GPx activity in the hepatopancreas of crabs given FO were considerably higher than those fed PO. However, compared to crabs fed PO alone, those given vitamin (VA addition) in PO dramatically boosted the activities of SOD and GPx and decreased the MDA content in the crabs' hepatopancreas. Different diets did not affect T-AOC in the hepatopancreas, whereas crabs fed PO displayed a lower value than those fed FO. Compared to crabs fed PO alone, VA added to the PO increased the T-AOC level in the crabs' hepatopancreas (Huang et al. 2022).

11.5.8 Effects on Inflammatory and Immune Response

Inflammation is crucial in the body's reaction to tissue damage and pathogen invasion. The process begins quickly and subsides when the infections are eliminated, restoring the tissue damage. Numerous different molecules act as mediators and controllers of immunological and inflammatory responses. Proteins, pro-inflammatory cytokines like tumor necrosis factor (TNF) and interleukin (L)-1 and -6, membrane phospholipid derivatives like diacylglycerol and ceramide, eicosanoids like prostaglandins (PG) and leukotrienes (LT), and other molecules like CAMP, inositol phosphates, and reactive oxygen species are among these molecules (Abasubong et al. 2022). The immune system primarily produces pro-inflammatory cytokines, but endothelial cells and fibroblasts can also produce them. On a biological level, TNF is a catalyst that starts a cascade of cytokine synthesis. The molecule is rapidly released in response to inflammatory and infectious stimuli and encourages the production of numerous other cytokines, such as IL-1 and IL-6, with many shared functions (Akira et al. 1990). In an animal model, iNOS, nitric oxide, cytokines (IL-4, IL-8, and TNF-), COX-1, COX-2, NF-kB, and prostaglandin E2 were evaluated as indicators of inflammation. TRF dramatically decreased the production of pro-inflammatory cytokines and inhibited the release of prostaglandin and nitric oxide, making it effective against inflammatory responses in a dose-dependent manner. TRF suppressed the expression of NF-kB and stopped the induction of iNOS and COX-2 at higher concentrations.

In the liver of the large yellow croaker *Larimichthys crocea*, dietary palm oils significantly reduced expressions of arginase I and interleukin 10, and elevated expressions of tumor necrosis factor, interleukin 1, toll-like receptor 22, and myeloid differentiation factor 88 (Mu et al. 2019). Large yellow croakers fed the 100% PO diet had the most significant levels of IFN, IL-1, and TNF mRNA expression compared to those fed other diets. Compared to the control, fish fed a diet containing 100% PO had the lowest mRNA levels of all dietary treatments in large yellow croakers (*Larimichthys crocea*), which exhibited a negative trend for IL-10 mRNA expression (Li et al. 2019). The mRNA level of the Keap1 gene was considerably higher in crabs fed the PO diet compared to crabs fed the FO diet, whereas crabs fed the PO + VA (palm oil with an addition of vitamin) diet had lower levels of Keap1 mRNA than crabs fed the PO diet. Compared to crabs fed the FO diet, crabs on the PO diet had lower levels of LZM and proPO gene expression. However, in the hepatopancreas of crabs fed the PO diet compared to those on the FO diet, there was a significantly greater gene expression level of ADAM17, LITAF, IL-16, MyD88, Toll2, and Relish, while MyD88, Toll2, and Relish gene expression was reduced in crabs fed a PO + VA diet compared to those on a PO diet. (Huang et al. 2022).

11.6 Conclusion

In conclusion, our research shows that palm oil is a better option than other vegetable and fish oil in terms of availability, affordability, and sustainability. Furthermore, it can be concluded that palm oil can partially or entirely replace fish oil in aquafeeds without harming growth, feed utilization, body and fatty acid composition, antioxidant, and immunological response. Due to the abundance of palm oil in developing nations compared to the scarcity and high cost of fish oil, we advise using palm oil instead of fish oil to reduce the cost of feeding fish species that might be sustainable.

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Chapter 12
A Dynamic Study of the influence of *Jatropha curcas* on Growth and Haematological Indices in Finfish

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Abstract *Jatropha curcas* is a multipurpose tree that has the potential to be a biodiesel alternative. Although the jatropha plant is grown worldwide, it is most commonly found in Central and South America, Africa, and South Asia. The Jatropha plant produces various valuable products, the most notable of which is the oil-producing seed. Its components can also be used to produce human food, animal feed, fertiliser, fuel, and traditional medicine. The seed cake of Jatropha curcas is a low-value byproduct of biodiesel production. The seed cake is high in protein, but it also contains trypsin inhibitors, phytic acid, lectin, and saponin, as well as phorbol esters, a poisonous substance. Before the seed cake can be used as aquafeed, various detoxification techniques must be used. This chapter discussed the chemical composition of this plant, antinutrient components, the detoxification process, and its applications in aquafeed. The Jatropha plant can produce goods for various purposes other than serving as a dietary alternative to fishmeal, which should be investigated and improved. Finally, we believe that the use of Jatropha in

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aquafeeds should be encouraged, and more research into its effects on non-specific immunity and the expression of genes involved in growth, stress, and apoptosis in aquatic species should be conducted.

Keywords Aquaculture, *Jatropha curcas* · Protein isolate · Functional properties · Anti-nutritional factors

12.1 Introduction

As we near the middle of the twenty-first century, the supply of high-quality, nutrient-rich food confronts vast challenges due to the growing human population; by 2050, there will be 9.7 billion people on the earth, needing a 25–70% increase in food production (Hunter et al. 2017). In addition, competing interests exist for agriculturally based input commodities, and the basis of natural resources is depleting (Benton et al. 2018). Although the livestock and food industries are increasing production to meet demand, this poses serious problems such as overgrazing, water scarcity, and the loss of natural biodiversity (Benton et al. 2018; Rivera-Ferre et al. 2016; Michalk et al. 2019). It is now acknowledged that raising aquatic species for food (also known as aquaculture) would contribute significantly more to the world's budget for animal-derived protein. According to annual growth rates over the past three decades, aquaculture has been the fastest-growing food production sector, with annualised growth rates of 10% in the 1990s and 5.8% yearly between 2000 and 2016 (FAO 2018).

Aquaculture is now one of the world's fastest-growing agriculture sectors, thanks to recent advancements in its growth and development (FAO 2018). Due to the nutritious value of fish, demand has rapidly increased without a matching increase in output (Gogoi et al. 2015), resulting in a supply deficit. Farmers are urged to wake up to prevent the impending inadequate protein intake due to this severe supply shortage in a growing world population. In addition, it has been shown that fish feed costs between 60 and 70 percent of the overall recurring production costs (Tacon and Jackson 1985; Tacon 1994), essentially preventing fish producers from making a profit. This is a result of the limited availability of conventional fish feed and the high cost of the components due to its competition with people and businesses.

The lack of ingredients like fish meal, fish oil, and soybean meal is the main factor raising the price of aquafeed. The contribution of those substances to sustainable aqua-feed production may also be impacted by increased human demand for the nutrients they provide. Therefore, there is grave concern regarding the long-term availability of these feed ingredients for aqua-feed production (Cruz-Saurez et al. 2007; Cho 2010; Dedeke et al. 2013). Hence, finding a different protein source is crucial if we develop affordable feed ingredients for small- and medium-sized fish farmers based on sustainable and renewable feed resources (Agbebi et al. 2009; Barnes et al. 2012). It is also necessary to consider whether the selected feed ingredients conflict with concerns for human food security.

One of the most researched plants protein sources is soybean meal (SBM), which is a good component for aquafeed production (Kaushik et al. 1995). However, soybean meal prices have risen because of competition with human food and rising demand in other feed industries (FAO 2006). Also, Ray et al. (2013) reported that the yield trends of most crops, like rice, soybean, groundnut, etc., are insufficient to meet the human requirement in the coming years. Hence, exploring an alternative, less expensive, non-edible ingredient is imperative to satisfy the aquaculture requirement. Various studies have used different plants and their products, such as extracts, oils, and powders, as feed supplements in other animal species (Roy et al. 2014; Abd El-Hack et al. 2016). The global oil industry is now attempting to utilise non-edible seeds like rubber seeds, neem seeds, *pongamia, karanja, mahua, Jatropha* etc., for biodiesel production as there is debate on utilizing edible seeds for the same (Butler 2006; Meher et al. 2006).

A promising candidate for this industry is *Jatropha curcas*, a drought-resistant tropical shrub Jatropha (*Jatropha curcas*) is one seed that may have the potential for both nutritional and medicinal uses. Utilising non-conventional feedstuffs, such as jatropha seed meal, would help decrease the cost of feeds with a subsequent reduction in the cost of production. Jatropha belongs to the *Euphorbiaceae* family (Saetae and Suntornsuk 2010; Barros et al. 2015) and is cultivated primarily for biofuel production. The meal is a by-product of biofuel processing, with each ton of Jatropha's seed producing about 200–300 L of biofuel and 700–800 kg of the meal (Brodjonegoro et al. 2005). In addition, Jatropha is being sold in aqueous extracts or tincture forms for various health applications. The use of raw JM in animal nutrition has problems with anti-nutritional factors, including lectin, tannin, saponin, phytate, phorbol esters and trypsin inhibitors (Makkar and Becker 1999). These components can be removed or negated by either physical or chemical methods (Belewu and Sam 2010). Therefore, in this chapter, we reviewed the use of Jatropha in aquafeeds, considering its anti-nutritional factors, detoxification, and uses. Also, its dynamic study on growth and haematological indices in finfish were discussed.

12.2 *Jatropha* as a Plant

Jatropha is a gregarious shrub with a height of approximately 1.8 m that is a common weed of field crops and a member of the *Euphorbiaceae* family. It is typically grown in West African rainforests with high rainfall. Jatropha is well-known for its therapeutic uses, including as a purgative and laxative. It is a little perennial tree that can grow for another 40–50 years, depending on the soil and habitat (Foidl et al. 1996; Openshaw 2000). The plant begins flowering in about 6–30 months and takes 4–5 years or longer to reach the complete fruit-bearing stage (Islam et al. 2010a, b). Jatropha has robust branches, smooth, gray-colored bark, and thick, soft pale green leaves. Typically, seeds produce one tap root with four lateral roots, while cuts do not produce tap roots (Islam et al. 2010a, b). Jatropha seeds are dark in colour and weigh 50–75 g per 100 (Islam 2011). Although it can grow at higher altitudes and withstand moderate frost, it is mostly found at altitudes between 0 and 500 m, where average yearly temperatures are at least 20 °C. Extreme settings are places where it cannot grow. Jatropha is prompted to flower and produces fruit when the weather is more relaxed and it is raining.

Jatropha may be grown as a fuel crop in more than 80 countries globally, with 17 Asian nations. In regions with 250 to over 1200 mm of annual rainfall, Jatropha can be planted on farms as a cash crop or as a hedge to guard fields (Katwal and Soni 2003). It may quickly grow on soil with appropriate aeration and drainage systems but cannot grow in locations with harsh conditions (Islam et al. 2010a). Additionally, it may thrive on degraded fields and is well suited to marginal soils. Additionally, it may thrive on degraded fields and is well suited to marginal soils. Although it can grow at higher altitudes and withstand moderate frost, it is mostly found at altitudes between 0 and 500 m, where average yearly temperatures are at least 20 °C. Like the cassava plant, jatrophas are perennial shrubs or trees that can withstand drought and serve various purposes (Elbehri et al. 2013). The leaves of the deciduous jatropha tree fall off during the dry season. The lateral roots stop soil erosion, and the taproot holds the plant in the ground, securing the ground against landslides. The trunk has a smooth, grey bark that, when cut, leaks liquid, sticky latex.

The smooth leaves are 10–15 cm long and wide, 4–6 lobed, and often pale green (Raheman 2012). About 38% of the husks and 62% of the seeds make up the dry jatropha fruit. The black seeds resemble castor seeds in form (Raheman 2012) as shown in Fig. 12.1. They are composed of 60–70% kernels and 30–40% Testa (shells). Oil makes up about 44–62% of the kernels (King et al. 2009).

12.2.1 Anti-nutritional Factors in the Jatropha Plant

Anti-nutrients are compounds that interfere with the digestion of food and negatively impact animal health and productivity, either directly or by the metabolic products they produce in living systems (Makkar 1993). Animal consumption of plants is typically constrained by the many toxins they create, including alkaloids, terpenoids, tannins, saponins, cyanogenic, glycosides, and poisonous amino acids (Cheeke 1998). Total phenols in jatropha curcas meal vary from 0.2 to 0.4%, whereas tannins are present in insignificant levels at 0.02–0.04%. According to (Makkar et al. 1998), it is impossible to identify condensed tannins in jatropha kernel meal, and the stem bark's tannin content is shallow (outer dark bark: tannins 0.7% and condensed tannins 0.2%; inner green bark: tannins 3.1% and condensed tannins 1.7%; with tannins expressed as tannic acid equivalent and condensed tannins as leucocyanidin equivalent; (Makkar et al. 2008). The non-haemolytic saponin concentration in JM from various regions ranged from 1.8 to 3.4%. The main poisonous component of Jatropha curcas has been discovered as phorbol esters (phorbol-12-myristate 13-acetate) (Makkar et al. 1997; Makkar and Becker 1997, 2010). Phorbol esters are bioactive derivatives of diterpenes that have a variety of cell-related actions. The main anti-nutrient in Jatropha seed/seed meal is trypsin inhibitors (Goel et al. 2007).

Fig. 12.1 Jatropha plant parts: (**a**) male flower, (**b**) female flower, (**c**) mature fruits, (**d**) seeds, (**e**) Green leaves, (**f**) inflorescence, (**g**) Mature tree

Another antinutritional component of Jatropha is phytic acid, which has been shown to have detrimental effects on growth, feed intake, feed conversion ratio, and thyroid function, as seen, for instance, in Atlantic and Chinook salmon (Denstadli et al. 2006).

12.2.2 *Jatropha Detoxification*

Heat labile and stable heat chemicals are two different categories of anti-nutritional factors. Heat labile proteins rapidly inactivated by heat include antinutritional factors such as lectins, protease, and amylase inhibitors. Heat-resistant substances include phenols, tannins, and phytic acids. Compounds that are heat stable often withstand heat processing without being damaged. Antinutritional agents that limit specific enzyme secretion, such as protease and lipase inhibitors, are typically responsible for greater pancreatic enzyme secretion. This may affect how lipids, carbohydrates, and proteins are digested. Heat-stable anti-nutrients are eliminated through ingredient processing techniques, including solvent extraction.

Since raw Jatropha seeds or oil revealed distinct toxicities in several animal species, its use in animal diets is restricted due to anti-nutritional and toxic components. However, before employing JM as a source of nutrients for animal feeds, its antinutritive and harmful components must be reduced (Annongu et al. 2010; Agboola and Adenuga 2015). Following heat treatment, the non-toxic genotype protein or meal isolates could provide excellent protein-rich additions to the diet of animals (Makkar et al. 1999). Thermal degradation, germination, immersion in distilled water, extraction of methanol, lye treatment, hot water treatment, and fermentation can reduce amounts of anti-nutritional components to safe levels (Akande et al. 2006). After heat treatment, which removes components such as trypsin inhibitors and lectins that are anti-nutritional and can also reduce phorbol ester levels by 97.9%, the non-toxic JM has good nutritional value. Various treatments, including a combination of chemical, physical, and biological approaches to detoxify JM as animal feed, were reported in a study by Sumiati et al. (2007). The treatments used in this experiment were: (a) heat treatment using autoclave at 121 °C for 30 min; (b) addition of NaOH at 4%, followed by autoclaving at 121 °C during 30 min; (c) fermentation with Rhizopus oligosporous. The results showed that these treatments decreased the curcin and lectin effects and increased protein utilization efficiency and retention of the meal's phosphorus, calcium and metabolisable energy values. Fermentation using Rhizopus oligosporous was the best method to detoxify the meal and increase the nutritive value for poultry. However, when JM is used above 10% in the diet, it could cause higher bird mortality (Agboola and Adenuga 2015).

Although simple processing methods such as soaking and fermentation appear cost-effective (Kajihausa et al. 2014; Solomon et al. 2017; Okomoda et al. 2020); they are ineffective against thermal-labile antinutrients (Kumar 2008). Also, the cost implication and inability to reuse chemicals after detoxification hampered the acceptability of chemical extraction as a commercially viable method of feed detoxification (Aderibigbe et al. 1997). Though using heat treatments such as toasting and hydrothermal processing is successful, these techniques are critiqued for the additional expense of processing and the potential for denaturing vital nutrients when used for an extended period (Alatise et al. 2014; Tiamiyu et al. 2015; Okomoda et al. 2016). Solid-state fermentation has been proven to be a unique technique for detoxifying plant products, such as castor bean with tannin and phytate (Madeira et al. 2011), soybean bran (Wolski et al. 2009), Jatropha seed cake (Belewu and Sam 2010; Joshi et al. 2011), and sesame oil cake (Singh and Satyanarayana 2008). It might be due to the use of microorganisms in converting harmful or antinutritional substances in the substrate into less hazardous ones. A successful outcome was reported from the Pseudomonas aeruginosa PseA-based fermentation of Jatropha seed cake (Joshi et al. 2011).

12.2.3 The Potential Benefits of Jatropha curcas

Since the beginning of time, medicinal plants have been utilised both as a medicine and a source of cures for illnesses. An exceptional contribution to human health has been made by plant-derived medications, which have also served as a source for the creation of modern medications, drug compounds, and novel prescriptions (Jain and Tripathi 1991). Additionally, various active complex chemicals found in medicinal plants provide a plentiful supply of energetic substances utilised in the food industry, cosmetics, and medicine (Ahmed et al. 2016). The plant's broad therapeutic potential is demonstrated by the bioactive compound's many segments, which include the highest concentration of phytochemical substances, including tannins, phytosterol, glycosides, phenolic compounds, flavonoids, sapogenins, and steroids. (Agbogidi and Eruotor 2012). Additionally, phytochemicals comprise a variety of primary and secondary substances, including total sugars, amino acids, proteins, and phenolic substances, including terpenoids and alkaloids (Phull et al. 2020). Bioactive and phytochemicals in medicinal plants have distinct physiological effects on the human body (Chehregani and Malayeri 2007).

All plant components, including the leaves, seeds, and bark, are prepared for use in veterinary medicine and traditional medicine (Duke 1988; Asuk et al. 2015). Animals' hearts benefitted from the methanol extract of jatropha leaves. It is possible to stop bleeding from wounds by applying the sap emanating from the stem of Jatropha. According to Thomas et al. (2008), the roots of the jatropha plant are used as an antidote for snakebites. The plant's latex contains alkaloids such as jatrophine, curcain, and jatropham, which are crucial anti-cancerous agents. Numerous skin conditions have been successfully treated using jatropha oil (Marroquin et al. 1997). Jatropha kernel oil is potentially used in cosmetics due to its 36% linoleic acid (C18: 2) content. Regardless of the solvents used, this plant has a higher concentration of phytochemicals in its leaves and a lower concentration in its roots. *J. curcas* has abundant flavonoids and polyphenols in its parts (leaf, stem, bark, and shell), with the leaf showing the most substantial concentrations. These phytochemicals have anti-oxidative properties and protect against allergies, platelet aggregation, inflammation, hepatic toxicity, microbes, ulcers, viruses, and tumours (Gutierrez-Orozco and Failla 2013; Syed et al. 2013). There is potential for certain *J. curcas* diterpenoids to be used as antibacterial, antiviral, anti-inflammatory, and antihypertensive medications. These activities and substances may also have hallucinogenic, antioxidant, and sweetening effects (Kumari et al. 2003). The meal has a crude protein level of 58–60% and an actual protein content of 53–55% when processed in a cottage industry, retaining 11% of the meal's oil.

Due to its non-edible nature and recycling ability, jatropha oil seems to have much potential as a raw resource for industrial uses. Jatropha oil has drawn industrialists and academicians to investigate it as a material for the synthesis of alkyd resins due to its cost-competitiveness compared to other oils such as soya, rapeseed, etc. (Satheesh Kumar et al. 2010). Owing to the sociological, economic, and environmental benefits, polymers made from renewable resources, mainly plant oils, have received much attention lately (Lu and Wool 2008). Sunflower/palm oils, tallow (animal fat), and jatropha oil are comparable. It has fatty acid and is used as a base for soap manufacturing, among other things. Both primary and small industrial companies have employed jatropha oil to produce soap for decades. For instance, a significant industry uses it in India (Hindustan Lever). Additionally, the clear oil has been utilised as an insecticide, polish, varnish, candle fuel, and

Table 12.1 Uses of different parts of *J. curcas* L

Jatropha part	Uses	References
Leaves	For medicinal uses	Orwa et al. (2009)
	Anti-inflammatory substance	Warra (2012)
	Animal feed	Musa et al. (2018, 2021)
Fruits hulls	Combustibles	Brittaine (2010)
	Green manure	Orwa et al. (2009)
	Biogas production	Achten et al. (2008); Ghosh et al. (2007)
Latex	Wound healing	Orwa et al. (2009)
	Medicinal uses	Nahar and Ozores-Hampton (2011)
Seeds		
Seed oil	Soap production	Warra (2012)
	Fuel production	Lele (2007)
	Insecticide production	Srinophakun et al. (2011); Achten et al. (2008)
Seed cake	Fertilizer production	Achten et al. (2008); Ghosh et al. (2007); Patolia et al. (2007)
	Biogas production	Staubmann et al. (1997); Achten et al. (2008); Ghosh et al. (2007); Patolia et al. (2007)
	Animal feed production	Musa et al. (2018, 2021)
	Fodder (from non-toxic varieties)	Gaur et al. (2011)
Seed shell	Combustibles like fruit hulls	Brittaine (2010)

lubricant. Jatropha oil is less competitive than soybean and rapeseed oils despite seed oils being utilized to make biodiesel on a larger scale. Additionally, it is worthwhile looking into the idea of using jatropha oil to create alkyd resin because it has a high concentration of monounsaturated oleic and polyunsaturated linoleic acids, which indicate a semi-drying ability (Odetoye et al. 2010).

Jatropha's protein can be derived from the leaves and press cake (Lestari et al. 2011). The Jatropha seed cake primarily consists of proteins. Various proteins have been manufactured commercially for use in food and other products, including soy protein, gelatin, and casein. However, the poisonous curcin and phorbol esters are found in the jatropha seed (Lestari et al. 2010). Additionally, the seed cake contains these chemicals, which restricts the use of jatropha seed cake for food and feed applications without additional detoxification. Technical applications of protein from Jatropha press cake include emulsifier, coating, bioplastic, foaming agent, and adhesive (Lestari et al. 2011) (Table 12.1).

12.3 *Jatropha curcas* in Aquaculture Practices

Aquafeed is a critical factor in the expansion and development of aquaculture production. It represents a sizable portion (30–75%) of the average fish farm's overall operational costs (Rumsey et al. 1993; El-Sayed 2002). Fish meal has traditionally been the primary source of protein in aquafeeds for various reasons, including its high protein content, abundance of essential amino acids, excellent nutritional and energy digestibility, lack of antinutrients, and availability of vital fatty acids, energy, and minerals. Most freshwater and marine fishes find it highly appetizing and digestible (Watanabe et al. 1997; Glencross et al. 2004). Therefore, a prospective ingredient must have a few qualities to be a feasible replacement, such as widespread availability and a reasonable price. Additionally, it must be simple to transport and store. Plant protein sources should be considered for aquafeeds because they are readily accessible and economically priced. A range of plant protein components might make suitable replacements for fish meals as a source of protein in fish diets.

12.3.1 Chemical Composition of J. curcas *Leaves*

Jatropha leaves might be used as a source of protein. Additionally, amino acids from leaf proteins may be used to create functionalized bulk compounds. The chemical composition of the Jatropha leaf is shown in Table 12.2. According to Lestari et al. (2011), protein and acid-insoluble lignin made up most of the Jatropha leaf. In leaves, there were soluble sugar and polysaccharide carbohydrates. About 65% weight-for-weight of the polysaccharide was converted to glucose after severe acid

Table 12.2 Chemical composition of Jatropha leaf (Khalil et al. 2003)

Component	Compositions (% weight dry basis)
Fat	8.2
Crude protein	20.6
Carbohydrate	
Soluble sugar	15.3
Polysaccharide	10.2
Arabinose	0.6
Xylose	1.0
Mannose	0.6
Galactose	1.5
Glucose	7.1
Pectin	3.9
Lignin	
Acid insoluble lignin	23.5
Acid soluble lignin	2.8
Ash	12.0

hydrolysis. Ash, soluble sugar and lignin were all in significant concentrations in the jatropha leaf. This suggests that extracting and purifying the protein from Jatropha leaves should include acid washing to eliminate lignin that isn't soluble in acid and dialysis to get rid of salts.

12.3.2 **Jatropha curcas** *Meal (JCM) in Aquafeed*

Utilising non-traditional feedstuffs, like jatropha seed meal, could lower the price of fish feeds and production costs. Each ton of jatropha seed produces roughly 200–300 L of biofuel and 700–800 kg of meal as a byproduct of refining the biofuel (Brodjonegoro et al. 2005). Due to the high crude protein (CP) content of Jatropha curcas meal (JCM), which is produced following oil extraction, it has been suggested that JCM could be used to formulate animal feed (Makkar and Becker 2010; Makkar et al. 1998). However, compared to other plant protein meal sources, Jatropha meal tends to have a significant amount of crude protein, lipids, and ash content than CSM, RSM, SBM, and RPCM. As indicated in Table 12.3, the amino acid profile of the Jatropha meal seems similar to that of FM. Compared to soybean meal, jatropha kernel meal has higher concentrations of all essential amino acids (apart from lysine) (Kumar et al. 2010). Consequently, it is anticipated to be an excellent feed ingredient in the future and will likely replace fish and soybean meals.

The kernel meal recovered after oil extraction is a fantastic source of nutrients and comprises 58–62% crude protein (Makkar et al. 2008). However, their application in fish feed is constrained by the high concentrations of antinutrients such as trypsin inhibitor, lectin, and phytate (Makkar et al. 2008) and the critical poisonous component, phorbol esters (PEs) (Makkar and Becker 1997). As a result, modifications in the haematological parameters of fish after feeding them JCK can gauge how the antinutrients affect the fish's state of health (Musa et al. 2018; Okomoda et al. 2020). Similarly, it has been suggested that the high quantities of antinutrients in fish diets contribute to histological abnormalities in the liver and intestine (Dharmani et al. 2009; Kumar et al. 2019). Therefore, the feed elements must be detoxified before including in the fish diet. Jatropha kernel meal can be detoxified by deactivating lectin and trypsin inhibitors by heat treatment and extracting PEs using organic solvents. However, other methods include soaking (Okomoda et al. 2021), toasting (Musa et al. 2018, 2021) and fermentation (Shamna et al. 2014) as seen in Table 12.4.

12.3.3 Jatropha Oil in Aquafeed

Fish oil (FO) is the primary lipid source used in formulated diets for aquaculture. It contains high amounts of n-3 polyunsaturated fatty acids (PUFAs), such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which promote

Table 12.3 Typical composition of commonly used aquaculture feed ingredients

	JKM	SBM	CSM	RSM	RPCM	FM
Crude protein	665	441	449	378	665	645
Crude lipid	11.4	15	5	38	85.6	78
Crude ash	82	63	66	68	39	213
Essential amino acids composition (g kg^{1})						
Arginine	69.7	32.1	46.5	22.7	49.7	43.6
Histidine	21.7	11.6	11.1	10.1	15.4	14.4
Iso leucine	26.7	20.3	12.5	14.9	25.7	27.9
Leucine	46.7	35	24	27.2	52.9	52.2
Lysine	23.3	28.2	17.1	22	18.9	49.9
Phenylalanine	30.4	23.9	23	16.4	36.2	29.1
Methionine	10.6	5.3	5.7	7	20.2	20.6
Threonine	22	17.9	13.1	16.6	24.7	30.3
Valine	31.6	21	17.6	19.1	35	33.5
Non-essential amino acids composition (g kg^{1})						
Alanine	29.4	19.6	15.7	16.7	38.5	39.7
Asparginine	68.7	50.3	36.6	26	59	62
Cystine	2.3	6.2	6.4	7.6	13.7	10.1
Glycine	31.5	19.3	16.3	18.8	28	45
Glutamine	112.1	85.9	85.3	69.5	118.3	94.8
Proline	32.2	21.6	14.1	22.4	21.9	28.3
Serine	30.6	23.1	17.7	16.4	32.5	32.9
Tyrosine	18.8	16	11.3	11.1	32.4	25.1

JKM Jatropha kernel meal, *SBM* Soybean meal, *CSM* Cottonseed meal, *RSM* Rapseed meal, *RPCM* Rice protein meal, *FM* Fish meal

Adopted from Harter et al. (2011); Abasubong et al. (2018); Cai et al. (2018)

survival, health, and make balanced diets palatable and attractive (Pike and Jackson 2010; Teves and Ragaza 2016). The extraction and use of plant lipids as a substitute for FO in the diets of many fish species is well documented as it has been found to provide adequate fish growth and achieve commercial size within a reasonable time (Sutili et al. 2017; Turchini et al. 2010). Table 12.5 compares the fatty acid composition of *Jatropha curcas* oil with the fatty acid composition of other common vegetable oils. Results from these research efforts suggest that *Jatropha curcas* oil could be a valuable feedstock for biodiesel production, with a dramatic reduction in costs of production. Polyunsaturated fatty acids (PUFA) like linoleic acid (18:2n-6) and alpha-linolenic acid (18:3n-3) can be found in *Jatropha curcas*, which is also a good source of both saturated and unsaturated fatty acids, making it a reliable candidate for replacement of fish oil.

Table 12.4 Effect of processing methods on proximate compositions and anti-nutritional compositions of Jatropha curcas seed (adopted from Michael et al. (2019))

Nutrient (%)	Raw	Boiled	Toasted	Soaked	Fermented
Dry matter	93.50	94.13	94.80	93.88	93.50
Protein	37.68	28.33	30.46	29.65	31.46
Lipid	42.36	12.35	6.75	12.96	13.55
Ash	3.27	4.66	7.25	4.71	4.84
Fibre	3.40	2.86	6.13	3.02	2.16
NFE	6.79	45.93	44.21	43.54	41.49
Anti-nutrients (g/100 g dry weight basis)					
Tannins	0.151	0.036	0.011	0.038	0.042
Phytic acids	0.094	0.029	0.008	0.030	0.032
Saponins	0.092	0.046	0.013	0.048	0.056
Oxalates	0.067	0.045	0.013	0.050	0.055
Terpenoids	0.022	0.016	0.006	0.019	0.020
Trypsin inhibitor	0.425	0.196	0.052	0.231	0.285
Glycosides	0.061	0.026	0.013	0.030	0.033
Flavonoids	0.101	0.061	0.022	0.066	0.068
Alkaloids	0.070	0.026	0.015	0.028	0.032

Table 12.5 Fatty acid composition of plant oil

Fatty acid	GNO	SFO	JCO	SBO	CSO
Oleic (18:1)	58.68	21.1	44.7	23.4	17.2
Linoleic 18:2	21.77	66.2	32.8	53.2	55.0
Palmitic 16:0	8.23	–	14.2	11.0	24.4
Stearic 18:0	2.46	4.5	7.0	4.0	2.2
Palmitoliec 16:1	0.11	–	0.7	–	0.4
Linolenic 18:3	0.34	–	0.2	7.8	0.3
Arachidic 20:0	1.83	0.3	0.2	–	–
Myristic 14:0	0.12	–	0.1	0.1	0.8
Saturated	16.81	11.3	21.6	15.1	27
Monounsaturated	58.79	21.1	45.4	23.4	18
Polyunsaturated	22.11	66.2	33	61.0	55

GNO groundnut oil, *SFO* sunflower oil, *JCO* Jatropha oil’s, *SBO* soybean oil, *CSO* cottonseed oil

12.4 A Dynamic Study of Dietary Inclusion of *Jatropha curcas* in Aquafeed on Growth and Haematological Indices in Finfish

12.4.1 Substitution of Soybean Meal with Fermented Jatropha Kernel Meal: Effect on Growth Performance, Body Composition, and Metabolic Enzyme Activity of Labeo rohita

Phulia et al., (2017) developed four iso-nitrogenous (336 g kg^{1}) and iso-energetic (20 MJ kg^{1}) diets that contained 0, 100, 200, and 300 g kg^{1} FJKM in replacement of 0%, 33.3%, 66.7%, and 100% soybean meal protein, respectively in *Labeo rohita* fingerlings. These diets were designated control, T1, T2, and T3, respectively. From their findings, it can be deduced that the T2 and T3 groups performed better than the other groups in terms of weight gain (percent WG), specific growth rate (SGR), protein efficiency ratio (PER), protease, aspartate aminotransferase (AST), and alanine aminotransferase (ALT) activities, and PER, couple with a reduced feed conversion ratio. At the same time, there were no appreciable differences in the hepatosomatic index (HSI), intestinal somatic index (ISI), amylase, lactate dehydrogenase (LDH), malate dehydrogenase (MDH), superoxide dismutase (SOD), and catalase activity between the various dietary groups. When the fish's entire body composition was examined after the feeding trial, it was found that the control group had a considerably higher ether extract and a smaller amount of crude protein than the groups fed FJKM. They concluded that rohu fingerlings might use FJKM effectively without compromising growth performance, food utilization, or metabolic response.

12.4.2 Dietary implications of toasted Jatropha curcas kernel on the growth, hematology, and organ histology of Clarias gariepinus *fingerlings*

Musa et al. (2021) developed a diet using JCK that was nutritionally assessed after being toasted for various amounts of time (0, 10, 20, and 30 min). This was divided into four batches for the intended treatments. The control group was the initial batch (i.e., raw JCK without processing). The three other batches underwent 10, 20, and 30 min of toasting. Their findings imply that prolonged toasting increased the nutritional properties of the JCK since they showed more significant weight gain, specific growth rate, feed conversion efficiency, and survival in the fish-fed diet containing toasted JCK than those in control. This study also observed that dietary inclusion of JCK toasted beyond 20 min tends to decrease the growth performance of the fish significantly.

Contrary to this trend, protein accumulation in the carcass was not affected by the inclusions of JCK processed for a prolonged time. The protein content of the fish fed the toasted JCK was also significantly higher than those fed the raw *Jatropha*. However, the antinutrients continuously decreased with prolonged processing. The growth, carcass analysis, and haematology of the fish groups fed toasted JCK at varying duration also did better than those fed raw JCK. Notably, the performance tends to reduce for those fed JCK toasted beyond 20 min. The estimated cost of producing 1 kg of the fish is substantially reduced by feeding the processed JCK than raw JCK. Histological examination of the intestine and liver tissues revealed less histopathological degeneration for fish fed processed JCK compared to the control. It was concluded that the processing of JCK by toasting should not exceed 20 min to improve the nutritional composition of the feed ingredients and their dietary utilisation by fish.

12.4.3 Effect of Replacing Different Levels of Dietary Fishmeal with **J. curcas** *Kernel Meal*

Krome et al. (2014) created four diets by substituting JKM for fishmeal in various degrees: 0% (Control), 50% (J50), 75% (J75), and 100% (J100). JKM and blood meal were used in place of fishmeal in a fifth diet to replace 70% and 20% of the fishmeal to reduce the amount of crystalline lysine. According to their findings, fish fed the control diet gained much more body mass than fish given any other treatments. However, the specific growth rate (SGR) and feed conversion ratio (FCR) did not change substantially between the control, J50, and J75 diets. Fish fed the control diet had a lower body protein content than fish fed the JKM-based diets, but their body fat and energy contents were higher. It was also possible to see an adaptation in the fish fed diets J50, J75, and J100, which had worse FCR values for the majority of the first third of the trial but equal (or, in the case of J75, noticeably better) FCR values during the last 2 weeks. The authors added that despite significantly slower growth, JKM should still be investigated further in the hunt for substitute plant feedstuffs for tilapia diets because the growth observed in 75% replacement of fishmeal was highly encouraging.

The dietary inclusion of socked Jatropha curcas kernel (JCK) and its impact on *Clarias gariepinus* were studied by Okomoda et al. (2021). Three JCK treatments (i.e., soaking for 24, 48, and 72 h) and a control group were evaluated for 56 days. As opposed to the control JCK, the results demonstrated that soaking significantly enhanced proximate composition and decreased anti-nutrient. Along with the growth improvement, it was also reported that the dietary administration of soaked JCK increased haematological variables and carcass protein. Fish fed on diets containing soaked JCK (i.e., for 72 h) showed less evidence of histopathological degeneration than fish raised on diets containing raw JCK, according to histological analysis of the gut and liver tissues. The goblet cells in the intestine of the *C. gariepinus* fed raw

JCK were depleted, and the epithelial lining tend to shed off. however, in the treatment group, the epithelial lining appeared unaltered and the goblet cell was enhanced. The amount of necrosis in the liver of *C. gariepinus* fed raw JCK was significant, whereas the number of necrotic cells appeared to decrease in the fish fed soaked JCK. The authors concluded that soaking was consequently determined to be a considerably simpler way of nutritionally enhancing JCK for administration to *C. gariepinus*.

Musa et al. (2018) examined the nutritional value of hydrothermally processed *J. curcas* kernel meal (JCK) using *C. gariepinus*, an African catfish. The JCK's nutritional properties improved as the process went on (0, 30, 60, and 90 min). After that, four isonitrogenous (35% CP) and isocaloric (315 kcal g^1) diets were created and fed to *C. gariepinus* fingerlings for 56 days. The processed JCK used in these diets was at a 29% concentration. In comparison to the control diet, the processed JCK performed better. Using the second-order polynomial regression analysis, the ideal processing time that resulted in the most significant weight gain was 62 min. The blood parameters of the fish significantly improved after the processed JCK meal was added to their diet as opposed to when they were just given raw JCK. Similarly, adding the processed JCK lowered the cost of producing feed and fish. The nutritional profile of JCK and its dietary consumption by African catfish *C. gariepinus* fingerlings were shown to be enhanced by hydrothermal processing.

12.4.4 Dietary Inclusion of Detoxified **J. curcas** *Kernel Meal: Effects on Growth Performance and Metabolic Efficiency in Common Carp,* **Cyprinus carpio** *L.*

According to Kumar et al. (2010), common carp were fed isonitrogenous diets (38% crude protein) for 6 weeks, including a control diet containing fish meal (FM) protein-based protein and two other diets that substituted 75% of FM protein with detoxified Jatropha kernel meal (DJKM, Jatropha group) and soybean meal (SBM, Soybean group). Body mass gain, metabolic growth rate, protein efficiency ratio, protein productive value, energy retention, the effectiveness of metabolised energy for growth, and energy retention efficiency were determined after the experiment. For the Control and Jatropha groups, these parameters were high and statistically comparable, while for the Soybean group, they were significantly lower. A contrary pattern was seen for the energy expenditure per g protein kept in fish bod, heat released, gross energy uptake, metabolised energy intake, energy expenditure per g protein fed and apparently unmetabolized energy did not differ significantly from one another. Finally, the authors concluded that common carp–fed plant protein (DJKM and SBM) and FM protein–based diets exhibited equal average metabolic rates.

12.4.5 Heamato-immunological and Physiological Responses of **Labeo rohita** *Fingerlings to Dietary Fermented* **J. curcas** *Protein Concentrate*

Shamna et al. (2014) employed solid-state fermentation (SSF) to detoxify JPC, and a 45-day feeding trial was done to examine how feeding fermented JPC (FJPC) influenced the growth, haemato-immunological responses, and physiological responses of rohu fingerlings. Seven different iso-nitrogenous meals, including the control diet (without JPC or FJPC), J5 (5% JPC), J10 (10% JPC), J20 (20% JPC), FJ5 (5% FJPC), FJ10 (10% FJPC), and FJ20 (20% FJPC), were prepared and fed twice daily. The control and FJ fed groups showed a general, linear, and quadratic pattern in the weight gain and specific growth rate values. Additionally, there was a significant difference in feed efficiency, with the control group recording a higher value comparable to FJ fed groups and JPC fed groups recording the lowest value. All JPC fed groups and the 5% FJPC group had significantly lower amounts of red blood cells (RBC) and hemoglobin than the control and other FJPC groups, according to the results of the hematopathological tests. The greatest blood glucose levels of any group were found in the JPC fed groups at 10% and 20%. Similar to serum total protein and albumin, RBC and hemoglobin behaved similarly. The J20 group had the lowest globulin value, while the FJ10 group had the highest value, significantly greater than the other groups. J10 and J20 had the highest superoxide dismutase (SOD) activity in the muscle compared to other groups. J20 exhibited higher SOD activity in the liver. The outcome suggests that solid-state fermentation is the best approach for purifying protein concentrate made from Jatropha cake before feeding it to rohu. According to the authors, FJPC can be consumed by rohu at a rate of 20% without negatively affecting their hemato-immunological or physiological response.

12.4.6 Dietary Inclusion of Detoxified **J. curcas** *Kernel Meal: Effects on Growth Performance and Metabolic Efficiency in Common Carp,* **Cyprinus carpio** *L.*

According to Kumar et al. (2010), common carp were fed isonitrogenous diets (38% crude protein) for 6 weeks, including a control diet containing fish meal (FM) protein-based protein and two other diets that substituted 75% of FM protein with detoxified Jatropha kernel meal (DJKM, Jatropha group) and soybean meal (SBM, Soybean group). Body mass gain, metabolic growth rate, protein efficiency ratio, protein productive value, energy retention, the effectiveness of metabolised energy for growth, and energy retention efficiency were determined after the experiment. For the Control and Jatropha groups, these parameters were high and statistically comparable, while for the Soybean group, they were significantly lower. A contrary pattern was seen for the energy expenditure per g protein kept in fish bod, the heat released, gross energy uptake, metabolised energy intake, energy expenditure per g protein fed and apparently unmetabolized energy did not differ significantly from one another. Finally, the authors concluded that common carp–fed plant protein (DJKM and SBM) and FM protein–based diets exhibited equal average metabolic rates.

12.4.6.1 Growth Performance and Haematological Indices of African Catfish (*C. Gariepinus* Burchell 1822) Fed Graded Levels of Processed *Jatropha curcas* Leaf Meals

Four practical diets were created at various levels, representing T1, T2, T3, and T4 correspondingly, at inclusion levels of 0%, 1.5%, 3.0%, and 4.5%, and at substitution levels of SBM of 3.5%, 7.0%, and 10.5%. The manufactured diet (Coppens), which also functioned as the control, was the fifth treatment group (T5). The outcomes demonstrated that the treatment diets increased the performance of African catfish. When *J. curcas* leaf meal inclusion levels reached a particular threshold, the response variables rose and were statistically different for practically all of the parameters assessed. The haematological indicators revealed a considerable improvement in the performance of the catfish fed the treatment diets, suggesting that JLM had positive impacts on *C. gariepinus*. As a result, the authors concluded that, *J. curcas* leaf meal may be a reliable supply of protein components in aquaculture diets, which may assist reduce production costs.

12.5 Conclusions and Perspectives

Feed is the essential component of the aquaculture production system, and demand for aquatic organism feed is expected to nearly triple by the end of the decade due to a significant increase in population. Because of this expansion, more protein sources than fishmeal or soymeal must be used. Products derived from the Jatropha plant may be the best option for meeting a significant portion of the protein requirements of the growing feed market. Its use in aquaculture nutrition has been accepted due to its excellent amino and fatty acid composition, which is comparable to fishmeal. Regardless, the research discussed in this chapter broadens the range of feed ingredients available to the feed industry. It also demonstrates how food and energy security can be effectively integrated and establishes links between the bioenergy and feed industries. It is clear from the preceding discussions that the Jatropha plant can produce goods for purposes other than serving as a dietary alternative to fishmeal, which needs to be explored and improved. Finally, we believe that the use of Jatropha in aquafeeds should be encouraged and that more research into its effects on non-specific immunity and the expression of genes involved in growth, stress, and apoptosis in aquatic species should be conducted. Using raw Jatropha kernel meal in aqua feed, on the other hand, may cause intestinal inflammation due to antinutritional factors, which may be associated with growth retardation. As a result, JKM may be used to replace up to 50% of the protein in fishmeal without affecting shrimp development or nutrient uptake. If the replacement levels are exceeded, the nutrient profile of the feeds must be carefully reviewed to ensure that the intended production levels are met, and fish and shrimp health is maintained. Regardless of the detoxifying method, high JKM inclusion (>50% fishmeal protein replacement) may have a negative impact on growth and dramatically reduce protein, fat, and energy digestibility. The majority of these effects, however, were observed in *C. gariepinus* rather than other species, such as common carp.

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Part II
Water Quality Management

Chapter 13

Applications of Aquatic Plants in the Remediation of Aquaculture Wastewater: An Opportunity for African Aquaculture

Anna Alfeus and Ndakalimwe Naftal Gabriel

Abstract Aquaculture has proven to enhance food production to meet the growing population's food security demand. The sustainability of aquaculture farming requires environmental sustainability, particularly the disposal of wastewater produced during aquaculture farming. The large volume of wastewater exchanged during production poses a challenge to safe disposal. Wastewater from aquaculture contains high concentrations of nitrogen, chemical oxygen demand, and phosphorus, mainly from uneaten feeds. The nutrients contaminate water bodies and threaten the life of aquatic organisms in the water by boosting the growth of toxic algae. The treatment of wastewater from aquaculture before disposal is a necessity. Currently, small-scale farmers discard untreated wastewater into ponds that do not treat wastewater because of the inability to afford treatment facilities. Commercial aquaculture farming uses conventional methods that create secondary pollution of increased carbon footprint resulting from high energy consumption. Plants have proven to be efficient in removing nitrogen and phosphorus and improving the water quality produced in aquaculture. Therefore, this chapter has looked at studies using plants to remove contaminants in aquaculture wastewater, and as prospects for African aquaculture farmers.

Keywords Aquaculture · Wastewater · Nitrogen · Phosphorus · Phytoremediation

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13.1 Introduction

The global population continues to expand, with the current equivalence of 74 million births added to the world population every day until 2027, placing a high demand on food production to feed the growing population (FAO 2018). Responding to the population demands, agriculture supply, and global requirements in energy supply continue to grow, leading to the increase in waste products that will deteriorate the environmental quality if not correctly managed (Tian and Lin 2018). In the case of agricultural supplies, fish consumption has also increased, leading to fish production through aquaculture. The state of world fisheries and aquaculture has indicated that the production of fish worldwide has grown tremendously, contributing to food security and world economic growth with an estimated value of US$ 119 billion in 2010 (FAO 2012). By 2011 the world fisheries production stood at 154 million tonnes, with 63.6 million tonnes mainly coming from inland and marine aquaculture (FAO 2012). About 131 million tonnes of fish produced were for food consumption, with Asia accounting for the consumption of about two-thirds of total fish production (89.08 million tonnes). In comparison, Africa is the least consumer of fish, with 9.4 million tonnes (FAO 2012). Aquaculture fish farming is also increasing due to the increased usage of fish models in research and development activities (Johansen et al. 2006).

Fish farming requires a high volume of water during production, resulting in a large volume of wastewater discharged into the environment (Nogueira et al. 2018). The regular exchange of water is required to maintain the health and welfare of the fish by providing freshwater with feeds and removing wastewater (Johansen et al. 2006). The wastewater is usually discharged into water streams or pre-treated through sedimentation tanks. Sedimentation tanks aid in removing suspended materials, but not dissolved particles posing a risk to the receiving water bodies. The use of sedimentation tanks applies to small-scale and rural farmers who cannot afford advanced wastewater treatment facilities (Hendra et al. 2017). The inability to afford advanced treatment equipment leaves no explicit provision for communal aquaculture farmers to treat wastewater before discharging it into the environment; hence, the possibility of discharging untreated wastewater into the water bodies is unattended. Discharging untreated aquaculture wastewater has a detrimental effect on the water bodies and poses a severe threat to natural habitats and human health (Mustafa and Hayder 2021). The detrimental effects are mainly due to the high loading of suspended solids and dissolved nutrients from the accumulation of by-products, e.g., fish excretions and uneaten feed (Benedito et al. 2013). Wastewater from fish farming has a high concentration of nitrogen and phosphorus, which lead to the eutrophication of aquatic bodies where this wastewater is disposed (Evans et al. 2019). For these concerns, effective wastewater treatment before discharging into the environment is required (Mustafa and Hayder 2021). Developed countries such as Australia, China, and Denmark have enacted aquaculture legislation stipulating standards on ammonia, oxidised nitrogen, phosphorus, and suspended sediments and issuance of a discharge permit or license to the aquaculture facilities before discharging wastewater in the water bodies (FAO 2021). In addition, the Namibian Aquaculture Policy of 2001 stipulated that no person shall discharge wastewater generated by aquaculture facilities that may harm human or environmental health without treatment (FAO 2022). The Namibian legislation implies that aquaculture farmers should determine wastewater quality and then decide to discharge based on the results. Large-scale or commercial aquaculture facilities have used conventional treatment methods in treating wastewater, such as ion exchange, adsorption, reverse osmosis, chemical precipitation, and electrochemical treatment to remove organic and inorganic contaminants (Mustafa and Hayder 2021). However, these methods require high energy consumption and maintenance costs, as well as release high carbon emissions, and excess sludge discharge that would still contain toxic contaminants. The challenges associated with current waste water treatment methods indicate that there is a need to explore alternative methods of wastewater that are affordable, efficient, and easy to implement for rural and commercial fish farmers.

13.2 Phytoremediation as a Remediator for Aquaculture Wastewater

The phytoremediation technique employs the application of plants for wastewater remediation. Phytoremediation is efficient in improving ecological water quality (Hendra et al. 2017), removal of metals (Fawzy et al. 2012), xenobiotics (Del Buono et al. 2020) and herbicides (Mimmo et al. 2015), as shown in Table 13.1. Plants aid in removing physical, biological, and chemical contaminants in wastewater. Evidence of about 30 aquatic plants from the different levels of the aquatic environment exist in phytoremediation. These include the free-floating plants (*Pistia stratiotes*, *Salvinia molesta*, *Lemna spp., Azolla pinnata, Landoltia punctata, Spirodela polyrhiza, Marsilea mutica, Eichhornia crassipes,* and *Riccia fluitans),* submerged *(Hygrophilla corymbosa, Najas marina, Ruppia maritima, Hydrilla verticillata, Egeria densa, Vallisneria americana* and *Myriophyllum aquaticum*), and emergent plants (*Distichlis spicata, Cyperus spp., Imperata cylindrical, Iris virginica, Nuphar lutea, Justicia americana, Diodia virginiana, Nymphaea spp., Typha spp., Phragmites autralis and Hydrochloa caroliniensis*). The combination of free-floating, sub-emerged and emergent plants have been promising in the natural or constructed wetland (Jeke et al. 2015). A constructed wetland for phytoremediation purposes is an artificial system that simulates a natural ecosystem with various emergent, submerged, and floating aquatic species (Del Buono et al. 2020). In the constructed wetlands, the contaminants are physically removed and eventually degraded by plants or microbes or subjected to sedimentation (Shelef et al. 2013). For example, halophytes are salt phytoremediators or bio-indicators of water quality. A study by Shelef et al. (2013) found that *B. indica*, a halophytic annual, accumulates sodium to up to 10% of its dry weight. In addition, the study also demonstrated that *B. indica*,

Table 13.1 Phytoremediation efficiency of potential plants used in wastewater treatment from various sources

Types of wastewater	Types of plant	Function	References
Polluted river (domestic wastewater)	Water Hyacinth (*Eichhornia crassipes*)	Highly efficient in removing COD (68.21%), total nitrogen TN (89.4%), and ammonium nitrogen NH^{+}_{a}–N from a polluted river	Lu et al. (2018)
Polluted river (domestic wastewater)	Water lettuce (*Pistia stratiotes*)	Highly efficient in removing COD (68.21%) and total phosphorus (93.6%) from a polluted river	Lu et al. (2018)
Polluted Nile river (Industrial effluent, agricultural and domestic waste)	*Ceratophyllaceae demersum*	Absorb heavy metals (Pb, Cd, Cu, Zn)	Fawzy et al. (2012)
Contaminated soil and water	Maize, Sorghum, rice, cereal	High ability to absorb heavy xenobiotics (Naphthalic Anhydride, Flurazole, Fenclorim, Fenchlorazole ethyl)	Del Buono et al. (2020)
Contaminated water with pesticides (Agricultural waste)	*Italian ryegrass (Lolium multiflorum L.)*	Ability to remove about 30–40% herbicide terbuthylazine (TBA) in an aqueous solution	Mimmo et al. (2015)
Industrial wastewater	*C. cuprina*	Able to tolerate a mixture of heavy metal (Al, As, Cd, Cu, Cr, Fe, Mn, Ni, Pb, Sn, Zn) and hydrocarbons contamination (THC, PHE, PYR, LAS) from industrial wastewater	Guittonny-Philippe et al. (2015)
Industrial wastewater	*Alisma. lanceolatum*	Proliferate in the root-shoot ratio in a mixture of heavy metals (Al, As, Cd, Cu, Cr, Fe, Mn, Ni, Pb, Sn, and Zn) and hydrocarbons contamination (THC, PHE, PYR, LAS). Heavy metal caused an increase in leaf senescent in the plant	Guittonny-Philippe et al. (2015)
Industrial wastewater	*Iris pseudacorus*	The interaction of heavy metals (Al, As, Cd, Cu, Cr, Fe, Mn, Ni, Pb, Sn, and Zn) and hydrocarbons (THC, PHE, PYR, LAS) mixtures lead to the following: (1) an increase of R/S caused by the interaction between organic pollutants and metals; (2) an increase of the leaf senescent process mainly caused by metals; and (3) inhibition of aerial elongation mainly caused by organic pollutants	Guittonny-Philippe et al. (2015)
Aquaculture wastewater	*Centella asiatica*	Efficient in removing 98% of ammoniacal nitrogen (NH_3-N), 90% of total suspended solids, and 64% of phosphate	Nizam et al. (2020)

(continued)

Table 13.1 (continued)

Types of wastewater	Types of plant	Function	References
Aquaculture wastewater	*Ipomoea aquatica*	Efficient in removing 73% of ammoniacal nitrogen (NH_3-N) and total suspended solid and 50% of phosphate	Nizam et al. (2020)
Aquaculture wastewater	*Eichhornia crassipes*	Efficiently removing 74% of ammoniacal nitrogen (NH_3-N), 96% of total suspended solids, and 98% of phosphate	Nizam et al. (2020)
Aquaculture wastewater	*Pistia stratiotes*	Efficiently removing 78% of ammoniacal nitrogen (NH_3-N), 98% of total suspended solids, and 89% of phosphate	Nizam et al. (2020)
Aquaculture wastewater	*Salvinia molesta*	Efficiently removing 63.9% of ammoniacal nitrogen (NH_3-N), 89.3% of total suspended solids, and 88.6% of phosphate	Nizam et al. (2020)

reduced the concentration of H_2O_2, a marker for plant stress, in successive treatment stages, which indicates the improvement of the water quality (Shelef et al. 2013).

13.2.1 Mechanisms of Actions During Phytoremediation

There are five plant-based technologies of phytoremediation, with each having a different mechanism for remediating polluted water bodies:

Phytofiltration—This process involves the use of plant roots (rhizofiltration) or seedlings (blastofiltration) to absorb contaminants from aqueous mediums (Sarma 2011).

Phytoextraction—This process involves the ability of the plant to absorb contaminants from the wastewater through its root system (Mimmo et al. 2015). The contaminant subsequently translocates to the shoots for harvesting; hence, the process allows the removal of the contaminant (Sarma 2011). Since the harvested shoots contain toxic chemicals, farmers can use the tissues for non-food purposes such as energy production or incineration, followed by ash disposal in a landfill (Shelef et al. 2013). In some circumstances, especially in the case of metals that may have a commercial value, plant tissues can be processed to recover the metal as a salt after the phytoextraction and harvesting. The recovery technology of the metal salt is known as phytomining. Harvesting the plant is essential because it prevents the recontamination and recycling of contaminants in the water environment through decaying plant tissues.

Phytostabilisation—Plants reduce the mobility of the pollutants in the soil by binding them to the soil particles via complexation or precipitation. Consequently,

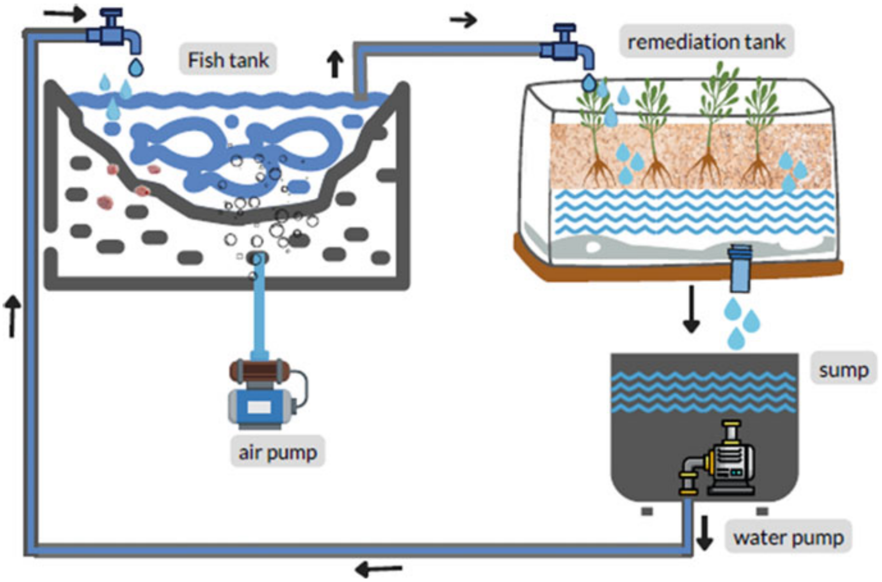

Fig. 13.1 Schematic diagram of a recirculation aquaculture system aided by phytoremediation in treating wastewater

this action prevents the leaching and runoff of the pollutant into the environment (Sarma 2011). Rhizostabilisation is the dominant phytoremediation process for removing trace elements from the water environment (Jeke et al. 2015). Rhizostabilisation happens because the translocation of trace elements from the roots to the shoots (above-ground biomass) does not occur in wetland plants. Thus, above-ground biomass harvesting becomes an ineffective strategy for removing trace elements (Jeke et al. 2015).

Phytovolatilization—The plant extract and volatilize the contaminants, releasing them into the atmosphere (Sarma 2011).

Phytodegradation—Refer to species capable of enzymatically transforming organic pollutants into no-more toxic derivatives (Fig. 13.1).

13.3 Factors to Consider in the Selection of Plants for the Phytoremediation Process

Plant selection is a vital phytoremediation management criterion (Sarma 2011). The selection of the plant influences the fruitfulness of the phytoremediation strategy. Native indigenous plant species are usually a priority for phytoremediation due to their excellent capacity to adapt to native climatic conditions and seasonal cycles (Sarma 2011). Some essential criteria in selecting plant species include:

- The level of tolerance with regard to contaminants known in the fish farm wastewater
- The efficiency in the accumulation, translocation, and uptake of contaminants
- High growth rate and biomass yield
- Tolerance to waterlogging and extreme drought conditions
- Availability and habitant preference, e.g., submerged, floating plant, or emerging plant
- Tolerance to high PH and salinity
- Root characteristics, depth of root zone

13.4 Success Stories of Plants Used in Wastewater Treatment

13.4.1 Pistia stratiotes

P. stratiotes are common plants used in wastewater treatment from agricultural processes (Mustafa and Hayder 2021). The wide application of these aquatic plants is due to their availability, resilience in a toxic environment, bioaccumulation potential, invasive mechanisms, and biomass potentials (Mustafa and Hayder 2021). *Pistia stratiotes* are also known for treating polluted rivers with domestic wastewater. The plant exhibits COD and nutrients removal properties from Shanghai, China.

Pistia stratiotes have shown 61.70% efficiency in the removal of COD concentrations. The COD concentration was reduced in the first four days of the experiment to less than 30 mg/L from the initial concentration of 60 mg/L at the beginning of the experiment (Lu et al. 2018). The experiment indicates that *P. stratiotes* improve water quality because COD is the chemical dissolved oxygen required to break down organic matters that lead to eutrophication in water bodies (Lu et al. 2018). Therefore the removal of COD preserves the aquatic inhabitants from ecological degradation and increases the biological oxygen demand reducing the algal growth and consequently reducing organic matters (Lu et al. 2018). The phytoremediation process used in the COD removal was phytofiltration. In the same experiment using *P. stratiotes* in the domestic wastewater from a polluted river, the TN (Total Nitrogen) concentration from the *P. stratiotes* ponds reduced from the initial concentration (Day 1) of 17.25–4.01 mg/L on day 20 of the experiment (Lu et al. 2018). The experiment showed a TN removal efficiency of 77% after 20 days of treatment. The removal of total nitrogen took place through the phytodegradation process. *P. stratiotes* showed 93% efficiency in removing ammonia nitrogen (NH_4^+-N), causing a steady decline in NH_4^+-N from 13.68 mg/L on day 1 to 0.9 mg/L on day 20, respectively (Lu et al. 2018). Contrastingly, *P. stratiotes* showed no uptake of nitrate nitrogen (NO_3^--N); therefore, the concentration of NO_3^--N increased from the initial concentration (Day 1) of 0.155–5.05 mg/L to day 11 of the experiment

(Lu et al. 2018). Again, *P. stratiotes* exhibited 88% efficiency in removing total phosphorus in the water resulting in a decrease in the TP concentration from an initial concentration of 1.70 mg/L to 0.2 mg/L after 20 days of treatment (Lu et al. 2018).

13.4.2 Spirodela Polyrhiza *and* Salvinia Molesta

These macrophytes *(Spirodela polyrhiza* and *Salvinia molesta*) have been proven to have efficient phytoremediation properties in treating water from the fish farm (Hendra et al. 2017). The evidence came from an in-vivo study for 14 days at 25 ± 1 °C under fluorescent tubes (1000 lux) with a 24 h-photoperiod. The study determined the impact of macrophytes on nitrate (NO_3–N), phosphate (PO_4^{3-}), ammonia (NH_3–N), chemical dissolved oxygen (COD), turbidity, MLVSS, (a procedure that tested the impact on the fixed and volatile solids) and pH (Hendra et al. 2017). In addition, the study evaluated the biomass of the macrophytes as a result of the uptake of nitrogen, phosphorus, and ammonia (Hendra et al. 2017).

Nitrate, ammonia, and phosphates are crucial nutrients the plant takes and requires for its growth. The *S. molesta* and *S. polyrhiza* recorded no nitrate intake on day 14 because the nitrate levels in wastewater were 45 mg/L and 25 mg/L, respectively (Hendra et al. 2017). The concentration kept increasing because nitrate concentration was zero at the inception of the experiment (Hendra et al. 2017). The occurrence of nitrate in the fish water system was due to the nitrification process. Nitrification is a microbial process where ammonia is oxidised to nitrite and nitrate. Ammonia-Oxidising Bacteria (AOB) and Ammonia-Oxidising Archaea (AOA) oxidise ammonia to nitrite and produce a nitrate (Hendra et al. 2017). The macrophytes' no uptake of nitrate was due to the plant's preference to take up ammonia instead of nitrate. The study showed that both S. *polyrhiza* and *S. molesta* were efficient in phosphate uptake, removing 16.05 mg/L phosphate on day 14 (Hendra et al. 2017). The achieved high efficiency was because the plant takes up phosphate by absorption through its roots, leaves, and shoots. The plants uptake phosphate and convert it to orthophosphates, which serve the metabolic activities (ATP) for the plant during growth and building other plant structural components (Hendra et al. 2017). *S. molesta* and *S. polyrhiza* macrophytes took up all the ammonia concentration in the wastewater by days 8 and 10, respectively. The significant drop in ammonia concentration is due to the direct consumption in the nitrification process that runs concurrently with the water treatment process.

13.4.2.1 Water Quality After Phytoremediation

The phytoremediation process affects the quality of fish farm wastewater. The parameters used to check for the water quality are chemical oxygen demand (COD), mixed liquor volatile suspended solids (MLVSS), turbidity, and pH (Hendra et al. 2017). COD determines the waste water's effect on the environment once discharged (Hendra et al. 2017). Therefore, COD measures the oxygen required to oxidise soluble and particulate organic matter in the water (Hendra et al. 2017). It is an important water quality parameter as it provides an index to assess the effect of discharged wastewater on the receiving environment (Hendra et al. 2017). By the end of the experiment (Day 14), the COD level for *S. molesta and S. polyrhiza* decreased to 75 mg/L and 30 mg/L, respectively. The significant reduction of COD during the treatment was due to the filtration of suspended solids and the increased absorption of dissolved nutrients in the roots (Hendra et al. 2017). *S. molesta and S. polyrhiza* had a similar trend in pH value, and pH fluctuations were minimum for both plants, ranging between 7.62 and 7.77 (Hendra et al. 2017). Phytoremediation using *S. molesta* and *S. polyrhiza* plants improved wastewater's turbidity after 14 days of the study period. The turbidity reading for *S. molesta* decreased gradually from 298 NTU on day 0 to 54 NTU on the last day of the experiment. The same goes for *S. polyrhiza;* the turbidity decreased from 137 NTU to 5 NTU on day 14 (Hendra et al. 2017). The study also showed that both *S. molesta* and *S. polyrhiza* reduced the concentration of total suspended solids (TSS) to 40 mg/L and 23 mg/L, respectively, at the end of the experiment.

13.4.2.2 Effect of Phytoremediation on Biomass

Phytoremediation increases the fresh weight of *S. molesta* and *S. polyrhiza* (Hendra et al. 2017). The new weight of *S. molesta* increased to 142.43 g, achieving an 85% increase in weight (Hendra et al. 2017). On the other hand, the new weight for *S. polyrhiza* rose to 141.62 g, achieving an 84% increase in weight (Hendra et al. 2017). The sufficient nutrients available in the fish farm wastewater to support the growth of macrophytes is attributed to the positive increment of biomass (Hendra et al. 2017). The nutrients came from inorganic dissolved nutrients and mineralisation of the organic suspended solids, originating from uneaten feed and fish excretion (Hendra et al. 2017). Aquaculture farmers can produce valuable by-products from the biomass, such as fertilisers, biofuel, and fish feed which can ultimately generate side income (Hendra et al. 2017).

13.4.3 Myriophyllum Elatinoides *and* Eichhornia Crassipes

A similar study compared the uptake of two forms of nitrogen namely nitrogen ammonia ($NH^{+}{}_{4}$), nitrate ($NO^{-}{}_{3}$) and phosphorus ($PO^{3-}{}_{4}$) by free-floating species, namely *M. elatinoides*, *E. crassipes*, and *A. philoxeroides* in an aquatic environment consisting of different level of nitrogen ammonia (10, 20, 50, 100, 200, 400, and 600 mg/L), nitrate (1, 5, 10, 20, 30, 50, and 100 mg/L) and phosphorus (1, 5, 10, 20, 30, 50, and 100 mg/L) concentrations in a constructed wetland (Li et al. 2021). The seedlings of *M. elatinoides*, *E. crassipes*, and *A. philoxeroides* were allowed to grow for 20 days; then, they were washed with deionised water and cultivated in calcium sulfate solution for 1 day to cause starvation, which maximised the uptake of N and P by plants during the experiments (Li et al. 2021). The initial weighting of the seedlings took place, and 10 g of each seedling stayed in a 1 L flask consisting of 800 mL of nutrients at different concentrations (Li et al. 2021). The study showed that *M. elatinoides* and *E. crassipes* were more favourable to the uptake of nitrogen and phosphorus than *A. philoxeroides*. The results of this study show that the uptake of NH_4^+ was higher than the uptake of NO_3^- by the two species, with the maximum uptake rate of NH_4^+ detected at 500 mg/L in *M. elatinoides* and 400 mg/L in *E. crassipes* (Li et al. 2021). The maximum dry weight for *M. elatinoides* and E. *crassipes* were 14.1 ± 1.0 mg/g and 13.6 ± 2.4 mg/g per hour, respectively (Li et al. 2021). The results show that *M. elatinoides* adapted better to wastewater with high NH_4^+ than E. *crassipes*. The result further demonstrated higher efficiency for *M. elatinoides* and *E. crassipes* in the uptake of NH_4^+ and that both species could tolerate high NH_4^+ concentration in the water environment (up to 600 mg/L) (Li et al. 2021).

Regarding the uptake of NO_3^-, the results for *M. elatinoides* and *E. crassipes* were 4.1 ± 0.2 and 4.3 ± 0.3 mg/g dry weight. The results implied that *M. elatinoides* and *E. crassipes* adapt very well and could efficiently remove NO_3^- in highly contaminated NO_3^- concentration water environments (up to 50 mg/L) (Li et al. 2021). It's worth noting that the results show that the uptake for NH_4^+ for all the species was three times higher than NO_3^-, suggesting that two species favoured the uptake of NH^4_+ more than NO_3^-, although *E. crassipes* had the highest preference for nitrate than any of the other species (Li et al. 2021).

With regards to the uptake of phosphorus ($PO^3{}_4$), the uptake rate increased rapidly with increasing concentration, although it decreased at the maximum concentration (100 mg/L) (Li et al. 2021). At the maximum concentration of exposure to phosphorus (100 mg/L), phosphorus uptake was 4.5 and 3.6 mg/g dry weight per hour for *M. elatinoides* and *E. crassipes*, respectively (Li et al. 2021). The results of this study indicate that *M. elatinoides* and *E. crassipes* could efficiently absorb more phosphorus from high P-concentration wastewater, and their ability did not deteriorate with increasing phosphorus concentrations up to 80 mg/L (Li et al. 2021).

A different study in Shanghai, China, tested the phytoremediation efficiency of *E. crassipes and M. spicatum* in a polluted river with domestic waste. Both plants showed efficiency in removing COD in wastewater with 68.21% and 62.55%, from the initial concentrations of 66 mg/L and 72 mg/L, respectively (Lu et al. 2018). *Eichhornia crassipes* was 5% more efficient in COD removal than *M. spicatum* because of *its* rich root system. These plants use phyto-filtration to remove the COD through the roots. The root system also provides a suitable environment for microorganisms to survive (Lu et al. 2018). Once these plants have removed COD, aerobic microorganisms degrade organic matter and nutrients into inorganic compounds, which the plants then utilise through phytodegradation (Lu et al. 2018). Therefore, these plants play two roles: COD degradation and nitrogen removal and fixation.

Eichhornia crassipes and M. spicatum reduced the total nitrogen (TN) concentration from the initial concentration (Day 1) of 16.57 mg/L and

16.85 mg L^{-1} to 2.2 mg/L and 3.89 mg/L on day 20 of the experiment (Lu et al. 2018). Therefore, *E. crassipes and M. spicatum* exhibited a TN removal efficiency of 87% and 77%, respectively, after 20 days of treatment (Lu et al. 2018). The phytoremediation process of nitrogen happens through three processes which are mainly: plant uptake, nitrification/denitrification, and volatilisation. Similarly, *E. crassipes and M. spicatum* showed 96% and 93% efficiency in removing ammonia nitrogen ($NH^4{}_+$-N), respectively. The initial concentration of $NH^4{}_+$-N concentrations of 12.45 mg/L and 11.8 mg/L reduced steadily to 0.53 mg/L and 0.82 mg/L on day 20, respectively (Lu et al. 2018). *E. crassipes and M. spicatum* showed no uptake of nitrate nitrogen *($NO_3{}^-$-N).* Particularly for *E. crassipes,* the $NO_3{}^-$-N concentration increased up to day 11 of the experiment, while the $NO_3{}^-$-N concentration remained the same during exposure to *M. spicatum* throughout the entire process, indicating that the nitrification-denitrification process was negligible with *M. spicatum* (Lu et al. 2018). Plants usually take up total nitrogen and ammonium nitrogen, which they need during growth. The denitrification and volatilisation process is vital for the removal of nitrate nitrogen. With regards to the removal of total phosphorus, the *E. crassipes and M. spicatum* showed 84% and 80.55% efficiency resulting in a reduction of TP from the initial concentration of 1.89 mg/L and 1.80 mg/L to 0.30 mg/L and 0.35 mg/L, respectively, after 20 days of treatment (Lu et al. 2018).

13.5 Limitation of Phytoremediation as a Wastewater Treatment Strategy

Phytoremediation has several limitations that require further intensive research on plants and their mechanisms. Phytoremediation is generally a slow process compared with conventional treatment options. Plants yield low biomass and have a reduced root system that does not efficiently support phytoremediation. Most likely, phytoremediation does not prevent the leaching of contaminants into underground water tables (Sarma 2011). Environmental conditions also determine the efficiency of phytoremediation as the survival and growth of plants are adversely affected by extreme conditions, toxicity, and general conditions of the water bodies. In phytoremediation technology, multiple metal-contaminated waters require specific metal-accumulating plant species and therefore require extensive research before the application (Sarma 2011). The phytoremediation strategies in a site contaminated with mixed heavy metals require a selection of different plant species that conform to one another. For example, the cadmium/zinc model hyperaccumulator *Thlaspi caerulescens* is sensitive toward copper (Cu) toxicity, which becomes a problem in the remediation of Cd/Zn from soils in the presence of Cu (Sarma 2011). Despite some limitations, there is a global acknowledgement of phytoremediation technology as a better environmental sustainability strategy. Various research laboratories are currently engaged in further research activities to overcome the limitations.

13.6 Conclusion and Prospects of Phytoremediation as Wastewater Treatment in African Aquaculture

This chapter outlines that fish consumption has increased tremendously due to population growth and the quest to ensure food security. Fish aquaculture activities will grow to provide for the increasing population. Africa has the world's highest birth rate and contributes tremendously to world population growth. Therefore, there is a need to intensify aquaculture activities in Africa as one of the fastest ways to ensure food security and income generation. The sustainability of fish aquaculture on the African continent is questionable unless there is an improvement in current wastewater disposal practices. The challenges associated with aquaculture farming on the African continent are due to the inability to afford conventional treatment methods of aquaculture wastewater. The phytoremediation technique employs plants for wastewater remediation that African farmers can use. This treatment method is affordable, efficient, and easy to implement. Evidence of *P. stratiotes*, *Sp. polyrhiza*, *S. molesta, E. crassipes and M. spicatum* towards water quality improvement and removal of nitrogen and phosphorus substrates in wastewater appear in this chapter. Despite that, there is a need to conduct studies on native species and their phytoremediation capacities from the African context.

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Chapter 14
African Aquaculture: Enhancement of Water Quality for Sustainable Freshwater Finfish Culture

E. Omoregie

Abstract Though Africa's contribution to global aquaculture production is still insignificant, aquaculture in Africa has come a long way since it was first introduced over 50 years ago. Commercial finfish aquaculture in Africa is on the increase, with Egypt, Nigeria and South Africa being important producers. The attributes of Africa include under-utilized water and land resources, available and inexpensive labour, high demand for fish and a climate that favours a year-round growing period. However, the optimal use of these resources has frequently been curtailed by poor infrastructure and a lack of production inputs. The potential for expansion is nevertheless considerable but requires several enabling factors that include: a positive perception of aquaculture, sound policies at the national level, strong public institutions, availability of nutrient inputs, conducive investment policies to attract increased private-sector participation, and access to credit for commercial-scale enterprises. In addition to these is enhancing water quality within the rearing systems for improved production. Water quality within the aquaculture rearing system includes all physical, chemical, and biological factors that influence the beneficial use of water for fish cultivation. Any characteristic of water that affects the survival, reproduction, growth, production, or management of fish in any way is of critical importance to the sustainability of growing aquaculture in Africa. This review article, therefore, highlights the various water quality parameters and management of the most important parameters for sustainable aquaculture production on the African continent. The review focuses on best practices in improving pond water quality, drawing on global experiences and research findings from the African continent in improving water quality for sustainable aquaculture in meeting local demand for protein intake per capita.

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14.1 Introduction

14.1.1 Current Status of Aquaculture in Africa

Global aquaculture (both inland and marine environments, excluding aquatic plants) has risen significantly over the past two decades to approximately 85.33 million tonnes in 2019, from an annual average of 14.9 million tonnes between 1986 and 1985 as reported by FAO (2021). Globally, in 2019, inland aquaculture produced mostly farmed finfish (51.3 million tonnes, or 62.5% of the world's total), mainly in freshwater, compared with 57.7% in 2000 (FAO 2021). The rapid growth in global aquaculture production as reported by Bostock et al. (2010) has been driven by a variety of factors, including pre-existing aquaculture practices, population and economic growth, relaxed regulatory framework and expanding export opportunities. While global aquaculture production continued to be dominated by China and other Asian countries, the contribution of aquaculture to global fish production reached 48.0% in 2019, up from 6.5% in 1980 (FAO 2021). Unfortunately, Africa's contribution to global aquaculture production is still insignificant. It is however worth noting that production in the continent has increased several folds within the three decades. In 2019, production from the African region was at 2.40 million tonnes, up from 0.11 million tonnes in 1995 (Fig. 14.1) and accounted for 17.9% of

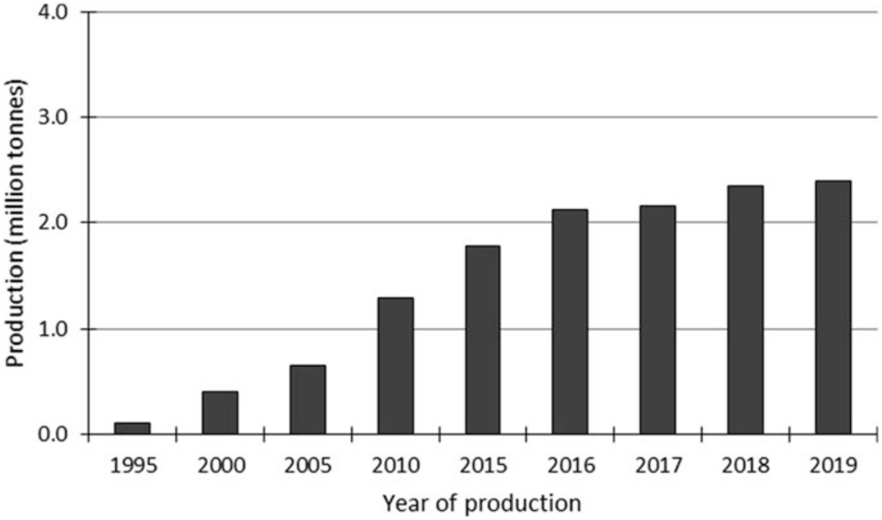


Fig. 14.1 Aquaculture production in Africa (1995 to 2019) (FAO 2020, 2021)

Table 14.1 Top 10 aquaculture producers in Africa in 2018 (Source: Adeleke et al. 2021)

No.	Country	Production (metric tonnes)	Regional share (%)	Global share (%)
1	Egypt	1,561,457	71.10	1.90
2	Nigeria	291,233	13.26	0.35
3	Uganda	103,737	4.72	0.13
4	Ghana	76,630	3.49	0.09
5	Zambia	24,300	1.11	0.03
6	Tunisia	21,756	0.99	0.03
7	Kenya	15,124	0.69	0.02
8	Malawi	9014	0.41	0.01
9	Madagascar	7421	0.34	0.01
10	South Africa	6181	0.28	0.01

total fish production in Africa (FAO 2021). Between 1995 and 2019, the region recorded a compounded annual growth of approximately 15.6% (Halwart 2020).

There is a considerable impetus for the development of aquaculture in sub-Saharan Africa (Machena and Moehl 2000). Aquaculture production in Africa is dominated by finfish in inland environments, with a production of 1.89 million tonnes in 2018, with very insignificant production of other aquatic organisms (FAO 2020). As reported by FAO (2021), Egypt and Nigeria are the only two African countries in the top ten global aquaculture producers. In 2019 production from Egypt was 1.64 million tonnes up from 0.92 million tonnes in 2010, while that from Nigeria was 0.29 million tonnes, up from 0.22 million tonnes in 2010.

In addition to Egypt and Nigeria, other key African producers are Uganda, Ghana, Tunisia, Kenya, Zambia, Madagascar, Malawi, and South Africa. Table 14.1 shows the top 10 aquaculture producers in Africa with their respective regional and global shares. These countries experienced significant growth within the past decade due to numerous factors such as capacity building in critical subject areas, embracing good governance, research and development, access to credit facilities and mainly due to the promotion of private sector-led aquaculture development (Satia 2017). Private sector-led initiatives gave rise to investments in sound management, emerging production systems, the formulation and utilization of aquafeeds and the emergence of dynamic and robust producer associations and service providers (Satia 2011; Adeleke et al. 2021). As documented by Maulu et al. (2021), aquaculture's relevance in the food production sector in Africa will depend on its ability to grow sustainably.

14.1.2 Freshwater Finfish Aquaculture Production Systems in Africa

Freshwater finfish aquaculture production systems in Africa range from small-scale to medium-scale. While small-scale systems are mainly extensive with minimal inputs, large-scale is intensive with profit being the main objective.

Small-scale to medium-scale systems, mainly carried out in rural settings and operated at household or community levels utilize extensive pond systems and are integrated to varying degrees with other agricultural enterprises. The main driving force is household or community food security. The level of intensity indicates that these systems will rely primarily on on-farm inputs including organic fertilizers and simple supplemental feeds. As reported by Jamu and Ayinla (2003) earthen ponds are the dominant production system in small to medium-scale systems in Africa. These systems generally require minimum or no capital investment and are not mechanized, with minimal paid labour in several African countries.

Large-scale systems could also be classified as commercial systems where profit is the main motive. Large-scale systems in African aquaculture production have been referred to as those having a water surface area of five hectares or more or producing more than five metric tonnes annually. These systems tend to be capital intensive, relying on wage labour, external energy sources and mechanization. There are commercial farms using ponds, cages, raceway, and recirculating systems; however, ponds are the principal production unit (Machena and Moehl 2001). Main large-scale aquaculture production systems on the African continent are in Egypt, Nigeria, and South Africa.

The use of cages in natural and artificial lakes for aquaculture production has gained increasing use in several African countries. Musinguzi et al. (2019) noted that cage aquaculture is expanding on African natural and artificial inland waters and has the potential to close the fish supply deficit in the region and provide other social benefits such as employment and income. The report by Musinguzi et al. (2019) revealed that the number of cage production systems in Africa was 263 installations in 2019, with more than 20,000 cages between them. These were divided among eight countries: Ghana having 36.1% of the installations, Uganda 17.9%, Kenya 16.4%, Tanzania 13.3%, Rwanda 8%, Zimbabwe 3.8%, Zambia 3% and Malawi 1.5%. The rise in cage culture has been attributed to the improvement of technology for cage culture in reservoirs and water bodies not suitable for conventional fisheries and the availability of technical support and high-quality inputs like fish feed or fry (Eng and Tech 2002).

14.1.3 Major Freshwater Finfish Cultured Species in Africa

Production of several species of tilapias has dominated aquaculture production on the African continent, the main reason being that aquaculture research and development on the continent have concentrated on these species (Jamu and Ayinla 2003). Other indigenous fish species with high local demand have also contributed to higher aquaculture production on the continent. For example, clariids such as the African catfish (*Clarias gariepinus*) have overtaken tilapia as major culture species in Nigeria (FAO 1999, 2022a), and the common carp (*Cyprius carpio*) production in Egypt is in decline in preference to the indigenous Nile tilapia (*Oreochromis niloticus*) (Brummett 2000). Currently, the production of the Nile tilapia from Egypt is more than 200,000 tonnes per year (FAO 2022b). This market demand trend dictating the choice of indigenous fish species for culture will likely continue in the future and direct aquaculture expansion towards fish production for niche markets. Almost half (43.6%) of African aquaculture production consists of Nile tilapia (Kausar and Salim 2017), followed by the African catfish (11.9%) and common carp (10.5%) (Tumwesigye et al. 2022).

14.2 Water Quality in Aquaculture Production System

In all aquaculture production systems, be it earthen ponds, raceways or recirculatory rearing environments, water quality depends on the physical, chemical, and biological parameters that influence the beneficial use of water that leads to anticipated fish growth. Interactions between these various parameters, either within the rearing environment or external sources, are vital to enhancing the growth of the fish being reared. It is therefore of paramount importance that African aquaculture producers are familiar with the role of these parameters and how to ensure optimal water quality within the production system.

Increasing aquaculture production within the rearing systems involves overcoming a series of limiting factors within the systems. In several African countries, emphasis has shifted to improving water quality and waste management. Assuming some minimum initial set of environmental conditions (such as proper water temperature, low dissolved oxygen, salinity, ammonia, and pH), the limitations on productivity progressively shift from providing more food to providing more oxygen and removal of growth-limiting waste products (Tucker and Hargreaves 2012).

Ibrahim and Naggar (2010), Bhatnagar and Devi (2013), Adebola et al. (2015) and Adeleke et al. (2021) have all highlighted the importance of water quality parameters in aquaculture production in Africa. Of these parameters, Ibrahim and Naggar (2010) noted that temperature, dissolved oxygen, carbon dioxide, ammonia, pH, and salinity are paramount, as uncontrolled fluctuations in these parameters lead to low production. Rutaisire et al. (2017) noted that apart from production cost and fish management practices, aquaculture production in several developing countries is highly dependent on the water quality of the rearing systems. For this reason, improved knowledge in the management and maintenance of enhanced water quality in the rearing systems will lead to improved freshwater fish production on the African continent.

14.2.1 Temperature

Suitable water temperatures for maximum growth for fish species cultured in Africa range between 25 and 32 °C. Temperature, as noted by Boyd and Lichtkoppler (1982), has a pronounced effect on chemical and biological processes within the fish-rearing environment. During colder months (when water temperatures are below 20 °C), the growth of the cultured fish is reduced due to lower metabolic activities and a reduction in food consumption (Abdel-Tawwab and Wafeek 2017). Water temperature could also affect metabolic activity, kinetics, and oxidative stress in fish (Kammer et al. 2011), thereby affecting energy metabolism and many other processes, hence unfavourable water temperature is detrimental to increased aquaculture production.

When the Nile tilapia which has an optimal temperature for growing between 25 and 28 °C (El-Sayed 2006) was exposed to cadmium under different temperature regime, Abdel-Tawwab and Wafeek (2017) observed that unfavourable water temperature combined with the energetic cost associated with the cadmium exposure resulted in altered haematological responses in the fish, ultimately leading to reduced growth in the fish (Table 14.2). In addition, the metal uptake rate in fish can increase with increasing exposure temperature (Bervoets et al. 2009). Finally, temperature itself may become a stressor, especially near the thermal tolerance limits, in which case mixture exposure principles such as antagonism and synergism may be applicable (Heugens et al. 2003).

As most aquaculture production in Africa is from earthen ponds, control of water temperature is almost non-existence as the reduced growth during colder months is compensated for by the faster growth rate during favourable months of warmer water. In the more commercial production in the recirculatory system in some African countries such as Egypt, Nigeria and South Africa, the use of electrical heaters to maintain a uniform temperature all year round is gaining acceptance despite the associated cost.

14.2.2 Carbon Dioxide

The primary sources of carbon dioxide in the aquaculture-rearing environment are derived from respiration by phytoplankton and aquatic animals, including the fish being cultured. Another primary source is the biochemical degradation of organic matter within the pond sediments. Carbon dioxide is not particularly toxic to fish, but fish generally avoid carbon dioxide concentrations above 5 mg/L (Boyd 2020), and uncontrolled level within the pond system is a limiting factors to higher production (Boyd et al. 2020). Contractions above 20 mg/l can stress the cultured fish if they are exposed for several hours, while higher levels can have a respiratory and physiological effect, eventually leading to death. Generally, the overall effect of higher

Table 14.2 Changes in red blood corpuscles (RBCs), haematocrit (Ht), and haemoglobin (Hb) in Nile tilapia exposed to waterborne Cd concentrations at different water temperatures for 8 weeks (Source: Abdel-Tawwab and Wafeek 2017)

Water temperature (°C)	Cd conc. (mg/L)	RBCs ($\times 10^{6}$/μL)	Ht (%)	Hb (g/L)
		Individual treatment means[a]		
20	0.0	1.252^{c}	12.63^{c}	44.2^{c}
24		1.601^{a}	15.12+	$56.2^{a,b}$
28		1.612^{a}	15.54^{a}	58.3^{a}
32		1.513^{b}	13.85^{b}	50.3_{b}
20	0.5	0.936^{e}	9.24^{e}	28.3^{e}
24		1.004^{d}	11.77^{d}	31.8^{d}
28		1.008^{d}	11.87^{d}	32.5^{d}
32		$0.987^{d,e}$	9.28^{e}	$30.0^{d,e}$
Pooled SLM		0.057	0.524	2.35
		Means of main effects		
Water temp.				
20		1.094	10.94	36.3
24		1.303	13.45	44.0
28		1.310	13.71	45.4
32		1.250	11.57	40.2
	Cd conc.			
	0.0	1.495	14.29	52.3
	0.5	0.984	10.54	30.7
Two-way ANOVA		*P* value		
Water temperature		0.0001	0.0001	0.0001
Cd concentration		0.0001	0.0001	0.0001
Temperature × Cd conc.		0.0001	0.0001	0.0001

[a] Treatments means represent the average values of three aquaria per treatment. Duncan multiple range test was conducted for individual means only if there was a significant interaction (ANOVA: $P < 0.05$). Means followed by the same letter are not significantly different

[b–e] Means followed by the same letter are not significantly different ($P > 0.05$)

levels of carbon dioxide concentration in water is the reduction of respiratory efficiency and the tolerance of cultured fish to low dissolved-oxygen concentrations.

Carbon dioxide concentrations in aquaculture ponds typically are 5–10 mg/L in the morning hours but can exceed 20 mg/L in ponds with significant feed inputs. Carbon dioxide concentrations in fishponds are usually highest when dissolved-oxygen concentrations are lowest (Hargreaves and Brunson 1996; Makori et al. 2017) due to the relationship between the production of carbon dioxide during respiration and its day-time consumption during photosynthetic activities within the pond water. There is a diurnal cycle of carbon dioxide within the pond water, with increased levels during the night and decreased levels during the daytime (Fig. 14.2).

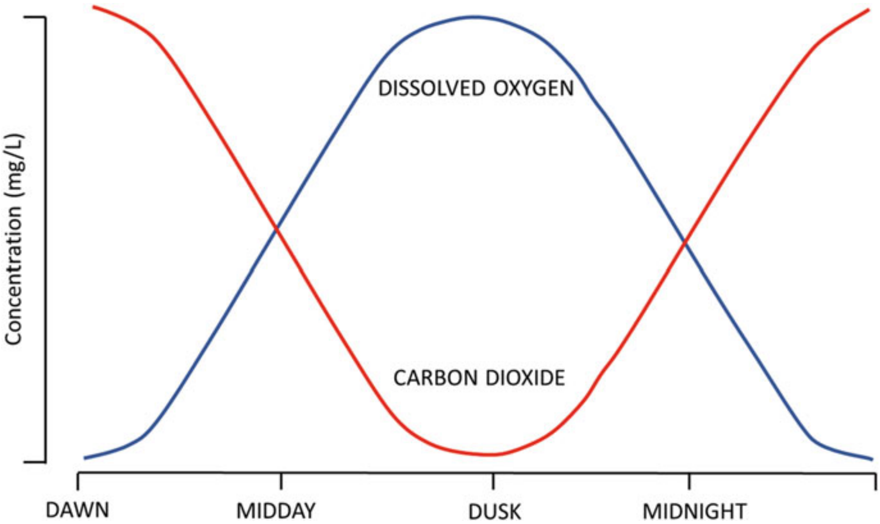


Fig. 14.2 Diurnal variations of carbon dioxide and dissolved oxygen levels in a fish pond (Source: Hargreaves and Brunson 1996)

The relationship between reduced tilapia production in Africa and carbon dioxide levels in the rearing environment has been reported in some countries. In a study by Makori et al. (2017), the growth of the Nile tilapia, *Oreochromis niloticus* in earthen ponds in Kenya, low pH values were observed in these ponds because of elevated carbon dioxide levels; this subsequently led to low tilapia yield in these ponds.

14.2.3 Dissolved Oxygen

In Africa, dissolved oxygen is probably the most critical limiting factor within the rearing environment for aquaculture species production due to higher water temperatures all year round. Even though the atmosphere is a vast reservoir of oxygen, the solubility of oxygen in pond water is highly dependent on other factors, such as temperature, phytoplankton concentrations, excess organic wastes, and stocking density. Though oxygen will diffuse into the water from the atmosphere, its rate of diffusion is relatively prolonged. Photosynthesis by phytoplankton is the primary source of dissolved oxygen for cultured species. Due to photosynthetic activities within the water, dissolved oxygen concentrations in production systems undergo a diurnal pattern over a 24-hr period with the highest concentrations usually being in the daytime and the lowest concentrations at night (Fig. 14.2).

Dissolved oxygen can rapidly be lost from the rearing water, the main reason being respiratory activities of the biota (including the fish being cultured) and biodegradation of organic materials. For enhanced aquaculture production, more

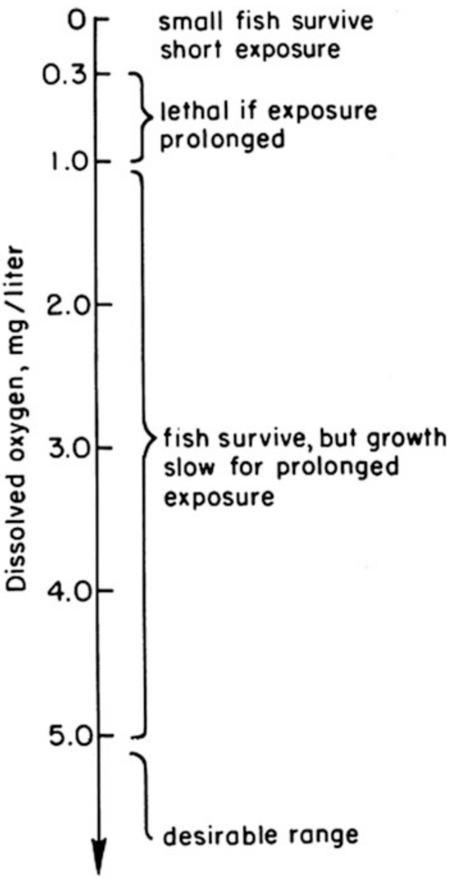


Fig. 14.3 Effects of dissolved oxygen levels on pond cultured fish species (Source: Boyd and Lichtkoppler 1979)

oxygen must enter the water than being utilized for respiratory activities and biodegradation. Cultured species require adequate levels of dissolved oxygen for survival and growth and the minimum levels for survival will depend on the length of exposure. Consistence pond water of ranges above 5 mg/l is preferable for most species, while ranges below 5 mg/l over considerable period are considered not adequation for good production (Fig. 14.3). A fish may survive a given minimum level for 1 day or so; however, when exposure is for several days, it will die. Low levels of dissolved oxygen also predispose the culture species to become more susceptible to diseases which will eventually lower production.

It is well known that tilapia can tolerate hypoxic and even anoxic conditions for short periods and are thus better suited than other species to hyper eutectic conditions that may exist in static water aquaculture systems (Lim et al. 2006). This is one of the most important contributing factors to why the successful production of pond tilapias has been sustained in several African countries. Studies have shown that the incipient oxygen requirements for the Nile tilapia (*Oreochromis* niloticus) are between 1.39 mg/l and 2.92 mg/L (Tsadik and Kutty 1987). These authors also reported that the food conversion ratio (FCR) for the Nile tilapia was inversely proportional to the dissolved oxygen level (1.45 at higher dissolved oxygen levels and 6.75 at lower dissolved oxygen levels).

14.2.4 Ammonia

Ammonia, which is a colourless, pungent gas reaches cultured fish production systems as a product of the biochemical metabolism of animals (including fish being culture) and biochemical bacterial degradation of organic materials. The un-ionized component of this gas is extremely toxic to the cultured fish at levels (above 3.0 mg/l); fortunately, concentrations in the rearing system are not too high to affect fish growth. The pH and temperature of the water regulate the production of un-ionized in the rearing system.

Ammonia blocks oxygen transfer from the fish gills to the blood and can cause immediate and long-term gill damage (Joel and Amajuoyi 2010). Studies have also revealed that ammonia chronic un-ionized ammonia exposure may affect pond fish in several ways, for example, gill hyperplasia, muscle depolarization, hyperexcitability, convulsions and finally, death (Ip et al. 2001).

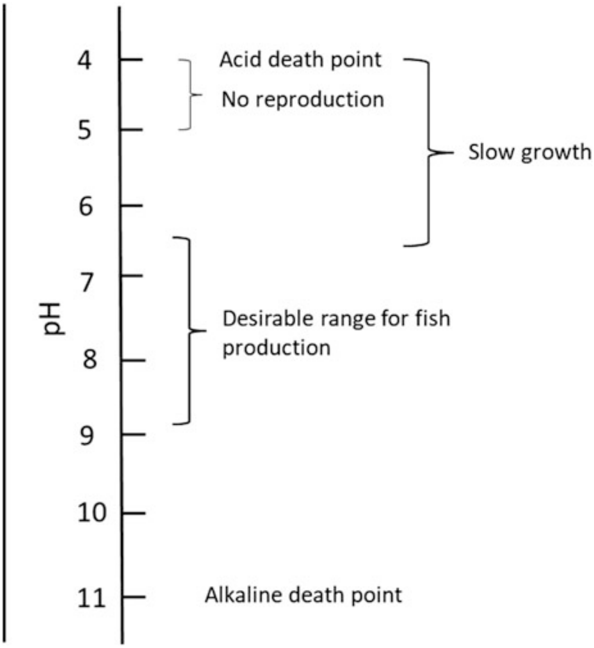
Ip et al. (2004) noted that in the tropics, air-breathing fish species, including the African catfish, can tolerate toxic levels of ammonia when stranded in puddles of water. Such environmental ammonia tolerance is usually associated with a high tolerance of ammonia at the cellular and subcellular levels (Saha and Ratha 1998). The African lungfish *Protopterus aethiopicus* was observed by Loong et al. (2007) to defend itself against ammonia toxicity when confronted with high concentrations (30 or 100 mmol/l) of environmental ammonia, as the *Protopterus aethiopicus* could decrease its skin permeability to ammonia when exposed to high levels of environmental ammonia.

14.2.5 pH

The pH, which measures how acidic or alkaline water is, depends on several factors interacting within the production system; most importantly is the level of carbon dioxide. The optimum pH range for most aquatic organisms is 6.5–8.5, and the acid and alkaline death points are around pH 4 and pH 11, respectively (Boyd 2020) (Fig. 14.4). During periods of active photosynthesis (daytime), carbon dioxide is removed from the water by phytoplankton and other aquatic plants, thereby increasing the water alkaline levels, hence pH is highest at dusk and lowest at dawn. Fish and other aquatic animals avoid high carbon dioxide concentrations.

Wokoma and Marioghae (1996) reported that the median lethal time (LT_{50}) for the tilapia, *Tilapia guineesnsis* increased with pH from 1.2 h at pH 2.0 to 62 h at pH 3.0. the critical median pH was 3.3 (Fig. 14.5).

Fig. 14.4 Effect of pH on pond cultured fish species (Source: Boyd and Lichtkoppler 1979)



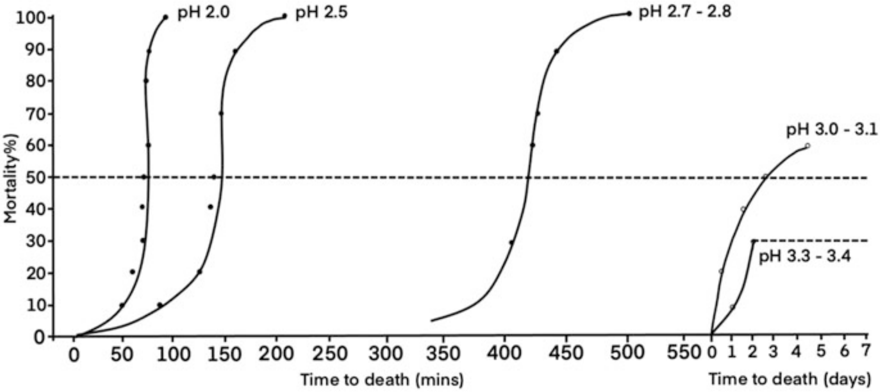


Fig. 14.5 Time to death of *Tilapia guineensis* juveniles in experimental tanks with various pH levels (Source Wokoma and Marioghae 1996)

Uzoka et al. (2015) observed that the optimum pH range for the best growth of the African catfish, *Clarias gariepinus* is between 6 and 7, while at values below 5 and above 8, survival rates were grossly affected (Fig. 14.6).

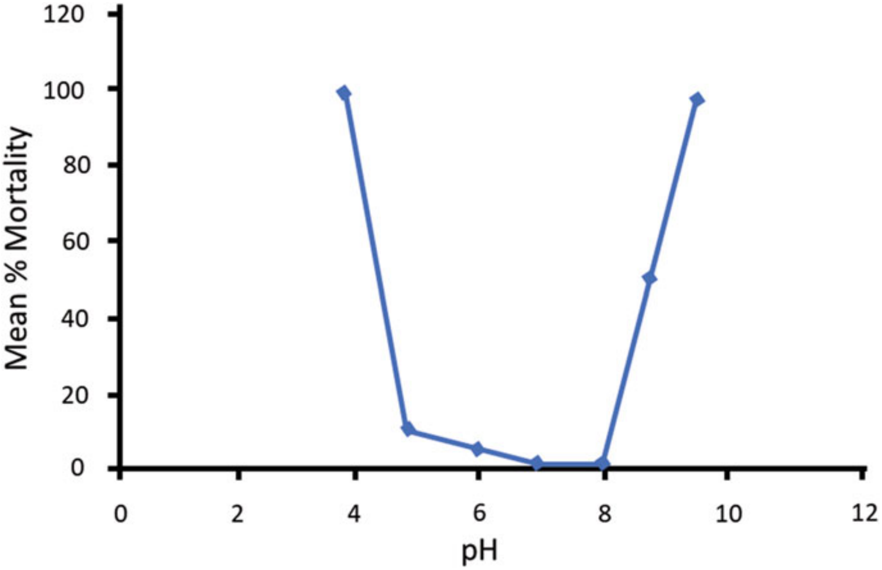


Fig. 14.6 Mortality of the African catfish, *Clarias gariepinus* reared at varying pH values at 6.0 mg/l of dissolved oxygen and 26.5 °C temperature. (Source: Uzoka et al. 2015)

14.2.6 Salinity

Salinity, the total concentration of all dissolved ions in water, is essential for thriving freshwater fish culture as the osmotic pressure of water increases with increasing salinity. Most aquaculture species have a relatively wide range of salinity tolerance; however, changes outside the optimal range lead to stress, and, if extreme enough, death could result (Ridha 2008; Qiang et al. 2013; Boyd 2020). Research suggests that a shift in salinity from the iso-osmotic point is associated with a reduction in fish growth and feed utilization, likely due to an increase in the energy required for osmoregulation (Sardella and Brauner 2008).

14.3 Water Quality Management in Africa Freshwater Fish Culture Systems

The maintenance of good water quality within the rearing system is a prerequisite for the successful production of cultured fish to meet the protein requirements of the ever-rising population on the African continent. Continuous monitoring of water quality parameters should be of high priority so that conditions that can negatively affect the growth of cultured fish be avoided for the sustainability of the system. Monitoring of a single parameter does not usually tell much, but monitoring several parameters put together can serve as indicators of dynamic processes occurring in the pond.

An intensive culture system requires intensive fish feeds to be provided. This result in nitrogenous compounds and other organic matter remains building up as wastes in the water leading to reduced dissolved oxygen (Hoang et al. 2020), eutrophication (Cao et al. 2016; Wu et al. 2020), algal bloom (Gobler et al. 2012; Sin and Lee 2020) and microbe growth including pathogenic bacteria (Liu et al. 2020). Additionally, high ammonia concentrations induce oxidative stress, immunosuppression, and even tissue damage in fish (Wang et al. 2020). High nitrite levels lead to inhibitory effects on the immune system (Guo et al. 2020).

Gondwe et al. (2011) demonstrated that establishing cage culture in the lake was a significant source of nutrients in the lake's epilimnion. Estimates from aquaculture production records indicate that 71% to 88% of nutrients added through the feed to fish cages in Lake Malawi are lost in the surrounding environment from fish cages.

Most of the water quality problems explained above can be solved with adequate water exchange, though this is not practicable with a cage culture system. However, water has always and will continue to be challenged in several African countries, hence the need for proper water quality management.

14.3.1 Maintenance of Dissolved Oxygen

In aquaculture systems, problems with inadequate dissolved oxygen for cultured fish are the consequences of eutrophication arising from unconsumed fish feeds and faecal droppings. The appearance of phytoplankton bloom indicates eutrophication; in the fertilized system, fertilization should be halted. In addition to maintaining the proper fish stocking density and avoidance of overfeeding (as decomposing faeces and wasted feed both lead to oxygen depletion), there are several methods to maintain appreciable dissolved oxygen in rearing systems, however, the best practicable and effective method is the use of mechanical devices such as tractor powered wheel aerators as reported by Boyd et al. (2018). The agitation and circulation of water caused by these mechanical devices increase the diffusion of atmospheric oxygen into the pond water.

14.3.2 Maintenance of Adequate pH RANGE

Pond water with high levels of alkalinity and low hardness would usually have above range pH value during eutrophication for an appreciable growth rate of cultured fish. Boyd and Lichtkoppler (1979) recommended the application of ammonium fertilizers to lower the pH of pond water. The ammonium ion in the applied fertilizer is nitrified to nitrate with the release of hydrogen ions, eventually lowering the pond's pH. On the other hand, in pond water with extremely low pH levels, agricultural limestone or other liming materials often are applied to neutralize bottom soil acidity and maintain an adequate pH within the pond water (Han et al. 2014). However, requirements for using modified lime on acid-sulphate lands or pyritic, an aquaculture regime, are found to be inappropriate and unreliable (Boyd 2017). Fitrani et al. (2020) observed that hydrated lime ($Ca(OH)_2$) and burnt lime (CaO) administered in acid-sulphate-containing soil and water raised pond pH from as low as 2.69 to desirable levels of 7.4–8.6. Fitrani et al. (2020) revealed that soil characteristics, type, and dosage of lime.

material are crucial elements to be considered in improving the pond bottom soil with acid sulphate content. Results from this study have demonstrated that every liming material used in different dosages will affect both soil pH and water pH significantly, which will reduce the percentage of organic carbon and enhance the alkalinity at varying degrees.

14.3.3 Best Practices for Fertilizer Applications

Both inorganic and organic fertilizers have often been applied in semi-intensive aquaculture systems to improve the primary production of the ponds and subsequently improve fish growth (Das et al. 2005). Inorganic fertilizers used in fishponds are the same for crops. Boyd and Lichtkoppler (1979) noted that primary nutrients in inorganic fertilizers are usually present as relatively simple compounds (nitrogen, phosphorus, and potassium) dissolved to give nitrate, ammonium, phosphate or potassium ions. However, due to the rising cost of inorganic fertilizers, especially in several African countries, greater attention has shifted to using organic fertilizers (animal manuals), as reported by Bwala and Omoregie (2009) in aquaculture production.

Various organic manures of animal origins have been tried with pond tilapia production on the African continent with good results (Naiel et al. 2022). In their research to investigate the effects of various organic fertilizers with or without adsorbents on the productivity, antioxidant status and immune responses of the Nile tilapia raised in cement ponds, these authors noted that it is possible to infer that the use of fish sludge in the presence of sawdust showed a preferable effect on performance, survival (Table 14.3), antioxidant and immune status of exposed fish (Table 14.4) without altering the biochemical parameters (Table 14.5) followed by fish sludge plus sugar beet pulp compared to the other treatments. This revealed the potential properties of fish sludge that enable its application as an organic fertilizer in fishponds. The utilization of an effective adsorbent such as sawdust or sugar beet pulp is recommended to purify water from impurities; however, sawdust was somewhat more effective than sugar beet pulp.

Bwala and Omoregie (2009) reported improved tilapia (*Oreochromis niloticus*) yield in ponds fertilised with the appropriate level of pig manure as the nutrients in the manure stimulated primary productivity in the pond leading to improved water quality (Table 14.6). In addition to stimulating primary productivity, fish production

Table 14.3 Growth performance, feed efficiency and survival rate of the Nile tilapia cultured in ponds fertilised with several types of organic wastes for 56 days (Source: Naiel et al. 2022)

	Experimental groups					
Parameters	CNT	CD	FS	FS + SD	FS + SBP	*P* value
IW(g)	51.96 ± 0.22	52.23 ± 0.19	52.46 ± 0.15	52.21 ± 0.17	52.13 ± 0.17	0.607
FW (g)	80.9 ± 0.25^{c}	81.5 ± 0.40^{c}	103.4 ± 0.75^{a}	104.7 ± 1.69^{a}	99.7 ± 0.20^{b}	<0.001
WG (g)	28.96 ± 0.25^{c}	29.29 ± 0.33^{c}	$50.90 \pm 0.81^{a,b}$	52.45 ± 1.70^{a}	47.59 ± 0.34^{b}	<0.001
SGR (%)	0.79 ± 0.74^{c}	0.80 ± 0.67^{c}	$1.21 \pm 0.15^{a,b}$	1.24 ± 0.30^{a}	1.16 ± 0.83^{b}	<0.001
FI (g)	56.13 ± 0.18	55.86 ± 0.14	55.31 ± 0.16	55.74 ± 0.19	55.75 ± 0.17	0.115
FCR (g/g)	1.94 ± 0.12^{a}	1.91 ± 0.20^{a}	$1.09 \pm 0.21^{b,c}$	1.07 ± 0.13^{c}	1.17 ± 0.02^{b}	<0.001
PER (g/g)	1.72 ± 0.16^{c}	1.75 ± 0.18^{c}	$3.07 \pm 0.52^{a,b}$	3.14 ± 0.19^{a}	2.85 ± 0.24^{b}	<0.001
SR (%)	100	100	100	100	100	0.191

Values within the same row having different superscripts are significantly different ($P < 0.05$)
Data were presented as the mean ± standard error.
CNT: control group with no fertilization; *CD*: a fertilized group with cow dung; *FS*: a fertilized group with fish sludge; *FS + SD*: a fertilized group with fish sludge combined with sawdust; *FS + SBP*: a fertilized group with fish sludge combined with sugar beet pulp; *IW*: initial weight (g); *FW*: final weight (g); *WG*: weight gain (g); *SGR*: specific growth rate (%/d)2; *FI*: feed intake (g); *FCR*: feed conversion ratio (g/g); *PER*: protein efficiency ratio (g/g); *SR*: survival rate (%).
$^{a\text{–}c}$The significance value of $P < 0.05$ provided in the row immediately below the Table

using manure may be similar to or even more significant than production using inorganic fertilisers, as the fish can also feed directly on the manure.

In an investigation by Elnady et al. (2016) on the impact of fish farm management on the physicochemical properties of water and sediments in earthen ponds in Egypt, the annual average dissolved oxygen concentrations were slightly higher in the fertiliser fish farm compared to the unfertilised farm, this they attributed to the presence of higher phytoplankton density induced by organic fertilization and accompanied by the higher photosynthetic rate of oxygen production.

14.3.4 Phytoplankton Management

Phytoplankton plays a significant role in stabilizing the pond ecosystem, minimizing the fluctuations of water quality and serving as the primary source of energy flow within the pond; for this reason, the monitoring and management of the phytoplankton population in aquatic production is very vital for improved fish production on the African continent. A healthy phytoplankton population in the pond enriches the

Table 14.4 Serum biochemical parameters of Nile tilapia reared in fertilized ponds with several organic wastes (Source: Naiel et al. 2022)

Parameters	Experimental groups					*P* value
	CNT	CD	FS	FS + SD	FS + SBP	
Serum protein constituents						
TP (g/dL)	5.64 ± 0.16	6.01 ± 0.13	5.65 ± 0.23	5.79 ± 0.17	6.15 ± 0.14	0.095
ALB (g/dL)	3.44 ± 0.07^{b}	3.72 ± $0.10^{a,b}$	3.95 ± 0.08^{a}	3.81 ± $0.21^{a,b}$	4.31 ± 0.44^{b}	<0.001
GLOB(g/dL)	2.20 ± 0.14	2.27 ± 0.15	1.69 ± 0.24	1.99 ± 0.26	1.84 ± 0.23	0.113
ALB: GLOB	1.59 ± 0.23	1.67 ± 0.13	2.42 ± 0.25	2.08 ± 0.32	2.58 ± 0.49	0.019
Serum hepatic and renal indicators						
ALT (U/L)	92.01 ± 1.61^{b}	102.30 ± 1.55^{a}	95.83 ± $1.18^{a,b}$	97.48 ± $0.71^{a,b}$	98.87 ± $0.51^{a,b}$	0.006
AST (U/L)	70.98 ± 0.64	66.20 ± 1.95	66.71 ± 0.56	66.75 ± 1.19	68.08 ± 0.72	0.159
Urea(mg/dL)	1.31 ± 0.11^{b}	1.44 ± 0.78^{b}	2.07 ± 0.19^{a}	1.29 ± 0.48^{b}	1.46 ± 0.43^{b}	0.011
Creatinine (g/dL)	0.004 ± 0.11	0.004 ± 0.21	0.005 ± 0.23	0.006 ± 0.03	0.006 ± 0.14	0.107

Values within the same row having different superscripts are significantly different ($P < 0.05$). Data were presented as the mean ± standard error

CNT: control group with no fertilization; *CD*: a fertilized group with cow dung; *FS*: a fertilized group with fish sludge; *FS* + *SD*: a fertilized group with fish sludge combined with sawdust; *FS* + *SBP*: a fertilized group with fish sludge combined with sugar beet pulp; *TP*: total protein; *ALB*: albumin; *GLOB*: globulin; *ALB/GLOB*: albumin: globulin; ratio; *ALT*: Alanine Aminotransferase; *AST*: Aspartate transaminase

^{a,b}The significance value of $P < 0.05$ provided in the row immediately below the Table

system with oxygen through photosynthesis and lowers the levels of carbon dioxide, ammonia, nitrite, and hydrogen sulphide. Using ammonia as a nitrogen source for growth can reduce unionised ammonia, which can be toxic to aquatic animals at relatively low concentrations. In ponds where supplemental feeding is limited, as in several African countries, phytoplankton form an abundant base of the food web, as they are the leading primary producers and serve as an essential food source for other organisms. In a study by Degefu et al. 2011 on fish cage farming in the Rift Valley and North Shoa reservoirs in Ethiopia, they noted the significance of phytoplankton in improving fish production. Notwithstanding the beneficial aspects of phytoplankton in aquaculture ponds, it is commonly accepted that most water quality problems in aquaculture ponds result from the unmanaged growth of phytoplankton communities (Smith 1991).

Dawah and Gomaah (2005) and El-Otify (2015) highlighted the significance of fertilization with inorganic and organic fertilisers in managing a healthy phytoplankton population to improve pond water quality in Egyptian aquaculture, which has subsequently led to Egypt becoming the top producer of farmed fish in Africa.

Table 14.5 Antioxidant and immunity activities of Nile tilapia reared in fertilized ponds with several organic wastes (Source: Naiel et al. 2022)

Parameters	Experimental groups					*P* value
	CNT	CD	FS	FS + SD	FS + SBP	
Oxidative stress assay						
GSH (nmol/L)	2.83 ± 0.22^{c}	5.06 ± 0.18^{b}	$5.80 \pm 0.36^{a,b}$	6.32 ± 0.20^{a}	$5.62 \pm 0.41^{a,b}$	<0.001
CAT (U/L)	100.2 ± 0.97^{b}	108.3 ± 0.21^{b}	122.8 ± 0.87^{a}	124.7 ± 0.81^{a}	125.2 ± 0.45^{a}	<0.001
MDA (IU/ml)	$13.98 \pm 0.13^{a,b}$	14.40 ± 0.35^{a}	12.93 ± 0.19^{b}	10.39 ± 0.24^{c}	9.88 ± 0.32^{c}	<0.001
TAC (ng/ml)	0.13 ± 0.58^{d}	0.14 ± 0.70^{d}	0.26 ± 0.22^{c}	0.35 ± 0.85^{b}	0.41 ± 0.67^{a}	<0.001
Immunity parameters						
ACH50(U/ml)	450.4 ± 0.66^{d}	569.4 ± 0.16^{c}	699.5 ± 0.10^{b}	$750.1 \pm 0.43^{a,b}$	803.8 ± 0.21^{a}	<0.001
Lysozyme (μg/ml)	19.36 ± 0.26^{c}	23.17 ± 1.02^{b}	30.47 ± 0.85^{a}	30.73 ± 0.39^{a}	30.87 ± 0.72^{a}	<0.001
NBT (mg/ml)	0.32 ± 0.33^{b}	0.82 ± 0.83^{a}	0.90 ± 0.69^{a}	0.89 ± 0.36^{a}	1.02 ± 0.31^{a}	0.001

Values within the same row having different superscripts are significantly different ($P < 0.05$). Data were presented as the mean ± standard error

CNT: control group with no fertilization; *CD*: a fertilized group with cow dung; *FS*: a fertilized group with fish sludge; *FS + SD*: a fertilized group with fish sludge combined with sawdust; *FS + SBP*: a fertilized group with fish sludge combined with sugar beet pulp; *GSH*: glutathione reductase; *CAT*: catalase; *MDA*: malonaldehyde; *TAC*: total antioxidant activity; *ACH50*: total complement activity; *NBT*: nitro blue tetrazolium

$^{a–c}$The significance value of $P < 0.05$ provided in the row immediately below the Table

Table 14.6 Mean values (±)* of water quality parameters in various experimental tanks during period of investigation (Source: Bwala and Omoregie)

Parameters	Treatment				*P* – value
	LCPD	MCPD	HCPD	Control	
DO (mg/l) - day	7.84 ± 0.38	8.92 ± 0.44	7.77 ± 0.56	7.77 ± 0.47	<0.01
DO (mg/l) - Night	5.28 ± 0.95	6.91 ± 1.03	6.82 ± 0.14	6.80 ± 1.08	<0.01
FCD (mg/l) - day	0.07 ± 0.02	0.10 ± 0.03	0.15 ± 0.034	0.05 ± 0.02	<0.01
FCD (mg/l) - Night	1.04 ± 0.02	1.00 ± 0.07	0.98 ± 0.02	1.00 ± 0.01	<0.001
TA (mg/l)	74.51 ± 2.30	70.92 ± 2.74	70.15 ± 2.81	63.63 ± 2.82	<0.01
pH (mg/l)	9.20 ± 0.10	9.50 ± 0.10	9.59 ± 0.11	8.99 ± 0.16	<0.05
Phosphate (mg/l)	0.03 ± 0.01	0.05 ± 0.01	0.05 ± 0.01	0.03 ± 0.01	<0.01
Nitrate (mg/l)	5.96 ± 1.29	8.17 ± 1.25	9.34 ± 1.47	1.51 ± 0.14	<0.01
Ammonia (mg/l)	0.29 ± 0.10	0.45 ± 0.12	0.55 ± 0.13	0.18 ± 0.06	<0.05
Temp (°C) - day	26.10 ± 0.37	26.28 ± 0.34	26.33 ± 0.35	26.56 ± 0.34	<0.001
Temp (°C) – Night	26.13 ± 0.48	25.25 ± 0.48	26.13 ± 1.18	26.25 ± 0.96	<0.001

*Values with different superscripts in a row are significantly different ($P < 0.05$)

DO: Dissolved oxygen; *FCD*: Free carbon dioxide; *TA*: Total alkalinity; *LCPD*: Low concentration of pig dung; *MCPD*: Medium concentration of pig dung; *HCPD*: High concentration of pig dung; Control (No-manure)

Otieno et al. (2021) observed improved growth of the African catfish when reared in phytoplankton enriched pond fertilized with both inorganic and organic fertilizers compared to unfertilized ponds, which was low in phytoplankton population.

14.3.5 Best Practices to Reduce Aquaculture Waste for Improved Water Quality

The growth in aquaculture production in Africa has led to the increased use of fish feed applied to the culture system. Unconsumed feeds eventually lead to poor water quality. In addition to unconsumed feeds, Turcios and Papenbrock (2014) observed that undigested feed ingredients, which are passed as faecal droppings by cultured fishes, also significantly lead to poor water quality. Similarly, a high volume of wastes in the rearing pond, especially toxic inorganic nitrogenous substances (NH_4^+ and NO_2^-), form part of the significant water quality problems in intensive African aquaculture systems as reported by Akinwole et al. (2016). For these reasons and others, the control and management of this waste play a significant role in improving water quality. Feed and feeding systems can effectively reduce wastes resulting from the fish feed through proper management of the inputs into the culture system.

To reduce waste arising from unconsumed fish feeds in the ponds, Westers (1995) recommended the following:

- That the species and fish size-specific potential performance of any diet to be supplied must be known,
- There should be knowledge of the biomass of the fish in the system,
- Adequate information on the health and physiological status of the fish must be available,
- Uniformity in the size of fish is very important for them to accept the same size of pellet,
- The feed should be sieved to remove dust and broken pellets before being fed, and.
- The feed must be fed effectively to ensure little or no waste results from the uneaten feed.

The use of grains that are low in phytate is also encouraged in fish feed formulation; this is to reduce the amount of phosphorus released into the water through unconsumed feed or fish metabolic waste. Hardy (2010) reported that the majority of the phosphorus in plant protein cannot be utilized by fish, which are monogastric animals. Orisasona and Ajani (2015) observed improved growth rate and mineral utilization in the African catfish, *Clarias gariepinus* fed phytase-supplemented toasted lima bean. These authors attributed the recorded improved performance to better water quality parameters in the culture medium as phosphorous in the diets was utilized by the fish, thereby reducing excessive eutrophication in the rearing system.

Table 14.7 Haematological parameters of *Clarias gariepinus* juveniles reared in alum and *Moringa oleifera* seed powder treated fish tank water (Source: Akinwole et al. 2016)

Parameters	Before	Control	Alum treated water	Moringa treated water
PCV (%)	35 ± 0.00	25.67 ± 5.03^{a}	17.00 ± 1.73^{b}	27.00 ± 1.73^{a}
Hb (g/100 ml)	11.6 ± 0.00	8.37 ± 1.60^{a}	5.37 ± 0.12^{b}	8.53 ± 0.15^{a}
RBC (10^3/mm^3)	3.21 ± 0.00	2.18 ± 1.04^{a}	1.14 ± 0.01^{b}	2.58 ± 0.55^{a}
WBC (mm^3)	14,000 ± 0.00	$12{,}933.33 \pm 3010.54^{a}$	$20{,}300 \pm 259.81^{b}$	$14{,}950.00 \pm 3377.50^{a}$
Platelet (mm^3)	220,000 ± 0.00	$168{,}333.33 \pm 62{,}947.0^{a}$	$266{,}666.67 \pm 37{,}527.77^{a}$	$177{,}666.67 \pm 89{,}645.60^{a}$
Lymphocytes (%)	70 ± 0.00	64.67 ± 5.86^{a}	48.67 ± 2.31^{b}	60.00 ± 5.57^{a}
Heterophils (%)	23 ± 0.00	27.33 ± 6.66^{a}	44.00 ± 1.73^{b}	34.33 ± 4.16^{c}
Monocytes (%)	3 ± 0.00	3.67 ± 0.58^{a}	3.67 ± 0.58^{a}	3.33 ± 1.53^{a}
Eosinophils (%)	4 ± 0.00	4.00 ± 1.00^{a}	2.67 ± 1.15^{a}	2.67 ± 1.53^{a}
Basophils (%)	0 ± 0.00	0.33 ± 0.58^{a}	1.00 ± 0.00^{b}	0.00 ± 0.00^{c}

Note: Values are expressed as mean ± SD. The values with different superscripts are significantly different ($P < 0.05$)

The settleable waste solids in the pond can be removed when accumulated through properly placed drains at the bottom of the cultured tank, while the suspended solids are more difficult to remove. The usual method for removing suspended solid wastes is by flocculation by adding coagulant or flocculation aids. Numerous substances have been used as coagulants in solid waste removal from water, including synthetic and natural materials such as aluminium sulphate (alum), ferric chloride, ferrous sulphate, and lime (Ebeling et al. 2004). One major drawback is the adverse impacts of these substances on the physiological effects of cultured species. Using agro-based materials as coagulants in fish tanks is receiving promising results (Raghuwanshi et al. 2002; Akinwole et al. 2016). One of such is *Moringa oleifera*. In an investigation on the haematological responses of the African catfish, *Clarias gariepinus*, Akinwole et al. (2016) reported that the fish cultured in tanks which had *Moringa oleifera* as a coagulant for the removal of solid waste from the tanks, did not exhibit signs of haematological impairment and were healthier than their counterparts in tanks with alum and tanks without any form of coagulant (Table 14.7).

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Chapter 15
Nutrient Budget of Cage Fish Culture in a Lacustrine Environment: Towards Model Development for the Sustainable Development of Nile Tilapia (*Oreochromis niloticus*) Culture

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Abstract Carried out fundamentally in an open system, cage culture-derived nutrients can exacerbate the quality of the lacustrine environment. Information on nutrient loading from African inland waters is scarce, yet sustainable development of fish cage culture depends on it. This chapter reviews siting of fish cages, nutritional content, digestibility of fish feeds, and nutrient load in wastes of Nile tilapia in African inland waters. In addition, this chapter proposes a theoretical model for nutrient (nitrogen N and phosphorus P) budget in a Nile tilapia cage aquaculture farm to calculate the amount (kg) of N and P produced and released to the environment for each ton of fish produced basing on best and worst-case scenarios. The review shows that majority of the cages are sited nearshore and/or in shallow areas that could exacerbate environmental challenges. Poor digestibility of fish feeds, particularly P, raises concern due to the risk of eutrophication. The majority of the feeds used in African inland waters for cage fish culture recorded N deficiency in relation to P that could lead to poor retention, hence high nutrient loading into the

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environment. The theoretical model shows that about 46% of N and 39% of P from feed input are released into the environment for each tonne of tilapia produced. However, when the feed loss is high but at the same time the nutrient retention in fish is inefficient, 91% of N and 89% of P from feed input are discharged into the environment. Sensitivity analysis shows that nutrient loading from cage culture is very sensitive to feed loss, FCR and nutrient retention. The paper concludes with recommendations that need to be considered to minimise nutrient loading and its impact on the environment.

Keywords Nile tilapia · Cage culture · Digestibility, Nitrogen, Phosphorus · Nutrient loads

15.1 Introduction

Globally, wild fish stocks are at their production limit at a time of rapid human population growth, urbanisation and income increase have sent demand for fish protein skyrocketing (Akintola et al. 2013; FAO 2016; Anderson et al. 2017). The dwindling catches have increased the interest in cage culture as an alternative source of fish (Aura et al. 2017; Musinguzi et al. 2019; Hamilton et al. 2020; Musa et al. 2021a), and aquaculture will necessarily play a central role in bridging the widening gap between fish demand and its supply (FAO 2018; Obiero et al. 2019; FAO 2020).

Cage fish culture is an old practice and dates to the late 1800 in Southeast Asia (Bao-Tong 1994) but has recently expanded throughout the world due to its benefits. As compared to pond fish culture, cages can be stocked at higher densities hence high production per unit volume of water; many types of existing water bodies can be used, hence reducing pressure on land, a relatively low initial investment is required in an existing body of water, ease of harvesting of fish, less manpower is required and high return on investment (De Silva and Phillips 2007; EL-Sayed 2006). For a long time in Africa, cage fish culture has been reported to be still in its infancy (Bostock et al. 2010; Asmah et al. 2016; Aura et al. 2018). However, by 2010, the cage fish culture industry in Africa was reported to be emerging at a faster rate than any other region (Bueno et al. 2015). The rapid expansion of cage fish farming on African inland waters has been reported in Lake Victoria in Kenya (Aura et al. 2018), Lake Victoria in Uganda (Blow and Leonard 2007), Lake Volta in Ghana (Asmah et al. 2016), Lake Kariba in Zimbabwe (Berg et al. 1996), Lake Malawi in Malawi (Blow and Leonard 2007), with Lake Victoria recording the highest number of cage aquaculture installations by the year 2019 (Table 15.1). In sub-Saharan Africa, the production of aquaculture fish has increased more than sixteen-fold since 1995 (FAO 2018), driven primarily by the expansion of tilapia cage aquaculture (Satia 2011).

While cage aquaculture is expanding in sub-Saharan Africa, such systems may have negative environmental consequences. Contrary to pond fish farming, which depends on fertilisers with high N and P contents to promote biological productivity, cage systems are seldom fertilised. Yet, N and P are essential elements for

Table 15.1 Estimated number of cages on African inland water bodies by 2019, adopted from Musinguzi et al. (2019)

Country	Water body	Estimated total number of cages
Kenya	Lake Victoria	12,086
Ghana	Lake Volta	3817
Ghana	River Volta	3184
Zambia	Lake Kariba	254
Rwanda	Lake Kivu	208
Rwanda	Lake Muhazi	199
Uganda	River Nile	135
Malawi	Lake Malawi	53
Uganda	Lake Albert	
Uganda	Lake Kyoga	102
Uganda	Kazinga channel	10
Uganda	Lake George	10
Uganda	Lake Kawi	3
Tanzania	Lake Kumba	40
Uganda	Lake Mugogo	
Uganda	Lake Pallisa	4
Tanzania	Lake Tanganyika	
Uganda	Reservoir	10
	Total	20,114

organismal development (Ackefors and Enell 1994; Von Sperling and Chernicharo 2005). Consequently, fish feeds for cages have higher N and P content (Musa et al. 2021b). Cage aquaculture raises concerns about water quality deterioration due to solid wastes (Ngupula et al. 2012; Aura et al. 2018) and soluble wastes, especially nitrogen and phosphorus compounds. Over time, this may cause eutrophication (Aura et al. 2018), algal blooms and changes in zooplankton community structure (Braaten 2007; Ngupula and Kayanda 2010; Villnas et al. 2011; Kashindye et al. 2015; Egessa et al. 2018). Therefore, the rapid expansion of cage fish culture in most African inland lakes, such as Lake Victoria, systems already under severe environmental stress (Hecky et al. 2010), is highly questionable.

With the burgeoning industry coupled with little regulation, the use of more inputs, mainly fish feed, is likely to skyrocket (Henriksson et al. 2018; Musa et al. 2021b), synonymous with increased waste generation. Moreover, the high densities of fish in cages would translate to the high production of wastes from unused feeds and faeces. This could be detrimental to the lake's ecosystem health, threatening the future sustainability of capture fisheries even more and preventing the development of a sustainable blue economy.

Sustainable cage fish culture and the development of a sustainable blue economy will depend on understanding the nutrient loads of cage farms in freshwater aquaculture since every ecosystem has a maximum assimilative capacity, which is determined by the maximum acceptable environmental impacts (Samuel-Fitwia et al. 2012). Furthermore, reducing the environmental footprint of cage culture operations requires estimating the amount of waste associated with such systems and their management. Yet, the fate and quantitative contribution of the new N and P sources emanating from feed wastage in cage fish culture in African inland waters is scarce. Understanding the nutrient budget of cage fish farms is useful in lacustrine development, management, and policy formulation. This chapter reviews factors affecting nutrient loads and their impacts, quantify nutrient loadings from cage fish culture in African inland waters from reported literature and hypothesised nutrient budget and carries out sensitivity analysis on the hypothesised model to explore and better understand the effects of uncertainties on nutrient loadings in the production of Nile tilapia to guide cage culture investments.

15.2 Factors Affecting Nutrient Loads and their Impacts on Inland Waters

15.2.1 Siting of Cages

Cage systems, if not correctly cited, can cause eutrophication, habitat degradation, and cause conflicts with other users (Beveridge 1984). These scenarios are highly likely to occur in African inland waters due to the burgeoning industry and because most cage fish farms in African inland waters use backyard fish feeds with low water stability (Musa et al. 2021b), which can worsen environmental challenges from such systems (Beveridge 1984). The majority of the fish cages (>70%) in African inland waters are sited nearest to the shoreline (Table 15.2), contrary to best practices that require cages to be placed within the 200 m distance from the shoreline of the lakes. Furthermore, almost all cages in African inland lakes are in shallow waters (4–8 m) (Musinguzi et al. 2019) despite recommendations that cages should be placed in deeper waters (>10 m) (Kamadi 2018). Nearshore and shallow areas have low flushing rates, resulting in high nutrient loading and increased phytoplankton

Table 15.2 Estimated distance (range and mean) between the shoreline and cages (Musinguzi et al. 2019)

Water Body	Distance of cages from shoreline (m)	
	Range	Mean
Lake Kariba	220.2–1759.8	894.4
Lake Kivu	5–120.1	41.3
Lake Kumba	N/A	66.7
Lake Malawi	N/A	1100
Lake Muhazi	48.23–150	82.6
Lake Tanganyika	141.99–142.0	141.99
Lake Victoria	21–665	211.6
Lake Volta	0–860	191.7
River Nile	13.4–621	178.5
River Volta	0–321	30.2

biomass from excess feeds. Most inland lakes, such as Lake Victoria, are already choking on excessive nutrients from industrial and agricultural wastes. Therefore, inappropriate siting of cages could exacerbate environmental challenges. Moreover, a regulatory framework for cage aquaculture for most African inland lakes is inadequate. Therefore, the burgeoning industry may pose a threat to ecosystem health.

The majority, if not all, of the African inland lakes, have not been mapped for suitable sites for cage culture, hindering sustainable development of the industry. However, preliminary delineation of suitable sites for cage farms in the Kenyan part of Lake Victoria has been undertaken, with approximately 9% of the total area delineated as most suitable for fish cages (Fig. 15.1) (Aura et al. 2021). The findings could be a model for other African inland lakes where tilapia cage culture already occurs or may occur in the future.

15.2.2 Nutritional Content and Digestibility of the Feeds

Just like other cultured species, nutrition is essential, not only for the growth of tilapia but for the environmental sustainability of cage systems (Musa et al. 2021b). Kong et al. (2020) reaffirm that fish feed quality is a critical factor in determining the environmental impact of aquaculture. Most of the studies carried out on fish feeds in Africa (Table 15.1) have shown that the dietary protein content for feeds follows the recommended levels (25–35%) for Nile tilapia larger than 10 g (Balarin and Haller 1982; Tacon 1987; El-Sayed and Teshima 1991; Khattab et al. 2000). However, backyard feed in Africa seems to record higher fibre content, hence inferior to extruded feed (Table 15.1). Fibre content above 8–12% is undesirable in fish feed because it reduces digestibility (De Silva and Anderson 1995; Leal et al. 2010); hence would translate to high nutrient loading into the environment. A high level of fibre has also been reported to reduce dietary protein utilisation in several species (Leary and Lovell 1975; Fontainhas-Fernandes et al. 1999). The low digestibility of backyard feed could also be attributed to high ash content, which is in line with Kitagima and Fracalossi (2011), who reported low dry matter digestibility for fish and shrimp offal meals with high ash contents. Similar results have also been observed in rainbow trout (*Oncorhynchus mykiss*) (Bureau et al. 1999) and hybrid tilapia (*O. niloticus* × *Oreochromis aureus*) (Zhou and Yue 2012). Overall, the high digestibility of nutrients in extruded feed could have been enhanced by extrusion cooking (Cheng and Hardy 2003; Barrows et al. 2007; Gaylord et al. 2008), thereby making commercial feed superior to backyard feed.

Most of the fish feeds in Africa have higher P content (above 1%) (Table 15.3) despite recommendations that P content for tilapia feeds should be less than 0.7% (KEBS 2015). Hence, apart from losses due to unavailability, the excess P in fish feeds cannot be metabolically utilised by fish and will ultimately be released into the environment (Roy and Lall 2004; Kong et al. 2020). This can increase the pollution potential from fish feeds. Fish feeds are the significant production cost for

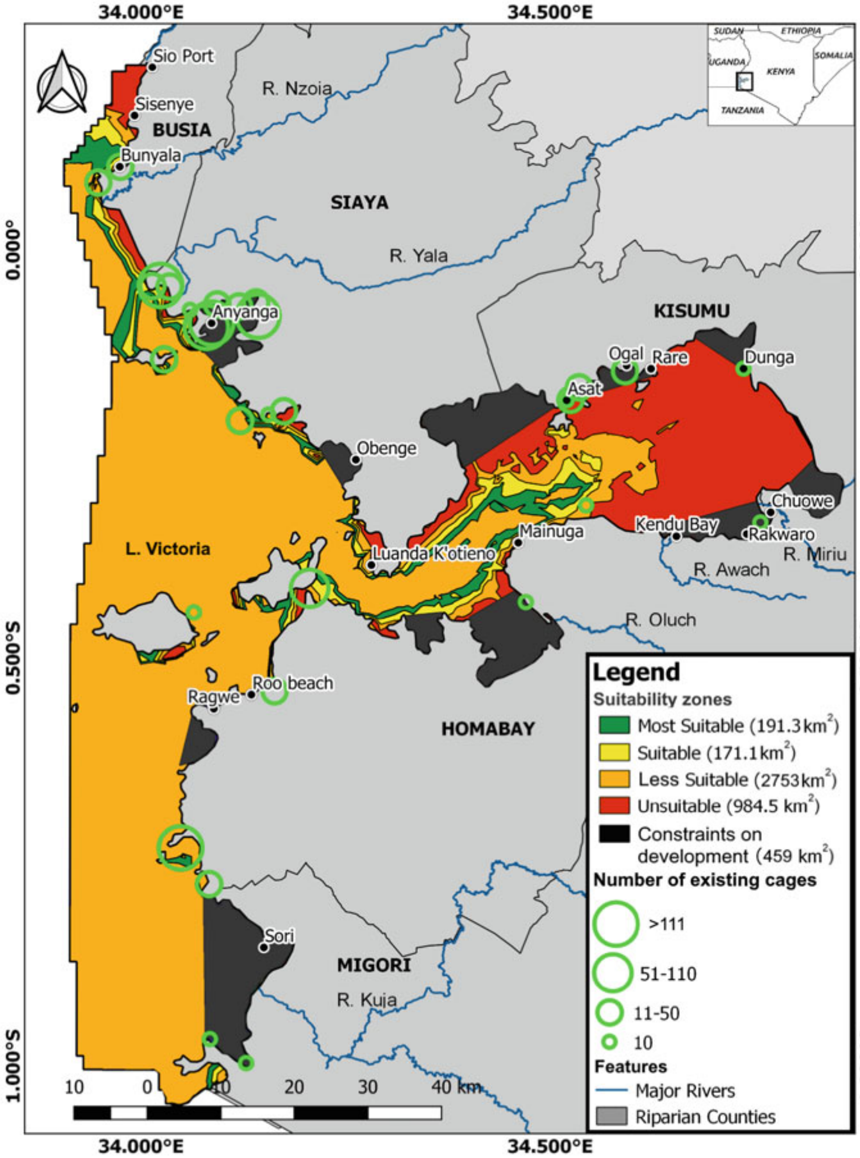

Fig. 15.1 Map of Lake Victoria, Kenya, showing potential suitability for cage fish culture. (Aura et al. 2021)

aquaculture (Naylor et al. 2000; FAO 2020) and commonly account for over 60–70% of the cost of producing tilapia (Bolivar et al. 2006; Elnady et al. 2010; Musa et al. 2021a). Due to the high costs of fish feeds, many efforts are being diverted to replacing the expensive animal protein with plant protein ingredients.

Table 15.3 Nutritional content (g kg^{-1}) for pelleted and extruded feed used for Nile tilapia cage culture in African inland waters

Nutrients (g/kg)	Musa et al. (2021a, b)	Musa et al. (2021a, b)	Neto and Ostrensky (2015)	Gondwe et al. (2011)	Karikari (2016)
Total dry matter	948	947.8	902.3	845	915.5
Digestible dry matter	680.7	560.3	608.5	–	–
Total organic matter	800.2	804.4	806.8	–	–
Digestible organic matter	605.2	577.3	578.9	–	–
Crude protein	301	282	276.7	359.4	350
Digestible protein	277.3	245	236.8	–	–
Crude fibre (g/kg)	42.1	168.2	42.8	–	–
Ash	92.4	130.4		–	77
Total phosphorus	10	11.5 ± 1.0	14.5	8.7	14
Digestible phosphorus	5.87	3.2 ± 0.6	6.5	–	–

Plant ingredients have been reported to increase the digestibility of protein fraction of plant ingredients (Pezzato et al. 2002; Neto and Ostrensky 2015). However, plant ingredients have been associated with higher P loss due to the low digestibility of P. According to Ravindran et al. (1994), Up to 80% of the total P content in plant ingredients is reported to be in phytate. Most monogastric aquatic animals lack endogenous enzymes for phytate hydrolysis (Cao et al. 2007). The low digestible P content in fish feeds in Africa, particularly in backyard feed, could be due to the high inclusion of plant ingredients in the diets (Musa et al. 2021b), raising concern due to the risk of eutrophication, especially in freshwater lakes such as Lake Victoria that has been reported to be highly eutrophic (Ochumba and Kibaara 1989; Lung'ayia 2000; Kling and Mugidde 2001).

15.3 Nutrient Load in Wastes in African Inland Waters

The amount of waste produced in cage fish farming depends on several factors, including feed quality, feed processing method and feed loss. Extrusion processing of fish feeds has been reported to produce quality pellets and improve faecal size and durability in water, hence reducing pollution in effluents (Welker et al. 2018). Notably, extruded feeds have been reported to have high water stability compared to pelleted feeds, hence fewer nutrients leaching from the feeds (Musa et al. 2021b).

Table 15.4 Reported types of fish feed, FCR and nutrient loading in cage fish farming in African inland waters

Reference	Type of feed	FCR	Total amount of nutrient involved (kg)		Nutrient recovered in fish (kg)		Net amount of waste output (kg)	
			N	P	N	P	N	P
Musa et al. (2021a, b)	Commercial feed	1.6	76.8	16	27.2	8.5	49.6	7.5
Musa et al. (2021a, b)	Backyard feed	2.8	126	30.8	21	7.8	105	23
Karikari (2016)	Commercial feed A	2	123.4	26.9	29.9	4.1	93.5	22.8
Karikari (2016)	Commercial feed B	1.7	105.4	22.95	29.83	4.41	75.6	18.6
Gondwe et al. (2011)	Commercial feed	2.7	155.3	23.5	50.6	8.1	104.7	15.4
Neto and Ostrensky (2013)	Commercial feed	1.35	69.23	19.86	24.23	5.56	45	14.3

This reduces the pollution potential from the aquaculture system. Table 15.4 shows the feed types and N and P budgets from available literature on tilapia cage culture in African inland waters. The N and P loading varied considerably with higher FCR (>2), giving the highest N (>100 kg/ton) and P (>23 kg/ton) loadings. Notably, the environmental loading of P and N per kg of tilapia produced seems to be more than twice as high when backyard feed is used compared to extruded feed (Table 15.4).

Mass balance analysis for cage fish culture has been carried out for a long time in temperate environments, and it has shown that about 31% N and 31% of P added through fish feeds were removed as fish biomass, and about 69% of N and 69% of P were discharged into the environment (Gowen and Bradbury 1987; Holby and Hall 1991; Hall et al. 1992). For the few mass balance models for tilapia in Africa, >30% of N added through fish feeds have been reported to be removed by fish at harvest. However, less than 25% of P added through fish feeds were removed by fish at harvest (Table 15.4). The assimilation of N from feed by fish in the tropical region was comparable to the temperate region, while the assimilation of P was much poorer than in temperate studies. The poorer assimilation of P in the tropical region herein could be because the majority of the fish feeds reported N deficiency compared to P, as indicated by lower N:P ratios in feed as compared to fish. The lowest N:P ratio in feeds in the tropical region confirms that P in fish feeds could be more than required for growth. Research in temperate and tropical countries concur that fish feeds are the primary source of added N and P from fish cage culture in a lacustrine environment (Gondwe et al. 2011; Neto & Ostrensky 2013; Karikari 2016; Musa et al. 2021b). Hence, the addition of N deficient fish feeds in African inland waters will not only reduce the growth rate of caged tilapia but will lead to poor retention and high nutrient loading into the environment. In most freshwater lakes such as Lake Victoria, phytoplanktons are limited by N rather than P (Guildford and Hecky 2000; Gikuma-Njuru and Hecky 2005; Mwamburi et al. 2020), favouring heterocystous N-fixing cyanobacteria. Loss of N deficient fish feed from cage farms could exacerbate this effect.

The environmental losses of nitrogen and phosphorus from cages in tropical countries proved to be threefold more significant than those reported in the literature for laboratory experiments and pond culture (Fernandes et al. 2007; Boyd et al. 2008; Azevedo et al. 2011). This could have been associated with culture systems, and it could also be because most of these studies did not estimate feed loss. It could also indicate that fish cage culture may have higher inputs of nutrients to the environment than pond fish farming, which could become a bone of contention for the industry.

15.4 Theoretical Mass Balance Model

In this section, we will use a theoretical mass balance model to estimate the levels of N and P discharged from cage fish farms producing a tonne of tilapia. The hypothetical model uses average values from published literature on the different components to formulate the model using various assumptions on feed loss, FCR, N and P content of feed and fish. The nitrogen content of farmed tilapia is 3% (on a wet weight basis) (Neto and Ostrensky 2013). The phosphorus content of tilapia is 0.85% (Musa et al. 2021a, b). The current cage culture of tilapia utilising commercial feeds limits feeding loss to 5% (Musa et al. 2021b). For juveniles > 10 g, 25–30% crude protein level is recommended (Balarin and Haller 1982; Tacon 1987; El-Sayed and Teshima 1991; Khattab et al. 2000). Phosphorus content in tilapia feeds have been reported to be between 1–1.6 (Neto and Ostrensky 2013, Musa et al. 2021b). Previous studies on Nile tilapia have reported FCR of 1.4–4.4 (El-Sayed 1998; Al-Hafedh 1999; Liti et al. 2005, 2006; Kubiriza et al. 2017; Musa et al. 2021b). In the hypothetical model, a total input of 64 kg and 16 kg for N and P, respectively, is required to produce a tonne of Nile tilapia (Fig. 15.2). With FCR of 1.4, a total of 26 kg (46.42%) N and 5.5 kg (46.88%) P is released into the environment for every tonne of Nile tilapia produced in cages. A total of 30 kg (53.57%) N and 8.5 kg (60.71%) P were retained by harvested fish. According to Boyd and Queiroz (2001), 61.9–77.2% of nitrogen from feed inputs is loaded into the environment, while phosphorus loads account for 43.8–89.4% of feed inputs. The low TN and TP loadings recorded in the hypothetical model (Fig. 15.2) were based on moderate values for FCR and feed loss in tilapia culture. However, higher FCR of >3 have been recorded for tilapia (Gondwe et al. 2011; Kubiriza et al. 2017); hence the nutrient loadings, in reality, may be higher than those recorded in the hypothetical model.

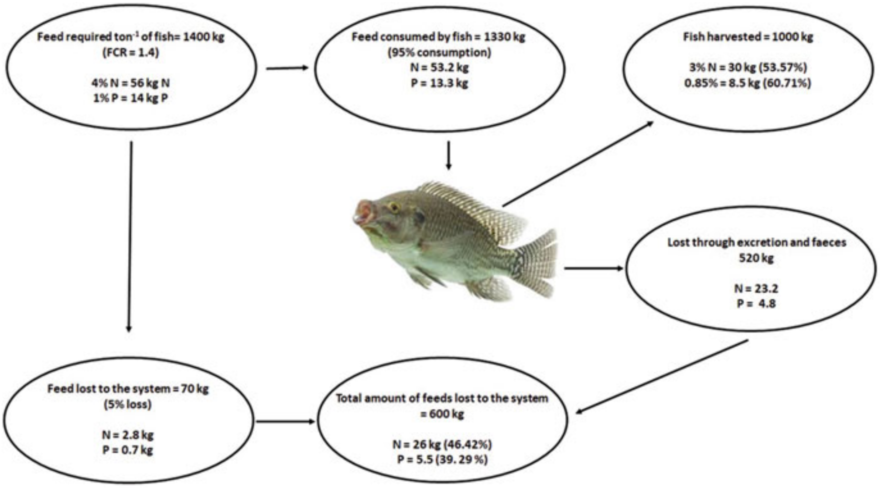

Fig. 15.2 Theoretical model for nutrient mass budget for a conjectured production of one ton of Nile tilapia in cages in a lacustrine environment

15.4.1 Sensitivity Analysis of the Model

Many factors can affect the loading rates of nutrients in a lacustrine environment; hence the nutrient loads reported in African inland waters in Table 15.4 above and in the theoretical model (Fig. 15.2) may vary with different factors. Musa et al. (2021b) reported a feeding loss of up to 25% for cage fish farms in Lake Victoria, Kenya. However, higher feed loss exceeding 30% has been reported under aquaculture elsewhere (Thorpe et al. 1990), with a corresponding increase in FCR values. Wu (1995) recorded a feeding loss of up to 40% when fish were fed on trash fish. Sometimes higher N and P have been reported in fish feeds (8% N reported by Hall et al. 1992 and 2.14% P reported by Foy and Rosell 1991) and lower in fish muscle.

In a scenario where cage farms use fish feeds with higher feed loss (e.g. 20%) and, in essence, higher FCR (e.g. 4), leaving other factors constant, the farm would discharge about 5 times the amount of N and 6 times the amount of P in the environment compared to the theoretical model (Fig. 15.3a). In the second scenario, where the feed loss is high, but at the same time the nutrient retention in fish is inefficient, the cage farms would discharge about 91% of N and 89% of P in the environment (Fig. 15.3b). This is in line with the studies of Handy and Poxton (1993), who showed that when the feed wastage is high and the N retention rate is lower, greater than 90% of the supplied N is lost to the system. The model indicates that nutrient loading from the cage culture of Nile tilapia is very sensitive to feed loss and, in essence, the FCR of the diet. Nutrient retention is the next factor that affects nutrient loading in a lacustrine environment. In aquaculture feed cost accounts to upto 70% of the production costs (Watanabe 2002; El-Sayed 2006; Cheng et al. 2010; Khalil et al. 2019; Allam et al. 2020). The values have been reported to be

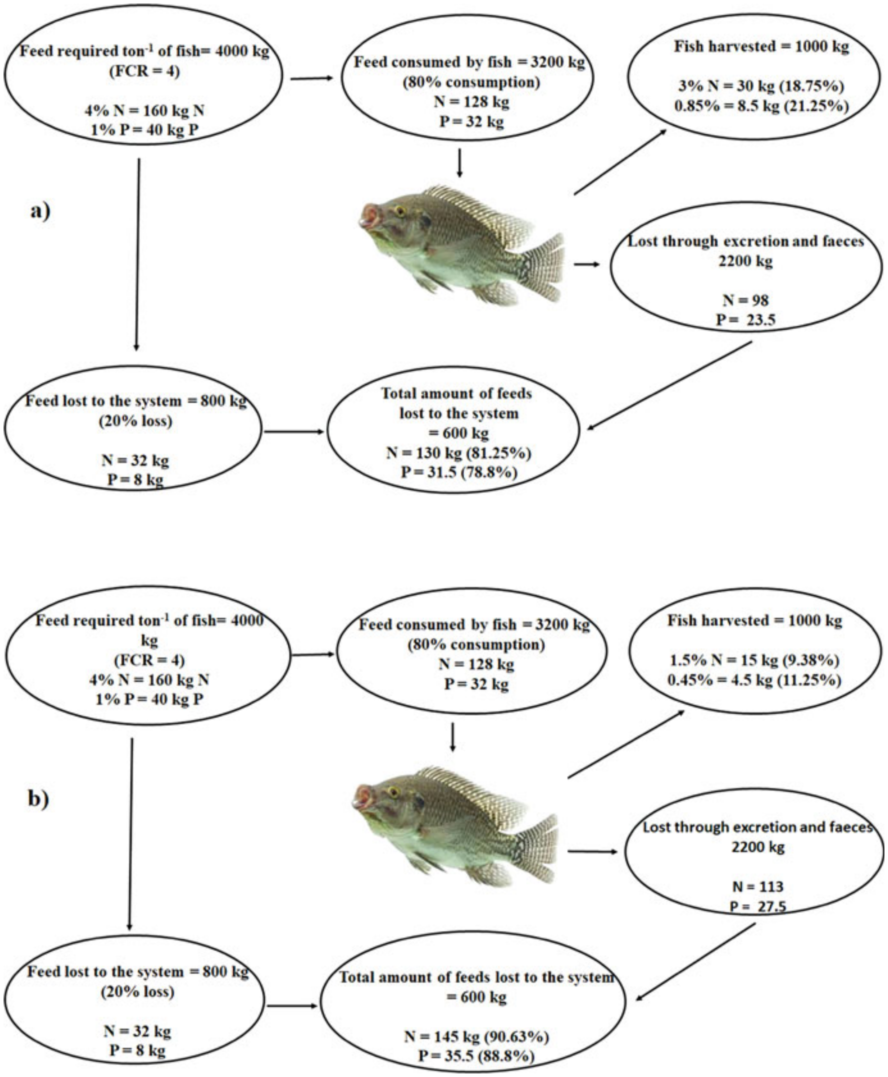

Fig. 15.3 Mass budget for a conjectured production of one ton of Nile tilapia in cages in a lacustrine environment for two different pollution scenarios: (**a**) when the rate of feed loss is high hence higher FCR and (**b**) when the rate of feed loss is high, FCR is high with poor N assimilation and retention

even higher (>70%) in cage culture (Musa et al. 2021b). The need to minimize feed losses cannot be overemphasized, not only for environmental sustainability in fish cage culture but for economic production issues (Talbot and Hole 1994; Musa et al. 2021b).

15.5 Conclusion and Recommendations

Feed quality is a key factor in determining the impact of aquaculture on the environment. The nutrient loads in African inland waters are higher than desirable due to the low digestibility of feeds translating to higher FCRs. The low N content in relation to P and high fibre contents of fish feeds result in a higher nutrient discharge into the environment. In addition, the use of backyard fish feeds for fish cage culture seems inferior to commercial feeds not only due to high fibre content but primarily due to low water stability that could cause a disproportionate increase in total P and N output loading from cage fish farming. The use of commercial fish feed is highly recommended for cage fish culture in African inland waters. We recommend the zonation of suitable sites for cage fish farming in all African inland lakes to ensure proper water circulation and, in essence, good water quality. Good water quality will ensure a high appetite for fish, resulting in the increased digestive function of the intestine and increased digestibility of nutrients in the intestines, translating to low FCRs. In addition, using best practices in feeding regimes will go a long way in reducing FCR and, in essence, the cost of production. There is a need to enhance the N content of fish feeds to reduce P discharge into the environment and limit the proliferation of nitrogen-fixing cyanobacterial species.

Furthermore, there is a need to incorporate phytase in plant-based fish feeds to enhance the bioavailability of P and reduce the nutrient discharge into the environment. The environmental sustainability of the cage culture industry is very sensitive to feed loss. Hence, feeding management practices, particularly those that reduce feed loss, is a crucial point in reducing the input of these nutrients in the aquatic environment. For example, using water-stable pellets through extrusion would be one way of reducing feed loss to the environment. We recommend fast-tracking of regulations for inland waters to control locations of new entrances and relocation of existing cages to appropriate locations. Furthermore, mapping suitable sites for cage fish culture in African inland waters coupled with best management practices is imperative so that aquaculture remains within the carrying capacity of inland water bodies for the environmental sustainability of the industry.

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Part III
Aquaculture Development and Innovations in Africa

Chapter 16
Aquaponics as a Sustainable Food Production System with Promising Development Perspectives in Morocco

Maryam El Bakali and Mustapha Aba

Abstract Moroccan water and land resources are under increased stress, which could have a negative impact on agricultural output, therefore, raising questions about food security. Due to the effects of climate fluctuations on Morocco's semi-arid and arid climate, as well as water stress brought on by the depletion of natural water resources, innovative agricultural techniques must be sustainably developed to ensure food security through agricultural food production. For these reasons, the aquaponics system in Morocco has the potential to significantly contribute to the environmental, social, and economic sustainability of the nation while conserving and rationalising water, a resource that is essential for the sectors of agriculture as well as aquaculture, which happen to be growth drivers of major economic importance in the country. As a matter of fact, aquaponics, which has gained popularity and credibility across the globe, functions by combining aquaculture and hydroponics in a recirculating system, promoting water reuse and nutrient recycling. In this chapter, alternative sustainable agricultural and aquaculture food production methods are presented, along with a theoretical overview of aquaponics and a discussion of its perspectives in Morocco based on the result of the first ever Moroccan study on small-scale aquaponics production systems. The intention is to incorporate these systems into Morocco's extensive agricultural sector to reap its socioeconomic and environmental advantages.

Keywords Aquaculture · Agriculture · Aquaponics · Water · Food · Sustainability · Morocco

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16.1 Introduction

Food security has emerged as a critical development issue in the twenty-first century facing the world's growing population, with the intensification of global food production as one of the most critical challenges to achieve it (Fróna et al. 2019). Food insecurity can drastically affect diet quality, potentially leading to undernutrition and obesity. In fact, ensuring access to a healthy diet is a prerequisite for achieving the sustainable development goals (SDG) target of eradicating all forms of malnutrition (FAO 2020). To attain this goal and ensure food security, it is essential to recognise the reliance of food production on the availability of resources, such as land, freshwater and nutrients (Conijn et al. 2018).

The most crucial factor in this regard is the amount of water. Although water is a renewable resource, non-renewable stocks are depleting, considering that 70% of all freshwater used by humans goes into agriculture (FAO 2020), and given the looming water crisis, particularly in the North African region, including Morocco, which has one of the world's poorest freshwater resources, which are primarily underground (Hamed et al. 2018). Morocco is a semi-arid Mediterranean country with irregular and scarce rainfall, making surface water and groundwater resources critical for socioeconomic development (Schilling et al. 2012). In a country where agriculture is an important economic sector and a heavy consumer of water, the most severe impact would most likely occur during water shortages, with serious consequences for rural livelihoods, economics, and food security (Corner et al. 2020). Accordingly, innovative solutions aiming to increase food production are required. Such solutions should strive to achieve less water consumption without further compromising the environment to ensure greater food security for the population. In fact, the increased demand for food and the scarcity of water makes it necessary to develop a sustainable system, primarily as the agricultural sector reflects its dependence on climatic conditions, particularly rainfall (Harbouze et al. 2019). According to the FAO (2016), to achieve food security objectives while considering the threat of climate change, the transformation and adaptation of agricultural systems that demand significant water resources, especially in semi-arid areas, will be required. For these reasons, the search for innovative forms of production that consume less water has become a mainly debated issue due to the need for food security and the depletion of natural water resources in Morocco. In that respect, the aquaponic production system is a technique that has successfully been used in many countries (Goddek et al. 2019a; b). In African countries, aquaponics systems are relatively new. The low adoption of this new technique may be related to the low penetration of innovative fish production systems such as recirculating aquaculture systems, which are an integral part of aquaponic systems (Obirikorang et al. 2021). Egypt, South Africa, and Kenya are the countries that appear to have relatively widely adopted this technology in Africa.

Morocco, like all countries around the world, faces numerous challenges in terms of food security and agricultural productivity, primarily the need to increase food production and availability as well as access to food (Toumi 2016). Despite all the advantages of aquaponics, such as low water consumption, reduced environmental impacts, and the production of two sources of income in a single system, its use in Morocco is still in its early stages (El Bakali 2022a, b). More research is needed to provide additional information to enable the implementation of this system in Moroccan conditions. In this context, this work aims to present an alternative form of sustainable food production using aquaponics and discuss its prospects in Morocco.

16.1.1 Aquaculture in Morocco

Morocco has a favourable geographical position due to its 3500 km of coastline spread across two seafronts and its 200 nautical mile Exclusive Economic Zone in the Atlantic. These assets, combined with a world-class upwelling zone, make the Moroccan coast one of the most fish-rich areas, with an annual production potential exceeding 1.5 million tonnes of fish (Doukkali and Kamili 2018). According to the Department of Maritime Fisheries (2019), Morocco's maritime fisheries sector produced nearly 1.46 million tonnes and was valued at nearly $1.2 billion. Morocco has implemented a strategy within the framework of the "Halieutis" plan, which is set to run until 2020, but the authorities have set goals for a second phase (2020–2030). The strategy comprises three major axes: resource sustainability, performance, and sector competitiveness (Saad & Maria 2017).

Aquaculture is defined by the FAO (2020) as the activity of rearing aquatic organisms and is one of the world's fastest-growing production modalities. Its prospects for growth continue to soar as a result of its enormous potential, as it aims to meet the growing demand for fish, despite the current stagnation of extractive fishing. Statistical data show that aquaculture has begun to contribute to more than half of the world's fish supply, highlighting its importance both locally and globally. Recognising the state of global aquaculture production acceleration, Morocco has chosen to position itself in the aquaculture sector to diversify its economy, make aquaculture a growth driver for the fisheries sector, contribute to food security and become more integrated into the international seafood trade.

In Morocco, aquaculture activity is institutionally governed by two Departments of the Ministry of Agriculture: The Marine Fisheries Department (acronym: DPM) manages marine aquaculture through the National Aquaculture Development Agency (acronym: ANDA), and the High Commission for Water, Forests, and the Fight against Desertification manage freshwater aquaculture (acronym: HCEFLCD).

16.1.2 Marine Aquaculture

Marine Aquaculture is one of the 16 big projects of Halieutis strategy, and it is positioned at the level of the axis of durability as a priority sector, leading to the establishment of a driver of growth and job creation for the fisheries sector. Oyster farming in the lagoon of Oualidia introduced the marine aquaculture sector to Morocco in the 1950s, and it has been known as a significant development by the launch of many other projects (Kaddioui et al. 2018), with 290 new projects in 2021. Figure 16.1 shows the most essential stages in the development of Moroccan marine aquaculture.

16.1.3 Freshwater Aquaculture

Freshwater aquaculture is an older sector introduced by rainbow trout farming in 1924 in Morocco. The HCEFLCD has launched an ambitious plan from 2015 to 2024 to develop and promote aquaculture in Morocco, to reach 50,000 tonnes of fish by 2024, which includes 20,000 tonnes produced by the private sector and 30,000 tonnes through restocking (DPM 2019). The said strategic plan has outlined among its general objectives making fish farming one of the engines of socioeconomic development in rural and mountainous areas and establishing a profitable and sustainable fish farming sector in each region of the Kingdom, which creates value while respecting the environment. Moreover, it strives to position freshwater fish as an essential source of animal protein supply in rural areas. According to the Directorate of Water and Forests of the Ministry of Agriculture, the species of Moroccan freshwater aquaculture are classified into three main groups of species and their dates of introduction in Morocco are shown in Table 16.1 (Mouslih (1987), Azeroual (2003) and Aba et al. (2014).

16.2 Agriculture in Morocco

Morocco's agricultural sector, the mainstay of the country's food security, is highly vulnerable to climatic hazards, particularly drought and scarcity of water resources (Bouchaou et al. 2011). In 2017, the agricultural and fisheries sector represented 13.6% of Morocco's GDP. Moroccan economic growth is thus closely linked to that of the agricultural sector. Indeed, the substantial variations in the added value of the agricultural sector, which demonstrate the dependence of this sector on climatic conditions, and rainfall, are reflected in the GDP growth (Harbouze et al. 2019).

The Moroccan state is aware of the current constraints and future challenges facing agriculture and has developed a long-term strategy to address them (Belahsen et al. 2016). This strategy, called the "Green Morocco Plan" (PMV), extends from 2008 to 2020 and carries out the ambition to make agriculture a real engine of growth and socio-economic development for the country (ADA 2021). It stands on two main pillars: the first one aims to develop modern, efficient agriculture that meets the requirements of the market by relying on the promotion of private investment and the establishment of an aggregation model. The second pillar intends to evolve

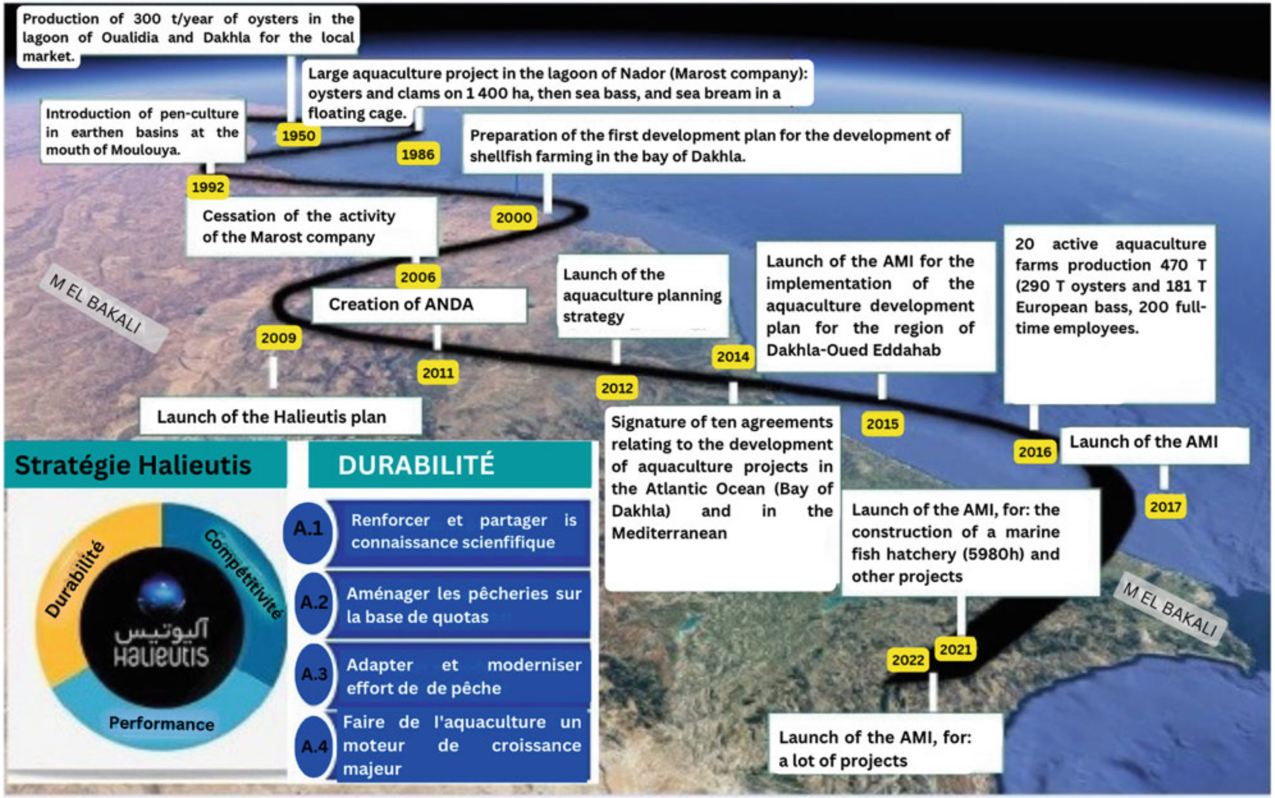

Fig. 16.1 Most essential stages in the development of Moroccan marine aquaculture

Table 16.1 Species of Moroccan freshwater aquaculture

Native species	Brown trout (*Salmo trutta*) Blue barbel Common barbel (*Barbus barbus*)
Migratory species	Allis shad (*Alosa alosa*) Eel (*Anguilla anguilla*) Muge cephale (*Mugil cephalus*)
Introduced species	Rainbow trout (*Oncorhynchus mykiss*) (1925) Pike (*Esox lucius*)) (1938) Black-bass (*Micropterus salmoides*) (Beginning of the last century) Silver carp (*Hypophthalmichthys molitrix*) (1983) Grass carp (*Ctenopharyngodon idella*) (1983) Common carp (*Cyprinus carpio)* (1924) Nile tilapia (*Oreochromis niloticus*) (2004) Gambusie (Gambusia affinis) (1929) Tanche (*Tinca tinca*) (1934) Pikeperch (*Sander lucioperca*) (1939) Rotengle (*Scardinius erythrophthalmus*) (1935) Red-footed Crayfish (*Astacus astacus*) (1914) American crayfish (*Orconectes limosus)* (1937)

the structure of Moroccan agriculture by supporting small farmers in securing and improving their income, with the aim of reducing rural poverty and consolidating the socio-economic fabric of the poorest territories. 12 years after the implementation of this plan, Morocco has launched a new strategy under the name of " Generation Green 2020-2030" that places the human element at the heart of its concerns. According to the Moroccan Ministry of Agriculture, the sustainable development of Moroccan agriculture has gained new momentum since the launch of this new strategy. Strongly linked to the human element, this foundation aims to consolidate the achievements of the Green Morocco Plan while making a qualitative and technological leap through specific actions on agricultural sectors, distribution chains, quality, and innovation, as well as in terms of preserving natural resources and strengthening the resilience of the sector. In this context, aquaponics, which incorporates aquaculture and hydroponics, can play an essential role in the sustainable production of agricultural food.

16.3 Aquaponics, an Opportunity for Sustainable Food Production in Morocco with Promising Development Perspectives

16.3.1 Introduction

Aquaponics, which combines the Greek words "hydro" (water) and "ponos" (labour), is a method of growing plants in various types of chemically inert

Table 16.2 Aquaponics: approaches, production scales, system designs

Aquaponics	
Level of production intensity (Foucard et al. 2019)	Production scales (Foucard et al. 2019)
Low-Tech • Usually lacking specific equipment dedicated to biological and mechanical filtration. • Clay beads and other culture media which may be sufficient in adequate quantity to filter the suspended solids which will then enrich the medium after microbial degradation. • The density of fish farming is generally very low (≤10 kg / m^3).	Small scale A small fish tank associated with a small surface of vegetable culture on gravel or NFT (nutritive technical film). Goal: Self-production or recreational use
Middle-Tech • Mechanical filtration system of the decanting cone type and/or filtration foams or even a ball or sand filter. • A specific compartment dedicated to biological filtration. • The density rarely exceeds 20 kg of fish per cubic meter of water.	Middle scale A fish tank associated with a plant culture surface on gravel or NFT (nutritive technical film). Goal: "Demonstrative" structures (urban environment, on the roofs of buildings or on land of local communities in urban areas
High-Tech • a biological filtration system • a very efficient mechanical filter (of the drum filter type) coupled or not with passive filtration. • the aeration of the water by mixing (when the density of fish farming is low: ≤50 kg/m^3). • and/or oxygenation of the water by supplying liquid oxygen (when the density of fish culture is high, ≥50 kg / m^3 up to a bearable biological limit specific to each species of fish).	Commercial aquaponics *Goal*: • commercial production, • integration of a level of technicality allowing the production up to a few tons of fish per year for large production areas.
Approaches (Foucard et al. 2019)	System designs
Fish farming approach: Fish production *Role of aquaponics:* • Treatment of solid and dissolved water discharges from existing fish farming facilities through systems combining filtration elements (simple and inexpensive). • Effective means to reduce the rate of nitrogen and phosphorus molecules present in the water before discharge into the water course.	Coupled Aquaponics Systems consist of one connected water layer like the UVI system (Rakocy et al. 2006). Fish is usually a secondary aquaponics product
Mixed approach: Plant and fish production *Role of aquaponics:* • Establishment of a balance between the fish and plant compartments. • Decrease of water consumption and production of plants on a large scale with the only help of fish effluents.	
Plant-based approach: Plant production *Role of aquaponics:* • Optimisation of the use of water and reduction	Decoupled Aquaponics Systems Consists of separated aquaculture and hydroponic systems with a controlled connection

(continued)

Table 16.2 (continued)

Aquaponics	
Level of production intensity (Foucard et al. 2019)	Production scales (Foucard et al. 2019)
of the use of N-P-K nutrient solutions, which have a significant environmental impact. • Feeding the plants with a nutrient solution (organo-mineral) as a main or a complementary intake to a conventional hydroponic nutrient solution.	(Goddek et al. 2015). Fish is usually a secondary aquaponics product

substrates, such as sand, gravel, or liquid (water), to which nutrients are added, but no soil is used (Savvas 2003; Douglas 1975). This is done within a closed recirculating system (Thorarinsdottir 2015, Rakocy et al. 2006).

The concept of aquaponics, using fish waste to fertilise plants, has been utilised for thousands of years with applications in early Asian and South American civilisations (Somerville et al. 2014). According to Watten and Busch, it was not until the 1990s that academic research on aquaponics was incorporated into contemporary food production systems. Aquaponics is now considered a new and emerging industry with a relevant place in the broader, global agricultural production context of technology integrating fish culture with the aquatic plant (Knaus and Palm 2017a, 2017b). Given the water crisis currently affecting the whole world in general and Morocco with its arid and semi-arid climate, Moroccan agriculture must adopt new cultivation systems which use water rationally to minimise the impacts of its depletion as well as the discharge of aquaculture effluents, both for aquaculture and hydroponics via the aquaponics technique. Organic farming systems combining both techniques were fostered to meet the abovementioned needs (Pollard et al. 2017) but not yet in Morocco. Aquaponics is now considered one of the "blue growth" approaches. A climate-resilient system that focuses on improving productivity and performance because it offers opportunities for innovation and for production in environments where agriculture would not be traditionally possible (FAO 2017a).

16.3.2 The Symbiotic System of Aquaponics

The symbiotic biological principle in aquaponics stems from the fact that the nutrients needed for plant growth and development are very similar to the waste produced by fish (Espinosa-Moya et al. 2018). The nitrogen needed for plant growth is derived from the proteins consumed by fish, which retain 20–30% of the ingested dietary nitrogen, while 70–80% is released into the water as waste (Schreier et al. 2010). The reliance on the bacterial ecosystem is a characteristic of aquaponics (Kasozi et al. 2021). The nitrification process is carried out by two major groups of nitrifying bacteria (Somerville et al. 2014; Zou et al. 2016; Daims et al. 2015), ammonia-oxidizing bacteria (AOB) and nitric-oxidizing bacteria (NOB). They metabolise ammonia in the following order: AOoxidises ammonium ($NH4+$), producing nitrite ($NO2-$), and the NOB further oxidise the nitrite to produce nitrate ($NO3-$). In aquaponics, the most common AOB is *Nitrosomonas*, and the most common NOB is *Nitrobacter*. In conclusion, the aquaponics ecosystem is entirely dependent on bacteria. Ammonia concentrations in the water will kill the fish if the bacteria are not present or are not working correctly. To keep ammonia levels near zero, it is critical to maintain and manage a healthy bacterial colony in the system at all times (Somerville et al. 2014).

In aquaponics, the filtration system is the critical component for the balance of this technique since it is where the conversion of nitrogenous compounds in aquaponics is the process of nitrification. This process involves the chemical element nitrogen (N), which is essential for all life forms, including plants.

The presence of nitrifying bacteria in aquaponics attached to the biological filtration system is mandatory. These microorganisms, represented by Nitrosomonas and Nitrobacter, are responsible for the natural process of nitrification from the waste generated by aquatic organisms from fish feed and for the conversion of ammonia ($NH3$) to nitrite ($NO2-$) and nitrite to nitrate ($NO3-$), thus transforming toxic substances produced by fish into nutrients assimilable by plants (Schmautz et al. 2017). By consuming these nutrients, plants, together with bacteria, play an essential role in the biological filtration of the water, ensuring its proper condition for normal fish development (Kasozi et al. 2021).

Figure 16.2 shows the summary of the process of the symbiosis principle in the aquaponics system.

16.3.3 Types of Aquaponics Systems

A typical aquaponics system includes a fish tank for aquaculture, a biofilter for nitrification, and a culture bed for hydroponics (Love et al. 2015). Aquaponics systems are classified into three types based on the type of culture bed used (Engle 2015; Delaide et al. 2017): nutrient film technique (NFT), ebb-and-flow (EAF), and deep-water culture (DWC), also known as RAFT beds.

16.3.3.1 Nutrient Film Technique (NFT)

The Nutrient Film Technique (NFT) is a soilless hydroponics technique in which a continuous shallow stream of water carrying all essential plant nutrients flows down a channel or gully, where it meets plant roots before making its way to a nutrient reservoir and is then recirculated, minimising pump usage (Al-Tawaha et al. 2018). NFT systems are however only suitable only for smaller vegetation, such as lettuce, spinach or other leafy greens and herbs, because channels can become clogged by

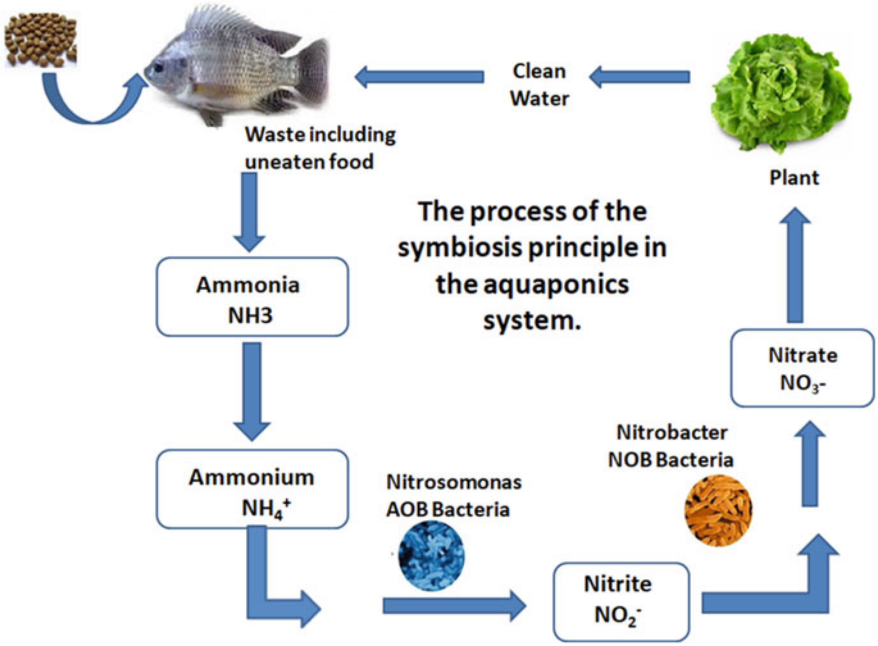

Fig. 16.2 The summary of the process of the symbiosis principle in the aquaponics system

plants with more extensive root structures or by unfiltered aquaculture wastes (Silva et al. 2015).

16.3.3.2 Floating Raft (Deep Water Culture)

Deep Water Culture (DWC) is a hydroponic technique that continuously supplies nutrient-rich water to the plants' roots, keeping them constantly submerged in water and oxygen (Forchino et al. 2017). The DWC system has the advantage of being highly oxygenated, using less fertiliser, and having low maintenance costs and monitoring time (Domingues et al. 2012; Wongkiew et al. 2017). Because it allows plants to absorb nutrients directly from the water, DWC is commonly used in aquaponics.

16.3.3.3 Media BED TEChnique

Media-filled bed units are the most common design for small-scale aquaponics. This method is highly recommended for most developing countries, as these designs are space-efficient, have a low initial cost, and are suitable for beginners due to their simplicity. The medium in media bed units is used to support the roots of the plants, and the same medium also serves as a filter, both mechanical and biological (Somerville et al. 2014).

16.3.4 *Aquaponics: Approaches, Production Scales, System Designs*

The following table presents an overview of the various approaches and system designs, as well as production scales that characterize aquaponics.

16.4 Aquaponics and the Sustainable Development Goals

The United Nations defined the Sustainable Development Goals (SDGs), a global agenda adopted in September 2015, with 17 goals to be achieved by 2030. These objectives include actions to eradicate poverty, promote prosperity and well-being for all, protect the environment and natural resources, and combat climate change. Aquaponics can directly contribute to the achievement of the SDGs, specifically SDGs 1, end poverty, SDGs 2, zero hunger and sustainable agriculture, which address the need to disseminate actions that promote food security; SDG 6, which aims to ensure the availability and sustainable management of water, SDG 8 for growth and employment, and SDG 12 which addresses responsible consumption and aims to ensure sustainable production and consumption patterns.SDG 13 for climate change resilience and water stewardship, as well as SDG 14 for marine resource conservation and sustainable use, are all highly relevant to aquaponics development (FAO 2017b).

16.5 Benefits of Aquaponics

A proper discussion regarding the sustainable development of the aquaponics technique requires the inclusion of three inseparable aspects: social, economic, and environmental issues.

16.5.1 *Economic Benefits*

Aquaponics has enormous potential as a sustainable solution, as it has shown promising results for the development of food production while also providing new opportunities for entrepreneurship and business creation (El-Essawy et al.

2019). Several studies (Goda et al. 2015; Sunny et al. 2019) have concluded that the revenues obtained can essentially cover the costs of aquaponics production. Other authors (Quagrainie et al. 2017; Greenfeld et al. 2018; Rizal et al. 2018) claim that the larger the aquaponics system, the more profitable it is, which appears to be true for many large-scale commercial systems.

16.5.2 Social Benefits

Aquaponics has a significant impact on several social dimensions, including health, well-being, and education (Hart Emily et al. 2013). It was also shown to facilitate community cohesion, another potential social dimension (Konig et al. 2016). Other potential social impacts of aquaponics include (1) improved community food security with a relatively inexpensive source of protein, (2) inspiration in design and personal conception of aquaponics farms, (3) income generation, and (4) job creation with better working conditions (Specht et al. 2014).

16.5.3 Environmental Benefits

To reduce the negative environmental impacts of agriculture, it is preferable to use more efficient methods to reduce waste disposal and recycle nutrients, significantly save energy, and reduce gas emissions within the system (Beddington 2011). Agriculture and aquaculture production currently occupies a large area across the mainland and aquatic environments, where it has a significant negative impact, causing soil erosion, soil and groundwater pollution from pesticides, fertilisers, and animal waste, as well as the production of greenhouse gases (Goudie and Heather 2013). The combination of crop production and aquaculture within aquaponics systems reduces the environmental impact significantly. Moreover, aquaponics can also help to reduce freshwater depletion by encouraging sustainable farming and food production practices (Greenlee 2009). Aquaponics has the potential to be an essential component of the "blue and green" water paradigm. Furthermore, it is possible to incorporate it into the local water cycle using treated grey water and rainwater instead of freshwater (Vadiee and Martin 2012).

6. The New Perspectives of Aquaponics in Morocco

Aquaponics systems are good candidates to respond to the challenges posed by Morocco's population growth, climate fluctuations the country often faces as well as limited access to water resources for agricultural activities. It is also a valuable tool to help design new models of the Moroccan agricultural system. One example is the case of the aquaculture industry. Like other human activities, its problems concern the scientific community in many ways, principally for its large waste discharges into the environment along with its accelerative growth rate (Martins et al. 2010).

Table 16.3 Water quality parameters of the aquaponics system tested in Morocco

		Experimental days					
		0	7	15	22	28	35
	Inlet	0.84 ± 0.05	0.99± 0.02	0.99 ± 0.06	0.96 ± 0.02	0.93 ± 0.04	0.97 ± 0.02
NH_3	Outlet	0.62 ± 0.08	0.82 ± 0.11	0.83 ± 0.02	0.76 ± 0.01	0.72 ± 0.13	0.85 ± 0.01
	% reduction	26.05	17.27	16.16	20.82	22.51	12.37
	Inlet	0.050 ± 0.004	0.061 ± 0.001	0.062 ± 0.005	0.070 ± 0.005	0.068 ± 0.002	0.067 ± 0.001
NO_{2-}	Oulet	0.042 ± 0.004	0.052 ± 0.001	0.054 ± 0.008	0.063 ± 0.005	0.060 ± 0.005	0.060 ± 0.001
	% reduction	16	12.90	14.76	10.01	11.76	10.45
	Inlet	48.92 ± 0.19	56.02 ± 0.22	60.98 ± 0.18	76.62 ± 0.32	79.99 ± ± 0.53	89.02 ± 0.45
NO_{3-}	Outlet	40.02 ± 0.15	45.22 ± 0.10	52.22 ± 0.08	66.92 ± ± 0.15	69.09 ± 0.21	78.12 ± 0.45
	% reduction	18.19	19.27	14.61	12.65	13.62	12.24

Thanks to the results obtained in this field, aquaponics has demonstrated sustainability benefits which will allow Morocco to develop economically viable aquaponic systems capable of cultivating species at variable densities, even with an unfavourable climatic regime and limited water availability.

Aquaponics is currently being tested and promoted in several countries across five continents, where the technology has improved and adapted to various conditions such as climate, cultivated species, and production costs, among others (Goddek et al. 2019a; b).

Except for one study on a small-scale aquaponics production system to produce a combined crop of carp and plants, experimental systems and commercial aquaponics farms have never been tested in Morocco, and research on aquaponics systems has so far been entirely theoretical and restricted to small-scales (El Bakali, 2022a, b). In this experiment, a DWC aquaponics system was installed and effluents from a Silver carp (*Hypophthalmichthys molitrix*) tank were redirected to plants (lettuce, pepper, mint). As mentioned above, bacteria transform in this process fish waste into nutrients that plants can absorb. The fish tank is then refilled with purified water. Each plant's height was measured once a week together with dissolved oxygen, pH, water temperature, NO3−, NO2−, and NH3 concentrations.

Fish growth was assessed using body weight and total length. The study reached encouraging results, particularly the evaluation of nitrogen removal efficiency and its effect on fish and plant growth rates (Table 16.3). The growth rates of fish and plants were remarkable, with no pathological abnormalities observed in fish. During the experiment, the mean growth of Silver carp had significantly improved ($P < 0.05$).

The average final length was 18.25 ± 1.89 cm, and the average weight was 85.06 ± 20.10 g. Plants grew quickly despite the absence of pesticides or fertiliser (the height was between 2.11 cm and 4.05 cm). Additionally, the water quality was excellent in terms of water temperature (19–22 °C), pH (6–7.3). This study found that using an aquaponics system had a significant impact on nitrogen reduction ($NO2-$ (12.6%), $NH3$ (19.04%), and $NO3-$ (15.1%). (Table 16.3).

Several reviews on the subject have been conducted, two of which have been published, to establish a database that can be used when establishing aquaponics and integrated aquaculture projects. One of them (El Bakali and Aba (2021) discussed using aquaculture phosphorus waste in integrated aquaculture. These discharges are pollutants that contribute to the eutrophication of aquatic environments, but they also contain macro-elements required for fish feeding and fertilisers for soil fertilisation. Therefore, exploitation of these effluents is required to ensure the aquaculture sector's environmental sustainability in the context of integrated aquaculture with agriculture. The other (Aba & El Bakali 2020) investigates the advantages of integrating aquaculture with irrigation in water resource rationalisation. Indeed, the water scarcity threatening agriculture in Morocco, as well as the desire to increase productivity while considering the environmental impacts of this production sector, necessitates the development and adoption of a more sustainable agricultural model based on ecological and socioeconomic considerations. Integrating aquaculture with irrigation is an excellent way to reduce nutrient discharge and convert aquaculture wastes into valuable agricultural products. Using aquaculture effluents for irrigation would be an unprecedented step forward in Morocco, ensuring food security and establishing a resilient foundation to the challenges posed by climate change.

16.6 Conclusion

Aquaponics is a sustainable food production technology that, despite its usage for several years in other countries, is not widely known in Morocco. Aquaponics exhibits the prospect for the sustainable development of food production in Morocco, as it can serve as an essential component of sustainable rural infrastructure, in line with current public policies, particularly when taking into account the implemented strategies for the sustainable development of the agricultural sector in Morocco, the climate variations that country is experiencing, and the scarcity of water resources. Within the framework of implementing this new technique in Morocco, it would be prudent to inventory the potentialities of each region, conduct pilot studies, and ensure the training of agricultural personnel. One of the main advantages of this type of innovative technology is that it can be adapted on a small or large scale while taking up minimal space, resulting in a significant positive socioeconomic impact at the local level with no negative environmental consequences.

The use of aquaponics as an agroecological alternative is an approach that aims to strengthen the resilience of Morocco's farming sector, as farmers are the first victims of climate fluctuations by providing a sustainable and inclusive response to nutritional issues and a better rationalisation of water resource use. Furthermore, aquaponics as an agroecological alternative paves the way for establishing the sustainable triad, which includes social, environmental, and economic aspects.

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Chapter 17
Enhancing Food Production Employing Integrated Aquaculture in Namibia. Fish Integration with Poultry

Medusalem Jairus

Abstract The global human population is increasing, putting pressure on several resources that are key to sufficient food production. Current agricultural practices are not efficient in food security for the projected world population; hence new food production technologies such as aquaculture integration must be practised. Aquaculture integration has the potential to increase food productivity and come to the rescue of Africa's fish food security crisis. Fish-poultry farming is a sustainable integrated farming system that involves raising birds such as chicken, duck, geese, and fish simultaneously. In this type of integration, poultry excreta are used as fish feed since it contains nutrients that are needed for fish pond fertilisation, which increases the pond's productivity. It has been found that there is a more efficient use of resources when integrating aquaculture with poultry compared to farming with fish alone, with the costs related to fish culture processes reduced by about 70%. However, this farming system has not gained so much recognition in Africa. Therefore, this chapter highlighted how food production could be enhanced using integrated aquaculture, with specific reference to fish integration with poultry farming in the Namibian context.

Keywords Aquaculture · Integration · Sustainability · Poultry · Food production

17.1 Introduction

Food security is one of the most vital and fundamental to human existence and survival. The global population is rising, and existing agricultural practices cannot guarantee food security in the near future. An approximation has been made that food production will be required to double by 2030 to sustain the anticipated human global population (Zajdband 2011). Thus, alternative food production techniques

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should be considered to avail sufficient food for human consumption. While considering other possibilities for food production maximisation, it should be noted that such techniques are sustainable and environmentally friendly. Traditional farming systems are proven capable of producing food in an environmentally sound manner (Herrero et al. 2010), and these may include some commonly practised farming systems in the aquaculture sector.

Aquaculture is one of the fastest sectors and means of food production globally. In 2014, aquaculture is said to have bypassed capture fisheries to become the major source of fish food for human consumption. Moreover, in 2016, global aquaculture production was estimated at 110.2 million metric tonnes (Tran et al. 2020). Aquaculture and capture fisheries have played a significant role in contributing to global food security (Center for Food Security, CFS 2014). However, due to the pressure imposed on wild fisheries using anthropogenic effects, such as illegal, unreported, and unregulated (IUU) fishing and the use of fish meal as feed in aquaculture (Choi et al. 2020), food security in this sector is expected to be reduced. Thus, meeting the increasing demand for fish in the future will continue to depend on the capacity to further expand aquaculture production sustainably (Tran et al. 2020). Aquaculture integration has the potential to increase food productivity and come to the rescue of Africa's fish food security crisis since Asia accounts for most of the aquaculture food production globally (FAO 2017).

Aquaculture integration is the farming of fish with either animal or crop husbandry. Integrated culture is not a new farming practice, but it also exists naturally. The natural ecosystem is a great example of integrated culturing where several plants and animals live together in the same area of land (Reddy and Kishori 2018). Integrated fish farming is a type of farming practice commonly practised in East and Southeast Asian countries, and it is one of the powerful and stable sustainable technologies (Gebru 2021). This farming system has not gained so much recognition in Africa. However, some progress on integrated aquaculture systems has been reported in a few African countries, such as vegetable fish farming in Ghana and Malawi (Gebru 2021). There are different aquaculture integration practices, and fish integration with poultry is one of them. Hence this chapter highlights how food production could be maximised through integrated aquaculture, with reference to fish integration with poultry farming.

17.2 Fish-Poultry Integration System

Fish-poultry farming is an integrated farming system that involves raising birds such as chicken, duck, geese, and fish concurrently. The waste or excreta from poultry serves as feed for the fishes in the fertilised pond (Adeyemi et al. 2022). Fish-poultry farming is still an understudied area in the field of land-use practice. However, this farming system is progressively becoming tolerable and popular among farmers (Adeyemi et al. 2022). The setup of a fish-cum-poultry farming system depends on the farmer's choice. It may also depend on the availability of materials to build a poultry house.

It is recommended that the poultry house is constructed over or adjacent to the fish pond to ensure maximum utilisation of poultry excreta (Gebru 2021). Raising chicken over the fish pond maximises land use, and the poultry house is always hygienic. The chicken house is built so that chicken excreta fall directly into the fish pond. Poultry manure is known to contain more nutrients than other livestock wastes. Based on Sana (2011), it naturally contains less moisture, fibre and compounds such as fish pond fertilisers. Much of the nutrient-constituting feedstuff supplied to poultry is discharged as urinary or faecal waste. The nutrients can then be utilised as pond fertiliser to stimulate the formation of natural nutritional organisms like phytoplankton and detritus (Sana 2011). The tropics, such as in Namibia, where average temperatures persist over 25 °C, are perfect for farming with fish using poultry excreta as a nutrient; however, this practice is also feasible in subtropical and lower-temperature (>20 °C) environments in appropriate seasons of the year (Sana 2011).

The proportion of nitrogen and phosphorus discharge, predominantly in the utmost existing forms (liquified inorganic nitrogen, dissolvable volatile phosphorus), has been employed as an indicator of faecal quality for fertilisation of fish pools (Little and Satapornvanit 1996). The feed constituents fed to poultry can affect the consequent manure value and emission of nutrients for fishpond fertilisation. For instance, manure attained from foraging Muscovy ducks fed different levels of a rice cellulose supplement (100, 75 and 50% of ad libitum) had different emission characteristics (Little and Satapornvanit 1996). Therefore, to avoid over-fertilisation of the fish pond, it is essential to understand what poultry integrated with fish consumes.

17.3 Significances of Fish-Poultry Integration

As a farmer, one always looks forward to maximising their gains by minimising farming inputs. Uddin et al. (1998), claimed that the integration of aquaculture with poultry results in more efficient use of resources than farming with fish alone. The costs related to fish culture processes are lessened by about 70% (Uddin et al. 1998) when integrated with chickens since fish farming uses chicken waste and excess chicken feed as food and fertiliser for the fish pond. A comparative study by Shoko et al. (2019), found out that, gross fish yield, net fish yield and net annual yields attained from fish-poultry integration were significantly higher than the yields from the non-integrated system. Additionally, their (Shoko et al. 2019) partial enterprise budget analysis indicated that fish-poultry integration was more lucrative than the non-integrated system.

The integration of poultry-fish agriculture gives chances to the families with a lack of resources with little monetary investments and resolves the matters of women empowerment and living security at the gross root level (Gangwar et al. 2013). The practice of integrating poultry and fish can give prospects for living standards and food security to the families of Namibian rural areas too. The implementation of combined poultry-fish agrobusiness in various arrangements such as intensive broiler farming, backyard poultry agrobusiness, etc. leads to the protection of natural resources and the creation of supplementary revenue or employment opportunities, particularly for the youths and female labourers in the communities (Gangwar et al. 2013). Some studies have indicated that traditional aquaculture production systems are wasteful and unprofitable, unlike integration systems (Olapade et al. 2017). The productivity of any aquatic body is generally linked to the quality and quantity of plankton available, which are crucial to fish production as they serve as fish food. Thus, poultry excreta increase pond biological productivity, resulting in increased fish production (Gebru 2021).

Fish-poultry integrated systems could be an excellent remedial action to use fishmeal as a feed component in aquaculture production. Fish meal is in demand not only for fish feed production but also for poultry and livestock feed production (Ngugi et al. 2017). Based on Ayoola (2010), aquaculture feeds usually contain a more significant percentage of fishmeal than other animal diets. Thus, calls for sustainable aquaculture have been made, where aquaculture can grow without putting pressure on wild fish stocks (Choi et al. 2020). It has thus been introduced when fish nutritionists and scientists look for alternative ingredients to replace fishmeal completely or partially (Ayoola 2010). Fish-poultry farming would then come in by fully replacing synthesised aquaculture feed, including fishmeal incorporated feed, with poultry excreta as feed or as a fish pond fertilisation agent.

17.4 Constraints in Aquaculture Integration

The integrated poultry-fish aspect of farming is still very new compared to other farming methods, such as mixed farming or rotational farming, which have been in existence for over a hundred years ago (Abiona et al. 2011). As a result of this, there is a necessity for more subject matter specialists in this area of farming to contribute speedy dissemination of information to practising and intending farmers in the coming years. Furthermore, the extent to which integrated fish farming could maximise farmers' revenues is inhibited by problems observed during farming operations. In a study by Abiona et al. (2011), most respondents identified inadequate finance as a significant problem, with 91.2% recorded for integrated fish farmers and 82.7 for nonintegrated fish farmers.

In the Namibian farming context, the case is very similar to Abiona et al. (2011)'s study; there are little to no funds to get this type of farming blooming, especially in rural areas. More farmers are involved in poultry farming, which is mostly domestication than they are involved in fish farming or both. However, to increase food production, especially in rural areas of Namibia, farmers should consider making use of available organic materials to construct poultry houses over fish ponds. Fish ponds could be in the form of earthen ponds, which are only burrowed into the ground and not constructed with concrete since the cost of concrete and labour would be high. There is a general view that well-off farmers with good farming skills and enough investment tend to intensify their farming systems, while the poorer farmers tend to move in the direction of diversification (Phong 2010). Thus, the poorer farmers need financial support, for instance, from the government, to diversify their farming on a larger scale. There is a necessity for discrete government financial support in the form of subsidies for the sustainable advancement of combined poultry-fish agriculture in African rural areas.

Water is one input that must be there for successful poultry-fish integrated farming. Global water coverage is estimated to be approximately 71%, but only 3% is freshwater (Bhandari 2003), and freshwater is essential for this type of farming. Almost one-fifth of the world's population lives in areas of physical water scarcity, and 500 million people are approaching this state (Nashima et al. 2013). Water scarcity is one of the constraints in poultry-fish integration farming in areas where rainfall is seasonal or dry areas such as most parts of Namibia. Smallholder farmers may be willing to get involved in such innovative and sustainable farming practices, yet they are faced with such challenges. This challenge may as well be tackled in different ways, and rainwater harvesting is one of them.

Rainwater harvesting is a method of collecting rainwater from natural or man-made surfaces to be stored and used for productive purposes such as human and livestock consumption, irrigation, and household tasks (Baker et al. 2007). Rainwater harvesting for agricultural purposes has gained some recognition recently (Eseoghene 2019), although less has been discussed it being used in aquaculture. Harvested rainwater is used mainly in the domestic, agricultural, and industrial sectors (Rahman et al. 2019). Thus, it can be a perfect solution for farmers willing to integrate poultry with fish to maximise their returns. Additionally, rainwater is said to involve less to no costs in harvesting, and it is also safe for agricultural purposes (Nashima et al. 2013).

17.5 Controversies around Aquaculture Integration

Although aquaculture integration, regarding poultry-fish integration, is promising in food security, it has been looked at with different opinions globally. Public health alarms have been raised about this specific integration on several occasions. The risks of direct pathogen transfer to humans in fishponds fertilised with manures, whether consumers, producers, or intermediaries, have been most evaluated (Little and Satapornvanit 1996). There have also been implicit connections between integrated livestock-fish systems and influenza pandemics (Maclean 1993). This distressing concept has therefore led to general commentaries and debates on the desirability and effects of integrated farming. As per Little and Satapornvanit (1996), the decisive eutrophication of water, leading to blooms of lethal blue-green algae, has also been pointed out as a problem. Although the possibility of intoxicating fish and mammals from poultry-waste fertilised water exists, their controlled use in fish ponds decreases the likelihood of contamination to other water bodies (Little and Satapornvanit 1996). Gabriel et al. (2007) have pointed out Cyanobacterial blooms to be undesirable in aquatic ponds because they are relatively poor aquatic food bases. In addition, such blooms are poor oxygenators of pond waters, with some species producing odorous metabolites, giving the cultured fish species an undesirable flavour (Gabriel et al. 2007).

17.6 Conclusion and Recommendations

Gebru (2021) recommended that the most suitable fish species for fish-poultry integration are those that can filter feed on phytoplankton and zooplankton from the water. Species including silver carp (*Hypophthalmichthys molitrix*), common carp (*Cyprinus carpio*), grass carp (*Ctenopharyngodon idella*) and tilapia (*Oreochromis spp.*) have been pointed out. It is also recommended that the poultry house be inside and raised over the pond (Fig. 17.1) or beside the pond since it allows poultry manure to fall directly into the pond thereby allowing the poultry house to be clean (Gabriel et al. 2007). Several studies have recommended chickens as the birds suitable for fish-poultry integration compared to other birds, including ducks and geese. In most cases, layer chickens have been identified to be suitable; however, broilers can also be utilised in such integrative practices. Olapade et al. (2017) have recommended that to maximise farm profits in aquaculture integration, a triple integration system must be chosen. They suggested a fish, rice cum poultry

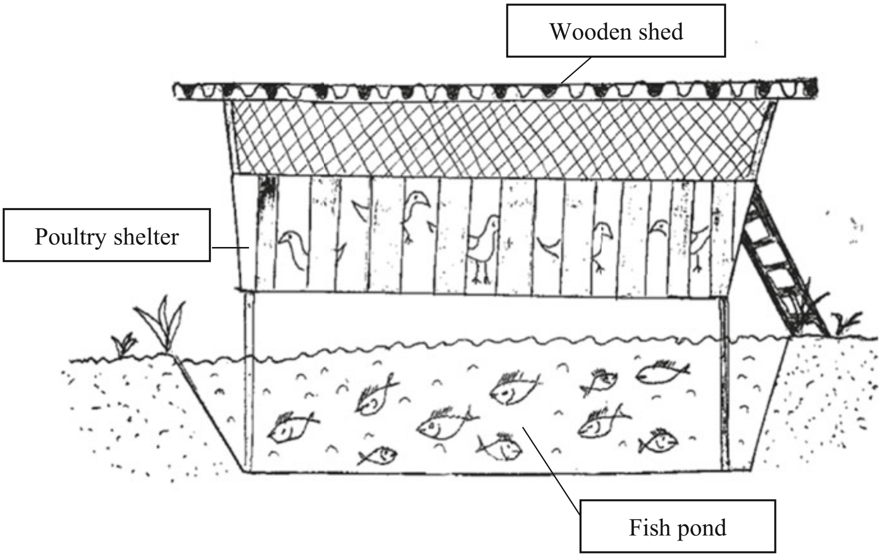

Fig. 17.1 The poultry-fish integration setup

system, which simply involves the raising of birds, culturing of fish (*Clarias gariepinus*) and alternatively the cultivation of rice. In Namibia, this type of integration would be appropriate in the Zambezi and Kavango regions because they are adjacent to rivers with plenty of water for rice cultivation.

Integrated aquaculture systems have not gained so much attention in the African agricultural sectors, yet it has so much potential for food security. This type of farming, about fish-poultry integration, has been found to reduce the farm's production costs. Some studies have indicated that traditional aquaculture production systems are wasteful and unprofitable, unlike integration systems. Poultry excreta increase pond biological productivity, resulting in increased fish production. The tropics, such as in Namibia, where average temperatures remain above 25 °C, are perfect for culturing fish with poultry concurrently. Nevertheless, various constraints exist in this farming practice, including short of funds and the water scarcity problem. On top of that, fish-poultry integration has also been linked to controversies, such as public health anxieties, including the risk of direct pathogen transfer to humans in fishponds fertilised with manures. However, the controlled use of chicken manure and proper pond management is key to the success of fish-poultry integration.

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Chapter 18
Fishing for Answers: Should Afrotropical Farmers use Cages or Ponds for Grow-Out of Nile Tilapia?

Safina Musa

Abstract Despite the scarcity of economic and environmental feasibility studies on aquaculture production systems, they are critical in determining which farming system to invest in. The system you select will determine the likelihood of your investment's success. This study looks at the aquaculture production systems used in Africa, as well as their output rates, cultivated species, economic viability, and nutrient loadings. The challenges and constraints to expanding aquaculture in Africa are highlighted, along with key considerations. According to the findings, the most common freshwater aquaculture culture system in Africa is an earthen pond-based semi-intensive method. Cage systems, on the other hand, are becoming more common in freshwater lakes. Pond farmers would earn more money if they produced fingerlings. However, the farm's overall productivity and profitability appear to increase as grow-out ponds are integrated with other farming systems, such as poultry. Despite the high initial investment, cage systems are preferred in Africa for grow-out tilapia aquaculture. However, due to the high nutrient loading of cage systems, they may be less advantageous than pond systems. The unprofitability of African grow-out ponds appears to be a managerial problem rather than a systemic one. Grow-out pond systems can perform better with proper management.

Keywords Aquaculture · Aquaculture-integration · Cage systems · Earthen ponds · Aquaculture economics

18.1 Introduction

In Africa, the fisheries sector plays various roles in supplying food, income, employment, and livelihood support services (De Graaf and Garibaldi 2014). According to AUC-NEPAD (2014), 10.4 million tonnes of fish are produced in Africa, where fish is the primary source of animal protein for more than 30% of the population

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(AUC-NEPAD 2014). According to De Graaf and Garibaldi (2014), 12.3 million people rely on the fisheries sector for their livelihood directly or indirectly, and the industry contributes 1.2% of the GDP (AUC-NEPAD 2014). Landings from wild capture fisheries have been dwindling worldwide while aquaculture surges (FAO 2022a, b). African nations are taking a closer look at the prospects given by aquaculture because of the decline in capture fisheries resources, overfishing in inland waters, rising population growth rates, and increased demand for fish.

Aquaculture has received and continues to receive enormous support from the national, county, and several non-governmental organisations throughout Africa, which see it as the new frontier for development. As a result, with a growth rate of 11.4%, aquaculture production in Africa was the fastest growing (FAO 2016). However, when the assistance is removed, most of these farms' operations cease. For example, under the Fish Farming Enterprise Productivity Programme (FFEPP), the Kenyan government assisted fish farmers in building ponds, lowering input costs, and providing agricultural inputs from 2009 to 2012. Thanks to the FFEPP, major milestones in Kenya's aquaculture sector had been achieved by the program's conclusion in 2012. More specifically, as more farmers joined the industry, Kenya's aquaculture output increased from 4000 to 20,000 metric tonnes, making Kenya the continent's fourth-largest producer of aquaculture (SDF 2016). However, by 2015, there had been a severe reduction in productivity: according to the KNBS (2015, 2018), tilapia pond production had dropped by 37%, and there were significantly fewer operating fish farms nationwide (SDF 2016). The majority of farmers gave up on maintaining their ponds in favour of other farming endeavours, leaving the nation littered with ponds. Pond fish farming appears to be the principal cultural system in the majority of African nations, similar to Kenya, with aquaculture still receiving substantial subsidies. The sustainability of pond fish farming in Africa depends on a number of important aspects, including high-quality seed and feed, effective management techniques, and system productivity. Low pond productivity, however, continues to be the primary obstacle to the development of aquaculture in the majority of African nations (Kubiriza et al. 2018; Mulokozi et al. 2021; Musa et al. 2022a). As a result, the sector is characterised by the constant emigration of old pond farmers and the influx of new/suspicious farmers, as reported in Ghana (Afram 2021), Uganda (Kubiriza et al. 2018), and Kenya (Musa et al. 2022a). As fish farming begins to take root in Africa, several questions will need to be addressed, among them: Can aquaculture gain impetus without subsidy in sub-Saharan Africa? Is pond farming economically sustainable for African countries?

The ability of aquaculture to remain lucrative and competitive over time is a prerequisite for its economic sustainability. Support for new fish farms may help aquaculture in Africa flourish, but if the enterprise is not viable or promotes ethical business conduct, it is of little use (Guillen et al. 2019). According to Hishamunda et al. (2014), aquaculture can only be sustained by subsidies if it is economically viable. It is vital to assess the viability of the culture systems for African entrepreneurs to assist them in evaluating and making an informed decision with their investment because the aquaculture sector is projected to contribute to food security and the reduction of poverty in the continent. However, there is a dearth of data on the economic performance of various African fish culture systems. Fish farming is therefore viewed as a marginal and risky industry in Africa which makes it extremely difficult for existing fish farmers to obtain loans from financial institutions and insurance for their investment (Pillay and Kutty 2005; Aura et al. 2018). Furthermore, the absence of performance measures discourages new recruits from joining the industry. Additionally, choosing the best production system is a crucial first step in starting or growing an aquaculture business. Thus, the current analysis emphasises the profitability of aquaculture production systems for Nile tilapia culture, aquaculture production systems in Africa, species grown, and nutrient loading of frequently used aquaculture production systems.

18.2 Aquaculture Production Systems in Africa

Africa primarily uses extensive, semi-intensive, and intensive aquaculture production techniques. Depending on the species being raised and the accessibility of land and water, these systems use concrete, earthen, and liner-lined ponds, tanks, raceways, and cages (Fig. 18.1). However, semi-intensive earthen ponds are the primary method of production for freshwater aquaculture in Africa, including Egypt (El-Gayar 2003; Kleih et al. 2013), Kenya (Musa et al. 2012b), Uganda (Isyagi et al. 2009), Tanzania (Mulokozi et al. 2021), and Nigeria (Anetekhai 2010).

18.2.1 Extensive Systems

These systems are characterised by low input, low-density stocking, no artificial feeds, and a poor yield per unit area. The fish rely only on naturally occurring food sources in the culture water. Typically, the stocked fish are allowed to reach the receiving water's natural carrying capacity. In Egypt, extensive systems have been used for many years, primarily in the form of net enclosures. According to Shaalan et al. (2018), some regions of Egypt still engage in substantial extensive aquaculture, with outputs of 0.25 to 0.75 tons per year (Shaheen et al. 2013; Soliman and Yacout 2016). The technique is mostly used in Kenya's dams and water reservoirs, with yields of 500–1500 kg/ha/year (Ngugi et al. 2007). In Nigeria, extensive systems are used, primarily for subsistence, in reservoirs and undrainable ponds (Daramola et al. 2017; Okwodu 2016). In Tanzania, the majority of pond fish farming is done extensively, mainly for subsistence (Mulokozi et al. 2021). Large stagnant ponds are used for massive fish farming in Uganda, with yield hardly topping 0.2 kg/m^3 (Shoko et al. 2011).

Earthen ponds
Source: Author

Liner ponds
Source: Author

Above ground/backyard ponds
Source: Author

Tanks
Source: Author

Concrete ponds
Source: Author

LVHD cages
Source: Author

Raceway
Source: Online

Recirculating aquaculture
Source: Online

Fig. 18.1 Culture systems in Africa. Note: LVHD (low volume high density)

18.2.2 Semi-Intensive Systems

Over 90% of African aquaculture systems use semi-intensive production methods (FAO 1999; FAO 2008; Mucai et al. 2011). To increase natural yield, the systems are fertilized with animal excrement such as that of cattle, sheep, and poultry, among others. In addition to natural foods, low-protein feed (10–30%) is available (Soliman and Yacout 2016). The pond's production cycle lasts between 5 and 6 months when the best management techniques are used (Anetekhai 2010). Most of these systems are used to cultivate low-value species such as catfish and tilapia.

More than 70% of aquaculture production in Kenya (Musa et al. 2012b) and Uganda (Kubiriza et al. 2018) is produced using semi-intensive methods. The output from semi-intensive ponds, under competent management, is between 1–2 tons/ha/year in both Kenya and Uganda (Brummett 1999). In Tanzania, semi-intensive ponds account for more than 50% of aquaculture production with a yield of 1.5 tons/ha/year under best management practices (Mulokozi 2021). The entire aquaculture production in Egypt is 73% semi-intensive pond culture systems, with fish yields ranging from 5 to 20 tons/ha/year (Shaheen et al. 2013; GAFRD 2014). Nigeria's production is predicted to be more than 10,000 kg/ha/year (Iruo et al. 2018).

18.2.3 Intensive Systems

Raceways, recirculating aquaculture systems (RAS), and cages are some of the intensive aquaculture systems used in Africa. According to research (Aubin et al. 2006; Colt et al. 2008), intensive systems are effective at using both land and water. The requirement for complete diets with crude protein values >30%, which is expensive and out of the price range for the majority of farmers, is a significant disadvantage of intensive systems. Additionally, because it raises operating expenses, the high energy need is a significant bottleneck for systems like RAS (Aubin et al. 2006; Colt et al. 2008). Intensive systems, like RAS, have a low adoption rate because of the initial financial investment. However, it has been noted that due to economic factors, semi-intensive systems are being replaced by intensive systems in African nations like Egypt (FAO 2020). The growth of intensive aquaculture in Egypt, according to GAFRD (2014), caused a 50% decrease in fish production from semi-intensive systems in 2012 compared to 2011. In Egypt, intensive methods have been reported to produce yields of between 100 and 150 tons per hectare per year (Shaheen et al. 2013). According to FAO (2016), the production from raceways in Kenya ranges from 10,000 to 8000 kg per year, whereas the production from RAS is 200 tonnes (SDF 2016).

Inland waters in Africa have seen a faster uptake of cage aquaculture, including Lake Victoria in Kenya (Aura et al. 2018), Lake Victoria in Uganda (Blow and Leonard 2007), the Lake Volta in Ghana (Asmah et al. 2016), the Lake Kariba in

Zimbabwe (Berg et al. 1996), and the Lake Malawi in Malawi (Blow and Leonard 2007). Production from cages has been estimated to range from 5 to 35 kg of fish per m^3 in Lake Victoria, Uganda (Mbowa et al. 2016), 50 kg per m^3 in Lake Victoria, Kenya (Musa et al. 2021b), 42 kg per m^3 in Lake Malawi (Gondwe et al. 2011), and 20 to 40 kg per m^3 in Lake Volta, Ghana's (Karikari 2016).

18.2.4 Integrated Agriculture and Aquaculture Systems (IAA)

The primary goals of integrating aquaculture into larger farming systems are to increase food production, protect the environment, provide food security, and diversify sources of income. In IAA, fish can be combined with poultry (Fig. 18.2), pigs, rabbits, sheep, goats, or cattle in a design that enables the use of waste products from one system as inputs into another. The systems' ability to create synergy amongst several businesses makes them unique (Edwards 1998; Rakocy et al. 2003). The systems are effective at utilising both land and water, making them perfect for rural locations where a lack of fresh water is a problem. However, the technique is not commonly used in Africa, and in the few instances that have been reported, it is primarily used for subsistence (Jamu 2001). Additionally, the approach has demonstrated improvements in farm productivity and profitability in the few cases reported in Africa (Dey et al. 2010; Shoko et al. 2011; Mulokozi et al. 2021).

Fig. 18.2 Integrated aquaculture system (Source: Author)

According to Shaalan et al. (2018), aquaponics and aquaculture-based rice farming are the most popular integrated aquaculture practices in Egypt, where 34,537 tons of fish have been produced annually (GAFRD 2014). Although not frequently used by farmers who mostly use farm animal manure for pond fertilisation, aquaculture operations are linked with crop or livestock production in Kenya (Ogello et al. 2013; Ogello and Opiyo 2011). IAA recorded production of roughly 200 kg/ha/year in Kenya (Van Dam et al. 2006). Notably, the adoption of IAA has led to a 2–26% increase in agricultural production and a 22–70% increase in total farm food production in Kenya. With integration, fish production in Malawi increased from 900 to 1500 kg/ha/year, and IAA's ecological footprint decreased nearly 42 times that of conventional farms (Brummett 1999). The most prevalent IAA system in Tanzania is the integration of tilapia and vegetables, with an estimated 3.2 tons/ha/year of production (Mulokozi et al. 2021). Fish raised in Tanzania under IAA have displayed faster growth rates than fish raised in conventional farms (Mulokozi et al. 2021). In addition, the IAA system generated greater economic benefits than a non-integrated one (Mulokozi et al. 2021). According to reports, IAA is still in its infancy in Uganda (MAAIF 2012). However, IAA has reported yields of up to 3.7 tons per hectare every year (MAAIF 2012; Maseruka 2004).

18.3 Cultured Fish Species in Africa

The Nile tilapia and African catfish dominate the aquaculture sector in Africa (Fig. 18.3). The Nile tilapia is the most widely cultivated freshwater fish in Africa, except for Nigeria, where catfish account for over 80% of aquaculture production

Fig. 18.3 Main cultured species in Africa

(Anetekhai 2010). This is because they are hardy, widely accepted, grow quickly, tolerate crowded conditions, are highly disease resistant, and feed primarily on very low trophic levels (Siddik et al. 2014; Amin et al. 2019; Mahmoud et al. 2021). Although in small amounts, other species, including carps and rainbow trout, are also cultured in Africa.

18.4 Profitability of Aquaculture Production Systems for Nile Tilapia Culture

The economic viability of an aquaculture operation is essential for its success. High-profit margins should be the goal because aquaculture has been viewed as a marginal investment, making it necessary for the farms to satisfy their debt obligations. Nile tilapia grow-out systems using pond and cage systems have shown positive returns above variable costs in both Kenya (Musa et al. 2021b) and Uganda (Kubiriza et al. 2018) (Table 18.1). Both ponds and cages are lucrative for tilapia growth in Kenya and Uganda, and probably across all of Africa, according to positive returns above variable expenses. According to studies conducted in Kenya, the total fixed production cost per kg of Nile tilapia produced in cages is \$0.2 (Musa et al. 2021b), while the cost per kg of Nile tilapia produced in ponds is \$0.8. (Unpublished data, KMFRI, Kenya). In light of this, grow-out pond farmers will report a negative return over total costs, whereas cage farmers will report a positive return. This shows that running pond systems for grow-out is not financially viable over the long term in Kenya and Uganda, and probably in all of Africa. As a result, likely, grow-out pond

Table 18.1 Productivity of grow-out ponds and cages in Uganda and Kenya (data for ponds and cages in Uganda is derived from Kubiriza et al. (2018); while for cages in Kenya is derived from Musa et al. (2021a, b) while for ponds is from unpublished data from aquaculture farms in Kenya)

Parameter	Pond (Uganda)	pond (Kenya)	HVLD cage (Uganda)	HVLD cage (Kenya)
Volume of common facilities (m^3)	1000	450	22.5	8
Cost/m^3	1.46	1.29	35.6	20.3
Body mass of stocked Nile tilapia (kg)	0.002	0.005	0.008	0.015
Stocked biomass (kg/m^3)	0.005	0.015	0.75	1.9
Survival (%)	60	80	72	91
Biomass harvested per cubic metre (kg)	0.63	0.7	26.9	51.2
Production duration (months)	9 to 14	8 to 12	6 to 8	6 to 8
Production cycles per year	1	1	2	2
Average farm gate price (USD)	2.3	3	2.3	3
Gross profit above variable costs (USD)	107.1	36.1	725.8	806.5
Profit margin per kg of fish above variable costs (USD)	0.17	0.18	1.2	1.97

fish growers in Kenya, Uganda, and perhaps throughout Africa are losing money, but they continue to operate. The persistence of the grow-out pond farmers is unclear. Two theories have been put out, though. The first is that farmers do not keep good records and are therefore unaware that their operations are not earning them profits. Second, pond farmers can survive thanks to subsidies from the government and other organizations.

Investment costs for cages appear to be higher than those for ponds in both Kenya and Uganda and likely throughout all of Africa (Table 18.1). This might prevent it from being adopted, especially by smallholder farmers. However, low volume high density (LVHD) cages are superior to ponds for growing tilapia because they offer more significant profit margins per kilogram of fish produced in Uganda and Kenya, respectively (Table 18.1).

Similar research on the financial viability of ponds for the production of fingerlings has been undertaken in Kenya and Uganda. In Uganda, fingerling production has been claimed to provide money per cubic meter (USD) of ponds that is approximately 177 times greater than for grow-out of tilapia (Kubiriza et al. 2018). Similarly, in Kenya, producing fingerlings generates about 150 times more money per cubic meter (USD) of the pond than grow-out tilapia (Unpublished data, KMFRI, Kenya). The results show that ponds are more profitable for producing tilapia fingerlings in Kenya and Uganda than grow-out tilapia, and probably throughout Africa. Which brings up the crucial question Why does producing fingerlings in ponds pay off better than grow-out of Nile tilapia? Why are cages more profitable for the grow-out of Nile tilapia than ponds?

According to Table 18.1, the size of fish in cages is around three times that of fish in ponds. This would imply that fish in cages would grow to market weight more quickly than fish in ponds. Additionally, when fed a nutritionally balanced diet, Nile tilapia appears to take roughly 12 months to reach table size (500 g) in pond systems. The fish would require 6 to 9 months in cages to reach the same weight (Kubiriza et al. 2018; Musa et al. 2021b). According to this, cage farmers—unlike pond farmers—can have two production cycles each year. In Uganda, it has been estimated that 3500 fingerlings/m^3 are generated every 21 days when ponds are used for Nile tilapia spawning (Kubiriza et al. 2018). According to Musa et al. (2012a), each female tilapia in Kenya has a fecundity rate of about 1050 eggs per 30 days, which translates to roughly 4000 fingerlings/m^3 every 30 days.

On the other hand, after a year, pond farmers stocking roughly 4 fish/m^3 would only get less than 2.5 kg/m^3. Pond farmers who produce fingerlings would make over USD 180/m^3/month in contrast to those who produce table-size fish and only make less than USD 10/m^3 after more than 10 months, based on the lowest price of fingerlings in the Lake Victoria basin of 0.05 USD and the highest farm-gate price of tilapia of 3.57 USD (Ngugi et al. 2017). Therefore, the current analysis shows that pond systems are better for producing fingerlings than table-sized fish in Uganda and Kenya, as well as likely throughout the rest of Africa. Even the production of fingerlings would have produced poor results if the issue of low productivity in ponds was related to the system. Considering all of these aspects, low pond profitability can be more of a management problem than a facility one.

18.5 Nutrient Loading of Commonly Utilized Aquaculture Production Systems

Wastes in effluents from aquaculture systems are often produced by uneaten food and fish waste. Deterioration of the quality of the water and bottom sediment can result from these (Musa et al. 2022b). Nutrient enrichment and eutrophication of the lacustrine environment are predicted to take place as a result of the aquaculture sector's fast expansion in Africa, notably the expanding cage culture sector. Because of the high temperatures, it is anticipated that receiving waters in the tropics may react to pollution, particularly oxygen depletion, more quickly (Beveridge and Phillips 1993; Gowen and Rosenthal 1993; Berg et al. 1996). However, little is known about the nutrient loadings from the diverse culture systems in Africa and the tropics in general. A comparison of nutrient loadings from different culture systems would be helpful for guiding aquaculture investments to ensure the sustainability of the sector.

According to nutrient loading tests conducted in ponds and cages in Africa, cages appear to have more nutrient loading than ponds (Table 18.2). Unless the water quality deteriorates, farmers typically do not exchange pond water very often. In this sense, pond bottoms could act as sinks for organic debris and nutrients. On the other hand, cages operating in open systems may release more nutrients into the environment. This may suggest that cages have a larger potential for environmental pollution than fish ponds if they are not managed appropriately. Fish ponds may have a high retention capability for P and N, limiting the eutrophication of downstream aquatic ecosystems. More so in most freshwater lakes like Lake Victoria, which are already choked by large nutrient loads from industrial and agricultural wastes (Hecky et al. 2010), discharge of P and N from fish cages into the lacustrine ecosystem will cause industry strife. This would disfavour cage culture compared to pond fish farming.

Table 18.2 Nutrient loads from pond and cage systems in Africa

System	FCR	N load (kg N/tonne)	P load (kg P/tonne)	Source
Pond	1.6	53.2	8.5	Boyd et al. (2008)
Cages	2.8	105	23	Musa et al. (2022a, b)
Cages	2	93.5	22.8	Karikari (2016)
Cages	2.7	104.7	15.4	Gondwe et al. (2011)
Cages	1.4	45	14.3	Neto and Ostrensky (2013)

18.6 Challenges/Constraints in Aquaculture Development in Africa

Fish consumption will primarily come from culture fisheries due to the decrease in capture fisheries and the explosive growth in demand for fish. One cannot overstate the importance of having effective production systems to close the gap between the rising demand for fish and the available supply. However, a variety of unrelated circumstances may have an impact on aquaculture production systems' prospects, reducing the output of even the most effective systems. Generally speaking, the limitations in Africa appear to be nation-specific (Table 18.3). However, challenges like low pond productivity, high feed costs, low fish prices, and insufficient aquaculture policies appear to be present in Kenya, Tanzania, Uganda, Egypt, and Nigeria (Table 18.3), as well as likely across all of Africa. More than 60% of

Table 18.3 Constraints in Aquaculture and fish farming in Africa (Rutaisire et al. 2009; Munguti et al. 2014; Igoche et al. 2019; Kaleem and Sabi 2021; Mulokozi et al. 2021)

Challenges/constraints in fish farming in Africa				
Kenya	Tanzania	Uganda	Egypt	Nigeria
Poor infrastructure	Limited extension services	Availability of fish feeds	Weak control	Inadequate infrastructure
Lack of quality fish feeds	Poor adoption of BMPs	High cost of feeds	Lack of reliable marine hatchery	Inadequate supply of fish feed
Poor quality seeds	Inadequate funds	Low price of fish	Pressure on natural fry	Irregular electricity supply
High cost of fish feeds	Poor hatchery facilities	Poor extension services	Food supply problems	Poor finance
Poor adoption of BMPs	Poor market/ price	Inadequate aquaculture policy	Lack of planning and control	High cost of feed
Low price of fish	Limited funding	Subsistence approach	Frequent pollution and eutrophication risks	Land acquisition
Post harvest losses	Irregular electricity supply	Poor pond productivity	Reduced market	High price of input
Lack of comprehensive aquaculture policy	Poor infrastructure	Poor adoption of BMPs	Limited availability of sites	Disease and poaching
Poor extension services	Post harvest losses	Post harvest losses	Chronic pollution hazard	Poor extension services
Poor pond productivity	Poor pond productivity	Inadequate infrastructure	High prices	Poor market/ price
Subsistence approach	Inadequate aquaculture policy	Poor pond pruductivity	Poor hatchery facilities	cannibalism

Note: *BMP*: best management practice

aquaculture production costs are related to fish feeding (Watanabe 2002; El-Sayed 2006; Cheng et al. 2010; Khalil et al. 2019; Allam et al. 2020). In cage culture, the figures have been reported to be much higher (>70%) (Musa et al. 2021b). Therefore, a marginal return on investment would result from the high price of fish feeds in African nations. The primary fish species raised in African nations is tilapia, which is also a low-value and hence relatively inexpensive fish species. Thus, high fish feed costs, low fish prices, and competition from low-cost imported fish would further cut into aquaculture profitability. Inadequate aquaculture policies also result in an unfavourable economic environment in Africa for this type of industry.

18.7 Conclusion and Recommendation

For successful aquaculture, appropriate production systems are vital. In Africa, the pond system is the most common culture system. However, in Kenya and Uganda, and probably, the whole of Africa, ponds seem to have higher productivity for tilapia fingerling production while cages seem to be more efficient for grow-out of tilapia. Furthermore, most grow-out pond fish farmers are making losses and they may not even be aware of it. However, IAA in all cases reported in Africa has proved to be more profitable than the typical unitary pond farming, yet very few farmers have embraced this approach. Hence, IAA could be the “lost coin” for present and future sustainable aquaculture development in Africa. Investment costs for LDHV cages seem higher than ponds, but the returns appear to be more lucrative than ponds. However, nutrient loading from cages seems to be higher than pond systems. In order for small-scale farmers to maximise returns on investment, there is a need to prioritise the development of ponds for fingerling production in Africa as opposed to the current grow-out production. However, low productivity from grow-out pond seems to be more of a management issue than a system issue. The suggestion is to prioritise ponds for fingerling production and cages for the grow-out of Nile tilapia in Africa. Furthermore, nutrient management from cages is paramount for the sustainability of the sector. In addition, there is a need to develop and adopt sound aquaculture policies and strategic framework in African countries to create enabling business environment. In particular, specific policies targeting IAA is highly recommended for African countries.

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Chapter 19
Aquaculture Development Perspectives in Sierra Leone: The Challenges of Critical Inputs and Political Will

Julius Olufemi Olapade and Annmarie Bangura

Abstract This chapter discussed the challenges facing the aquaculture sector in Sierra Leone and the contributions that governance has made to its growth. Freshwater resources in Sierra Leone support aquaculture and the farming of aquatic organisms, mainly fish. Various aquaculture grant projects and interventions funded by USAID, the European Union, CORAF/WECARD, AfDB, and a variety of other international donor partners, including WorldFish, have recently benefited Sierra Leone. FAO has been an essential partner in aquaculture development since the end of the civil war, offering technical cooperation programs and implementing aquaculture projects throughout the country, particularly the TCP/SIL/3104 project. Njala University's Department of Aquaculture and Fisheries Management pioneered the integration of agriculture and aquaculture with assistance from CORAF/WECARD, a Multi-Donor Trust Fund (MDTF). Furthermore, since 2007, the university has trained people in fisheries and aquaculture. It has since produced a large number of accomplished professionals who are currently contributing significantly to Sierra Leone's aquaculture revival efforts. The species of culture that are of interest are *Clarias* spp. and *Oreochromis niloticus*. Sierra Leone's efforts to institutionalise fish farming, whose contribution to the nation's socioeconomic life is nonexistent, are still hampered by several factors. The nation's aquaculture infrastructure is hindered by a supply of genetically unsound fish seeds, the majority of which are obtained from the wild, a scarcity of high-quality, affordable fish feed, a lack of technical and technological know-how, albeit in moderation, and poor aquaculture governance. To ensure the long-term sustainability of the aquaculture sector, the governance of modern aquaculture businesses is thought to need to balance ecological and human factors. Poor governance is a source of resource misallocation, an indicator of industry stagnation, and an indicator of irreversible environmental damage.

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19.1 Introduction

Sierra Leone is endowed with suitable land and good waters comprising freshwater, brackish and marine, where fish species can be cultured. Its shoreline is approximately 560 km long, consisting of estuaries of three large river networks (the Scarcies, Sierra Leone and Sherbro rivers) and four coastal islands. The country's inland water resources consist of rivers, lakes, IVSs and floodplains that support a large number of aquatic organisms (Turner et al. 2000). Sierra Leone's lowland is made up of 690,000 ha of Inland Valley Swamps (IVSs), and 145,000 ha of large, saucer-shaped basins (bolilands). The lowland is interspersed with 130,000 ha of riverine grasslands and 200,000 ha of mangrove swamps. The country's ecosystem supports agricultural production and meets the resource needs of the local communities, especially through hunting, fishing, and foraging (Scoones 1991; Adams 1993). Fish is the number one source of animal protein in Sierra Leone and the cheapest, but it mostly comes from the marine fisheries sector, pressuring the resource.

Despite Sierra Leone's enormous resources endowment, food insecurity, a visible dimension of poverty and destitution, is chronically rife. Food security, as defined by FAO, is a condition when all people, always, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life. As in many other third-world nations, chronic hunger is widespread in Sierra Leone. The majority of her, over 6.3 million people, are faced with hunger and malnutrition, and according to the 2021 Global Hunger Index, Sierra Leone ranks 106th out of 116 countries; at a score of 31.3 on GHI, the country is classified as having severe hunger problems.

Notwithstanding the recent increase in food production, malnutrition is still rife, especially among children below the age of five, while households find it challenging to meet their daily nutritional needs. Poverty remains disproportionately rural, with 78% of the poor living in rural areas. As a result, many people are food insecure and suffer from malnutrition, are more vulnerable to shocks, need assistance and are unable to contribute to the national economy. It has been reported by FAO (2003a; b) that malnutrition in Sub-Saharan Africa is on the rise in both absolute and relative terms. FAO (2003a, b) reported that more than one-third (34%) of the population of SSA is undernourished. This figure which is an increase of nine million since the 1996 world food summit, most times comes with dire and irreversible consequences on the physical, social and economic development of the affected people. In 1990 alone, 2.4 million people were affected by malnutrition in Africa. According to the 1996 human development report, 22.5 million African children are malnourished; it is believed that this figure could have increased since then. Malnutrition remains an important contributor to infant morbidity and mortality in Sierra Leone. It is a major impediment to the manpower and economic development of the country. It is estimated that between 15,000 and 20,000 African women die each year (41–45 every day) due to severe iron deficiency anaemia. Vitamin A deficiency in children is common across the whole continent, contributing to the deaths of more than half a million African children annually (UNICEF 2004). Fish, a source of "rich food for poor people", is critical for improving Africa's food deficit and nutritional issues. According to FAO (2003a; b), fish provides 22% of the protein intake in SSA. In West African countries, for instance, where fish has been a central element in local economies for many centuries, the proportion of dietary protein that comes from fish is exceptionally high – 47% in Senegal, 62% in the Gambia and 63% in Sierra Leone and Ghana respectively.

The global decline in landing from the capture fisheries has created a huge supply gap, making it difficult to sufficiently meet the dietary protein needs of the poor people of Africa. Sierra Leone's annual landings from the marine fisheries are put at about 200,000 metric tonnes, a far cry from the pre-war values. This decline is a pointer to the fact that fish stocks have approached or even exceeded the point of maximum sustainable yield. This is a clarion call for the development and intensification of aquaculture, a sector of the economy with the potential to redress the fish demand-supply deficit, especially in response to the shrinking but economically and socially essential capture fisheries in terms of its contribution to households` food and nutrition security. According to FAO statistics for 2008, aquaculture, the rational rearing of aquatic organisms of economic benefits to man, is a fast-growing industry worldwide; it supplies almost half of all fish consumed globally. Aquaculture has a very high prospect of bridging the wide gap between fish supply and demand. The rationale behind aquaculture development is to make available good quality fresh fish that will provide affordable fish proteins to the poor and the fast-growing population. This will also reduce the pressure on captured marine environments. It is expected that an increase in production will greatly complement current efforts aimed at achieving the United Nations Millennium Development Goals (MDGs), especially the eradication of extreme poverty and hunger, reduction in child mortality, improvement of maternal health, prevention of diseases, promotion of gender equity and women empowerment. Bamba (2004) observed that aquaculture development in Sierra Leone needs refocussing using new approaches in order to make it relevant in terms of foreign exchange earnings, poverty alleviation and security of food and nutrition.

The country's aquaculture infrastructure suffers from the lack of good quality fish seed, lack of good quality fish feed and the lack of technical and technological expertise, howbeit sparingly, and defective aquaculture governance. It is believed that the governance of modern aquaculture business would need to reconcile ecological and human aspects to assure sustainable development of the industry over time. Bad governance is a precipitator of misallocation of resources, a precursor to stagnation of the sector and irreversible environmental damage. This paper explores the challenges of the Sierra Leone aquaculture industry and the roles of governance in its development (Fig. 19.1 and Table 19.1).

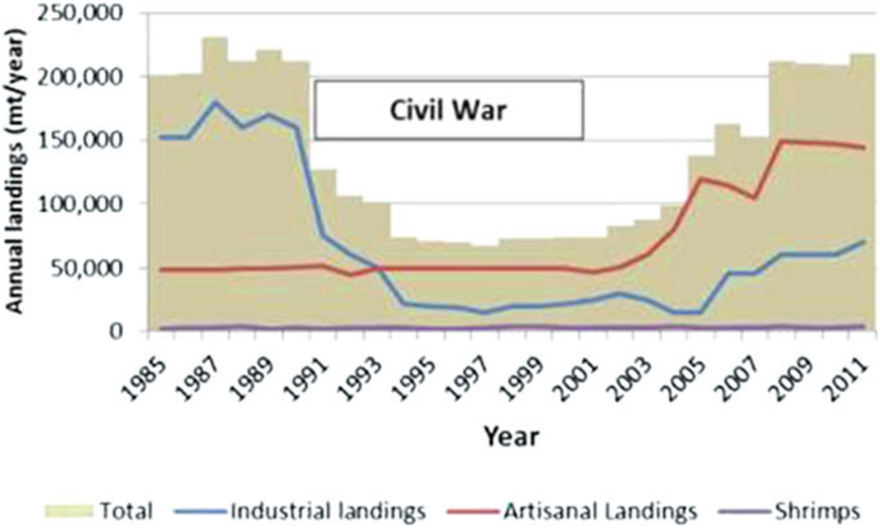

Fig. 19.1 Annual Fish landing Marine fisheries in Sierra Leone (Source: Hecht et al. 2012)

19.2 Tracing the Dynamics of Sierra Leone Aquaculture Development

It suffices to point out that aquaculture in Sierra Leone has made some gains since its inception in early 1970. Unfortunately, the pace of its development is slow and challenging. The enormous potential of fish culture in the country is yet to be fully commercialised, as it is still largely practised at the subsistence level and as a backyard activity. Its potential for food security, employment and household income generation remains adequately exploited. The aquaculture sector, due to its underperformance has not been able to contribute to reducing the pressure on captured marine environments and make available good quality fresh fish to the poor and fast-growing rural population of Sierra Leone. The government of Sierra Leone, through the Ministry of Fisheries and Marine Resources, implemented measures and put in place policies to promote inland fisheries and aquaculture development to make fish sufficiently available for the rural population, especially for those in the coastal villages.

Fish cultures in Sierra Leone are localised in the south (Bo, Moyamba and Pujehun), the north (Tonkolili and Bombali) and the east (Kailahun, Kenema and Kono). The reasons for establishing fish culture facilities, including earthen ponds, cannot be divorced from the existence of suitable IVs, good topography and clean all-year-round water, which favours the culture of tilapia by smallholder farmers. Integration of fish with other agricultural endeavour is not alien to Sierra Leone but recent. In early 1970, farmers received tilapia fingerling supply from Cote d'Ivoire to pioneer the culture of fish in earthen ponds, which was the prevalent system of fish culture in Sierra Leone.

Table 19.1 Fish production, import, export and the per capita availability of fish in Sierra Leone (Source: (COFREPECHE 2013)

Sector 2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Aquaculture 30	30	30	30	30	30	30	30	40	40
Inland fisheries 14,000	14,000	14,000	14,000	14,000	14,000	14,000	14,000	14,000	14,000
Marine fisheries 60,730	61,147	66,556	79,865	110,173	130,110	133,081	129,610	189,582	186,000
Fish export 6708	6197	7634	6330	5537	5961	5608	5619	5562	6128
Fish Import 2787	3433	2362	2603	1836	1781	1412	2733	1644	2288
Per capita Availability (kg/capital/year) 16.8	16.6	17.1	19.7	26.5	27.8	27.3	26.1	35.15	33.4

The promotion of tilapia culture *Oreochromis niloticus* in earthen ponds was an essential component in the Bo-Pujehun GTZ programme in the 1980s, and this acted as a trigger in the dissemination of fish culture technology in the Southern Province, primarily in Bo and Pujehun districts. Fish integrated into rice paddy was demonstrated to farmers in the Bo district as part of the Bo-Pujehun project. The culture of wild-sourced *Clarias gariepinus* and *Heterobranchus sp* in earthen ponds has also been promoted by research institutions and local and international Non-Governmental organisations. The 2005 Sierra Leone aquaculture baseline survey revealed the existence of 1127 fishponds nationwide. Only about half of these ponds (657) were active, while the remaining 40% have been abandoned.

In 2009 however, Dabo et al. (2009) reported that there were 2593 fishponds in 12 districts including the western area. According to Dabo et al. (2009), 83% of the ponds were located in Tonkolili district. The figures posted by Dabo et al. (2009) were not significantly different from the 2087 fishponds recorded by WorldFish in a recent aquaculture assessment for Tonkolili and Bombali districts alone. A significant proportion of these ponds (98.6%) is located in the Tonkolili district. Individuals/families owned about 84% of the ponds, with men holding 80%, while the remaining 4% of ponds belonged to women. The freshwater fishpond culture of Nile tilapia (*Oreochromis niloticus*) was initiated at Makali in 1977 by the Ministry of Fisheries and Marine Resources together with Catholic Relief Services, USAID, and the American Peace Corps (FAO 1992). Farmers owned 1–4 fishponds, with surface areas ranging from 100 to 500 m^2/pond. The yield from these ponds was put at 1.5 to 2.5 tonnes/ha/year, 50 percent of the maximum output attainable under the prevailing conditions during the initial stages of experimentation. The productivity of the ponds was probably limited by the lack of critical inputs such as the improved strain of fish and nutritional fish feed; the knowledge and technical capacity of the support beneficiaries then were at their lowest, thus the observed low performance. Rice bran, cassava peels, household left, and termites were the local feeds dispensed to fish in ponds by farmers regardless of the feeding habit and feed requirements of the fish under culture. Farmers in the districts often applied chicken and goat manure to boost the primary productivity of the ponds.

Available information on aquaculture production in Sierra Leone is provided by Dabo et al. (2009) Table 19.2. Aquaculture production figures are mere estimates because there is no detailed information on several ponds actively under culture. Fish farming accounts for only about 40 tonnes per annum, a small percentage of annual fish production (Agricultural Sector Master Plan Study, 1992). This production figure contradicted the 30 tonnes per annum posited by FAO in its statistical bulletin of 2001. The production figure put forward by FAO is composed of Nile tilapia (*Oreochromis niloticus*) valued at US$ 45,000, based on a cost of US$ 1.5/kg.

The mangroves, rivers, estuaries and intertidal zones of Sierra Leone were exploited freely by locals for crustaceans, especially oysters, which were in abundance (Olapade and Bangura 2019). An attempt was, however, made to domesticate oysters through culture practices. The first effort to culture mangrove and mud oysters in Sierra Leone was through a research trial conducted in 1964 in Bonthe. Unfortunately, the research trial failed due to improper site selection, which led to

Table 19.2 Results of the Aquaculture baseline survey of 2009 ((Dabo et al. 2009)

District	No. of Ponds	Average size ponds	Percentage active ponds (%)	No. of active ponds	Pond areas in production	Production (t/yr)
Bo	277	304	52	143	4.35	6.53
Bombali	28	479	36	10	0.49	0.73
Bonthe	3	325	66.7	2	0.07	0.11
Kailahun	20	330	70	14	0.47	0.70
Kambia	12	195	0	0	0.00	0.00
Kenema	5	384	40	2	0.08	0.12
Koinadugu	7	763	100	7	0.53	0.80
Kono	25	347	8	2	0.07	0.11
Moyamba	4	233	0	0	0.00	0.00
Port Loko	12	560	58	7	0.38	0.58
Pujehun	11	196	90.9	10	0.19	0.28
Tonkolili	2164	344	73	1590	54.76	82.13
Western Area	25	295	52	13	0.39	0.58

the total abandonment of the research effort. In 1973, a 10-year oyster culture research project was implemented jointly by the Government of Sierra Leone (GoSL) and the International Development Research Centre (IDRC) of Canada (Sankoh et al. 2018) as a sequel to the 1964 effort. The chosen culture species for the IDRC project was *Crassostrea Tulipa*, which was raised using rafts, trays and sticks. The success recorded after the trials indicated the suitability of the environment and the feasibility of year-round production. Oyster culture using raft showed promise, as the growth of 1 cm per month was recorded, with the possibility of obtaining market-size oysters in a 7-month cycle (Olapade and Bangura 2019). However, oyster culture in Sierra Leone could not be commercialised because wild oysters were abundant, and women efficiently harvest and sell them at lower prices in the market (Sankoh et al. 2018).

The culture of shrimp in Sierra Leone has not been vigorously pursued. Still, in the late 1980s, a feasibility study for shrimp culture was undertaken by the Sierra Fishing Company for the commercial production of shrimps in the country (Sankoh et al. 2018). Interest in promoting the mariculture of fin fishes and crustaceans in Sierra Leone is of late growing, with foreign investors reaching out to the Ministry of Fisheries and Marine Resources on the feasibility of marine aquaculture of fin fish and crustaceans.

In recent years, especially since early 2000, Sierra Leone has witnessed significant growth in aquaculture from projects implemented by organisations like FAO, CORAF/ WECARD, WorldFish/ USAID, European Union, World Bank and African Development Bank (AfDB), to name but few. FAO, 2001 has been partnering with GoSL to promote agriculture and aquaculture in Sierra Leone. The FAOTCP/ SIL/2904 project has contributed to the construction and rehabilitation of ponds, training of farmers, purchasing equipment (fish and animal feed production

Plate 19.1 Farmers` pond stocked with improved Nile tilapia by FAO

machines) and supporting the integration of fish with crops and animals for livelihood enhancement (Plate 19.1).

The Department of Aquaculture and Fisheries Management, Njala University, with funding provided by CORAF/WECARD on behalf of the Multi-Donor Trust Fund (MDTF), promoted the sustainable integration of rice with fish and piggery in Sierra Leone. The Poverty Eradication and Grassroots Empowerment through Sustainable Integrated Aquaculture Development: Fish cum rice and Piggery production (LFA/06/CF/CW/2011-14/) for the first time, raised awareness on the benefit of integrating agriculture with aquaculture for maximum resource utilisation and improved profits. Seawright Mining Company supported the Department of Aquaculture and Fisheries Management, Njala University, with the installation of Recirculation Aquaculture Facilities for research and training; these facilities are the first of their kind in the country (Plate 19.2). In 2016, the United States Agency for International Development (USAID)-funded the Feed the Future Sierra Leone Agriculture Project to develop rice and fish farming systems to optimise production and improve food availability, nutrition, and income of farmers. The project focusing on Tonkolili District was implemented by WorldFish (WorldFish 2016). The implementation outcomes were astounding as beneficiaries were trained to undertake fish farming as a business. Njala University is currently implementing the ENABLE Njala project, a sub-component of the Sierra Leone agribusiness and rice value chain project (SLARiS) funded by AfDB (SLARiS – 21,001,550,400,116/ P-SL-A00–019). The ENABLE project supports the commercialisation of aquaculture as one of its critical components. It is worth mentioning that some of the students who graduated from Njala University and IMBO – FBC have taken to self-employment in commercial aquaculture. The future of aquaculture in Sierra Leone looks promising, especially with the emergence of private aquaculture farms scattered all over the country.

Plate 19.2 Recirculation Aquaculture facilities at Njala University

19.3 Critical Challenge to Aquaculture Development in Sierra Leone

Aquaculture is the only viable alternative for filling the fish demand gaps created by declining capture fisheries in Sierra Leone. It has many prospects not only in alleviating undernutrition and poverty but as a source of foreign exchange for the country. In the face of the dwindling performance of the capture fisheries, Aquaculture has become a viable and sustainable alternative for meeting the increasing fish demand of the people. Sierra Leone's rural economy, which is based on subsistence cropping and extensive livestock grazing, favours the development of aquaculture, which essentially is also an agricultural activity. The operation of aquaculture on a small-scale, low-cost, utilising family labour or at a high cost under intensive operation provides opportunities for the poor and the rich to improve their living standards apart from providing employment opportunities. Despite the enormous opportunities and potential aquaculture avails in the country, the sector is still confronted with serious growth setbacks. The growth of the industry will depend upon its ability to compete and meet related challenges of availability of seed, feed, and credit, as well as ensuring an investment climate conducive to the commercialisation of aquaculture investment. A significant obstacle to aquaculture development is over-reliance on marine waters, rivers, lakes, floodplains and IVSs for fish supply. Sierra Leone does not lack sector-specific policies and regulations as was the case in some other African countries. Still, there appears to be a lack of implementation and monitoring to ensure the effective adoption of enacted policies and regulations. Public and market infrastructure, which are among the significant drivers of aquaculture, are poorly developed in the country. The government and the competent ministry, saddled with the management of the fisheries and aquaculture in the country, appears to be paying lip service to aquaculture, thus further crippling its development. Positive and pro-active political will to drive aquaculture growth seems to be lacking in principle. The development of aquaculture policies and strategies has always been the time lapse between policy formulation, policy adoption and the formulation of concerted action plans, so that strategy may no longer apply to rapidly changing circumstances. Inadequate or misdirected government funding is a critical inhibitor to the growth of the fledgling aquaculture sector. The discouraging poor performance of donor-supported aquaculture projects, which were anchored on a high-cost extension approach, could not be sustained by the government owing to a lack of funds; the system also failed to transfer a strange concept of animal husbandry to the beneficiary rural farmers.

The factors bulleted below are considered top constraints hampering aquaculture development in Sierra Leone.

- Poorly coordinated aquaculture development policies and strategies.
- Few fish farming traditions in the country.
- Inappropriate technologies and approaches and poor technical know-how of a significant proportion of the farmers.
- Lack of improved fast-growing fish seeds (fingerlings).
- Unavailability of high-quality but least-cost feed.
- Prohibitive transport costs and poor transport infrastructure.
- The existence of many non-functional government stations.
- Weak extension services hamper the effective coordination of research efforts.
- The weak feedback loop between researchers and end users of research outcomes.
- Inadequate information management systems (Plate 19.3).

Plate 19.3 Sinking fish feed production training for Njala University interns at MFMR Makali

19.4 Strategies for Sustainable Development of Aquaculture in Sierra Leone

The dwindling growth of aquaculture in Sierra Leone since its inception could be linked to the development strategies put forward in the 1980s, which promoted culture systems that are at variance with the traditional farming experiences of the rural farmers. Strategies that do not encourage production efficiencies and intensities to produce more fish using less land, water and financial resources will not auger well for the future of aquaculture in the country. In order, therefore, for aquaculture to be sustainable, there is a need to put in place appropriate strategies that appropriate the uptake of new technologies and takes care of the effects of climate change, environmental risks, biosecurity, and fish health concerns. Strategies that will not only enhance productivity but open up markets for fish sales (Ragasa et al. 2022). The African Union's aquaculture action plan for Africa, 2016–2025 (AU-IBAR 2019a), which has spelt out the vision for Africa's aquaculture sector, needs to be promoted and supported for the industry to contribute to improved fish supplies meaningfully and generate economic growth, wealth, and better nutrition. In turn, African member states need to continue improving or creating the necessary enabling policies and environments that would support private sector development and growth. This will strengthen aquaculture value chains and attract more investment. There is the need to encourage external investments as a springboard for growth, notably for establishing large integrated fish farms and feed mills. Having realised what aquaculture can generate, government support has generally increased. This has given the private sector the confidence to bring in emerging technologies, farm new species and apply best management practices (BMP).

Careful zoning, proper selection of sites suitable for aquaculture and improvement in the efficient use of resources, including energy and pond aeration, can aid aquaculture growth (Clough et al. 2020). The deployment of RASs and aquaponics in cities and areas with unfavourable temperatures for aquaculture will, according to Obirikorang et al. (2021) enable small-scale and medium-scale farmers to intensify and increase pond productivity. It is also imperative for research institutions in the country, especially the university, to embark on research on the genetic enhancement of aquaculture species to allow for faster growth and more efficient use of feed is needed. For meaningful production gains to occur, emphasis should be placed on developing better-performing strains through genetic enhancement. In addition, the development and application of improved broodstock and hatchery management techniques are required to avoid inbreeding, interspecific hybridisation, and contamination of improved strains through introgression from feral species.

19.5 Conclusion

The objective of modern commercial fish farming, besides playing a role in ensuring food security, is to produce fish for sale and earn profits from the farmer. Sierra Leone aquaculture no doubt has passed through phases of growth and the signs are obvious that the sector can contribute significantly to critical issues of the national economy, especially contributing to the government agenda of food security and zero hunger. The full potential of aquaculture as a job-creating venture for growing the rural economy and capacitating youths and women can only be realised if the associated drivers of the sector are appropriately addressed. Production must be well planned from the onset as an essential step in the farming investment. There is an urgent need to develop and promote aquaculture technologies that increase the intensification of production, coupled with the development of robust marketing strategies that allow farmers to respond better to changing consumer demands. Markets are the indispensable driver of aquaculture development, adaptation and innovation. The need to develop the markets and the aquaculture value chains is indispensable for the sustainability of the sector. There is also the need for alignment of government policies and regulations to favour aquaculture practices in the country. The competent authorities, saddled with the responsibility for the development of the sector need to devote more resources to policy research on the facilitation and promotion of aquaculture. The Ministry of Fisheries and Marine Resources (MFMR) must affect control, monitoring and evaluation of the sector's activities through robust extension services cum outreaches to ensure conformity with enshrined rules and regulations.

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Chapter 20
The Namibian Mariculture: Productivity, Challenges and Opportunities

Victoria Ndinelago Erasmus, Stephanus Shifafure Hamutenya, Oliver Numwa, and Elizabeth Petrus

Abstract Mariculture has grown rapidly worldwide; however, in Namibia, it remains relatively limited. Globally, mariculture has contributed immensely to food security and improved livelihoods, thus, these benefits can also be significant in Namibia if more effort is made to increase productivity and penetrate more international markets. In Namibia, mariculture is a lucrative industry, albeit of low-quantity production. In this chapter, we narrated the milestones leading up to the current mariculture status in Namibia, evaluated the current state of mariculture off Namibia, investigated the possible impacts of climate change on mariculture and analysed challenges in this subsector. There are major environmental and economic challenges associated with the mariculture of individual farms and the Namibian mariculture subsector at large, which require collective efforts to be addressed. We provide, for the first time, annual mariculture productivity from 2008 to 2019, which shows a declining trend that negatively impacts employment opportunities and economic gain. The most important part of this chapter is the identified opportunities that can advance this sector, in the quest to contribute to food security and economic growth.

Keywords Mariculture · Productivity · Challenges · Opportunities · Namibia

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20.1 Introduction

20.1.1 Aquaculture in Namibia

The growing human population coupled with an already existing nutritional challenge comes with an intense demand for food, a global pressing matter. Food produced/harvested from the ocean represents an important part of the solution to this dilemma; however, the current production levels are too low to meet these demands. For this reason, food production should be increased to ensure adequate food security for present and future generations. In addition to wild-captured fish, some food is produced through aquaculture to meet food demands for human consumption, reduce harvest pressures on land food production systems, combat nutritional challenges and contribute to economic growth (FAO 2020; Naylor et al. 2021). Globally, the aquaculture sector has grown exponentially over the past years, contributing immensely to food security (Ahmed et al. 2019). It was estimated that in 2018, aquaculture contributed 46% to the total seafood world production (FAO 2020). Countries such as China (Crona et al. 2020; Garlock et al. 2020), followed by India, Indonesia, Vietnam, Bangladesh, Egypt, Norway, Chile, Myanmar and Thailand (FAO 2018) are leading in aquaculture food production. Many initiatives regarding the aquaculture sector, such as the Aquaculture Stewardship Council (ASC), a leading standard for responsibly farmed seafood, have been developed to support this sector.

In other African countries, aquaculture is also making slow progress. Namibia has thrived in marine fisheries management and governance (Sumaila et al. 2004; Paterson et al. 2013). However, the same cannot be said about Namibia's aquaculture subsector, both the marine water and freshwater aquaculture collectively. Despite Namibia's extensive investment in infrastructure, Research, and development (R&D), training and capacity development, aquaculture production has remained relatively low (FAO 2020). For a lengthy period now, aquaculture has been deemed important to Namibia, as it is specifically addressed as a development priority in all five National Development Plans (NDPs) and Government's Vision 2030 and in the Harambee Prosperity Plan (HPP) document, wherein it is envisaged that by the year 2030, aquaculture will have grown to become a thriving industry (GoN 2012, GoN 2004). The fifth National Development Plan (NPD5), covering the period 2017–2022, indicates that aquaculture promotion is the desired outcome, and this will be attained by the promotion of investments in mariculture. Many sequential steps have been taken to get the Namibian aquaculture subsector to where it is now, starting with establishing the Aquaculture Policy in 2001 (MFMR 2001). Namibia then passed the Aquaculture Act 18 of 2002 in 2002 to regulate and control aquaculture activities, provide for the sustainable development of aquaculture resources and to provide for related matters. This step made Namibia one of the first Southern African Development Community (SADC) the Member States to translate the sector's policy into a legislative framework. The Ministry established the Aquaculture Directorate in 2003 with the mission of developing aquaculture responsibly and sustainably to achieve socioeconomic benefits for all Namibians, while also ensuring environmental sustainability. The aquaculture (Licensing) Regulations were gazetted as per government notice 246 of 2003, made in terms of the Aquaculture Act 18 of 2002, section 43. In 2004, the first Aquaculture Strategic Plan (MFMR 2004) was developed, the second strategic plan was developed in 2009, and the third strategic plan in 2017 ended in 2022. The marine aquaculture master plan, created in 2012, serves as a roadmap for the economic and social environment necessary for the industry's expansion. In 2020, a pilot project was implemented in three SADC Member States with existing National Aquaculture Strategies, namely, Botswana, Malawi and Namibia (SADC 2020).

Despite these developments, aquaculture remains an under-researched field in Namibia. Most studies concerning aquaculture in Namibia have been centred around fish feed (Gabriel et al. 2019), anaesthesia use in aquaculture (Gabriel et al. 2020), the contribution of aquaculture to food security (Villasante et al. 2015) and aquaculture Policy and Institutional Capacity (Britz 2006). Studies on mariculture are even more limited. The studies by Mapfumo (2009) on the history and development of shellfish cultivation in Walvis Bay and an emerging shellfish farming industry in Namibia (Murta and Kibria 2017) in Namibia are the most relevant to this discussion. Mariculture or marine aquaculture is a branch (subsector) of aquaculture in which aquatic species are raised within the marine environment. Looking at mariculture in the African context, in Nigeria, it is described as non-existent, while in Egypt, mariculture is still emerging and not as well developed as freshwater aquaculture. The South African mariculture industry is described as the most developed in Africa (Adeleke et al. 2021). This chapter evaluates the current state of mariculture in Namibia, including productivity, investigates the possible impacts of climate change on mariculture and analyse challenges and opportunities in the mariculture subsector in Namibia.

20.1.2 Milestones in the Namibian mariculture

Mariculture takes place along the Namibian coast, part of the nutrient-rich Benguela Current Ecosystem located between 17°S and 29°S, sharing borders with Angola and South Africa. Mariculture in Namibia is a very intimate subsector that is commercially exploited. Although the mariculture farms are privately owned, they receive support from the Ministry of Fisheries and Marine Resources (MFMR) through a routine water quality monitoring programme which provides timely information to producers about the occurrence of any pollution or natural phenomenon which may have a harmful or detrimental effect on the aquatic environment or any aquaculture product. The programme includes monitoring Harmful Algal Blooms (HABs) (MFMR 2018). Additionally, the Namibian Mariculture Association (NMA) coordinates mariculture farmers. In 2012, Namibia was listed among the top eight leading African countries in mariculture production, contributing 0.2% to Africa's mariculture production (Mmochi 2016). When our interest is in maximising economic growth, increasing the employment rate and improving food security, all sectors are going through microscopic viewing to identify gaps that need to be bridged to achieve the above. The maritime industry has many of these gaps; when closed, there is potential for maximum economic and livelihood security gain.

20.2 Mariculture Productivity in Namibia

Globally, most species farmed under mariculture are seaweed, molluscs, crustaceans and marine finfishes; however, off Namibia, only bivalve shellfish and molluscs are cultured. No marine finfishes are cultured in the Namibian marine waters yet. Currently, mariculture off Namibia is dominated by oysters (mostly Pacific oyster *Crassostrea gigas*, and to a lesser extent the European oyster *Ostrea edulis*), muscles (*Mytilus galloprovincialis*) and South African or perlemoen abalone *Haliotis midae* (Fig. 20.1a–c). Mariculture is dominated by oyster production in Walvis Bay, Swakopmund and Lüderitz (Pacific oyster and European oyster).

20.2.1 European Oysters

European oysters *Ostrea edulis* are endemic to the western European coast and south to Morocco and the Mediterranean but were translocated to Namibia in 1990 (Bromley et al. 2016). European oysters are not farmed for commercial purposes in Namibia but instead at a very minimum scale, mainly for research purposes. They are slow growing compared to the Pacific oysters (Fig. 20.1a). They are found among the Pacific oysters in a very minimum quantity of about 10 individuals out of 10,000 of Pacific oysters. European oysters are slow growers, and there is a limited market for them; hence more attention is on the Pacific oysters.

20.2.2 Pacific Oyster

The Pacific oyster, *Crassostrea gigas*, is the most common oyster species farmed worldwide, accounting for more than 98% of total oyster production. (Petton et al. 2021). In particular, in Namibia, the Pacific oyster is the main oyster farmed in Namibia (Murta and Kibria 2017) and would reach production of more than 1000 tons. Marine aquaculture in Namibia is majorly dependent on molluscan shellfish because these species are described as best suited to the physical–chemical features of the northern Benguela Ecosystem.

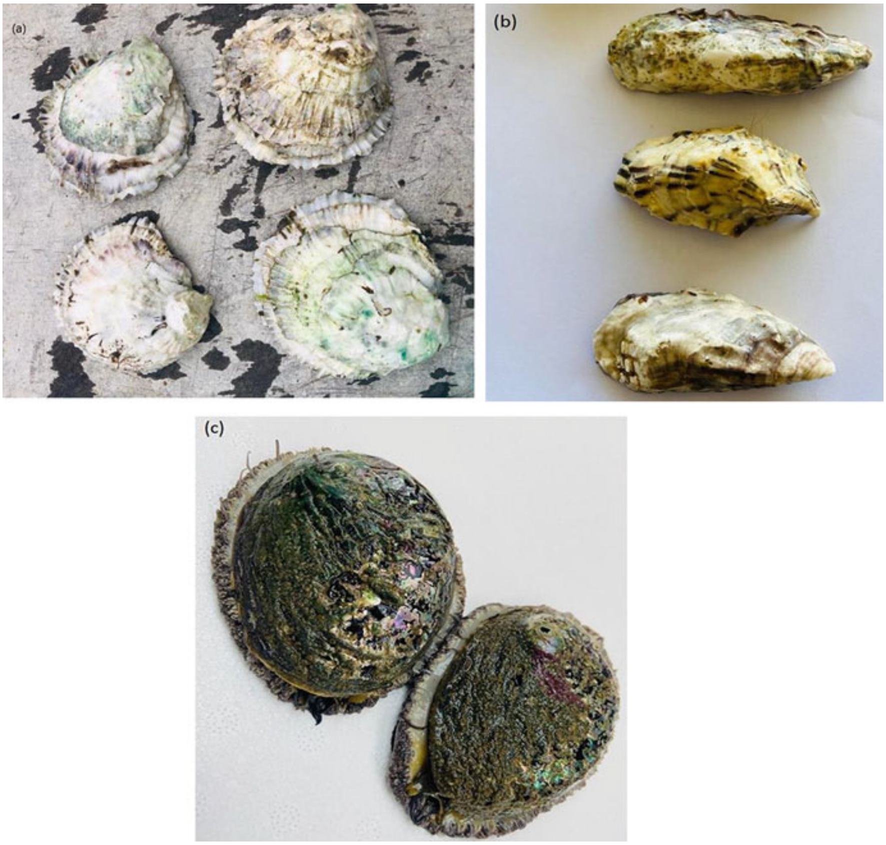

Fig. 20.1 Species (**a**) European oyster *Ostrea edulis*, farmed through mariculture in Namibia (picture credit: Elizabeth Petrus, August 2022). (**b**) Pacific oyster *Crassostrea gigas* farmed through mariculture in Namibia (picture credit: Elizabeth Petrus, August 2022). (**c**) Abalone *Haliotis midae* farmed through mariculture in Namibia (picture credit: Elizabeth Petrus, August 2022)

20.2.3 South African Abalone

South African or perlemoen abalones *Haliotis midae* are not endemic to Namibia; they were introduced in early 2000s (Faul and Coetzer 2020) and are now being farmed in Namibia, specifically in Lüderitz (Murta and Kibria 2017). Abalone spat production is mainly done in hatcheries using flow-through land-based systems (Murta and Kibria 2017). Abalones are slow-growing species that require 3–5 years to reach market size (Iitembu 2005).

Fig. 20.2 Mediterranean mussel, *Mytilus galloprovincialis* farmed through mariculture in Namibia (picture credit: Stephanus Shifafure Hamutenya, August 2022)

20.2.4 Mussels

Mussel farming in Namibia was based on two mussel species, the indigenous black mussel, *Choromytilus meridionalis* and the exotic Mediterranean mussel, *Mytilus galloprovincialis* (Murta and Kibria 2017). Mussels accumulate and depurate toxins more rapidly than other species (Rourke et al. 2021). Because of the frequent occurrence of toxins in the mussel flesh, this affected the mussel industry as they would test positive for the presence of toxins, and harvesting from the harvested would be put on hold until they are safe for consumption again. Currently, there is no mussel farming being practised in Namibia (Fig. 20.2).

20.2.5 Other Organisms

The red seaweed (*Gracillaria verrucosa*) has also been cultured off Namibia (Critchley et al. 1991; Iitembu 2005; Britz 2006). Although there have been mentions of seaweed culturing off Namibia (Britz 2006; Mapfumo 2009; Chiripanhura and Teweldemedhin 2016), no records for seaweed were given in the recent MFMR 2019 and 2020 reports. This is mainly because the use and consumption of red seaweed in Namibia are limited. There is a new company in Namibia working on a pilot project to farm Giant kelp, *Macrocystis pyrifera*. Kelp is currently being grown at their control site offshore. This is to determine whether the kelp will survive in Namibia because it is a foreign species that is being introduced for the first time into Namibian waters. So far, it appears to be well-adopted and rapidly expanding.

20.3 Mariculture Farming Systems in Namibia

Pond, cage, raceway, longlines and recirculation systems are the five primary aquaculture techniques. Oysters off Namibia are cultured in open waters on longlines and in shallow inshore flow-through systems in baskets/bags (Murta and Kibria 2017; MFMR 2018) (see Fig. 20.3).

Oyster farming in Namibia started in the 1980s; it is the most established and productive species farmed through mariculture in Namibia (Britz 2006; Murta and Kibria 2017). The main advantage of farming oysters is the fact that no feed is required; these animals enjoy an unlimited supply of nutrients from the marine waters. In freshwater aquaculture, especially in Namibia, feed is a major limiting factor. Although oysters generally take a prolonged period (even up to 18 months or longer) to grow to market size (±60 g), the Namibian-grown oysters, in particular, Pacific oysters are reported to grow faster (8–10 months) mostly due to readily available nutrients in the Benguela Current Ecosystem (Britz 2006; Mapfumo 2009). Pacific oysters would take about 2 years to reach market size elsewhere in the world, while in Namibia they would take 6–8 months to reach market size, of course, benefit from the nutrient-rich and cold Benguela current upwelling system. Although literature (Mapfumo 2009) indicates that the Pacific oysters thrive in temperatures between 14 and 27 °C, personal observations have shown that 20–27 °C is too high for oysters, it can cause mortality (Elizabeth Petrus-per. observation) A key achievement in the Namibian mariculture is the local production of oyster spats (in Lüderitz and Swakopmund) (Murta and Kibria 2017), although too small to sustain all the farms. Previously (in the 1990s and early 2000s), all oyster spats were sourced from overseas, mainly from Chile (Mapfumo 2009).

The farming of abalone in Namibia is mainly through onshore-based flow through a tank culture system and ranching that is based in Lüderitz. The naturally

Fig. 20.3 Buoyance on oyster bags suspended on ropes and embedded in water. Pictures were taken around mariculture farms in Lüderitz, Namibia, in March 2022. (Picture credit: Saima Kapia)

occurring seaweed known as kelp along the coastline of Namibia is used as feed for the adult abalone, juvenile feeds on the benthic microflora such as diatoms that are abundantly distributed in the seawater in the Lüderitz area.

20.3.1 Productivity Trends in Namibian Mariculture

The number of mariculture farms has an impact on production. Between 2018 and 2021, Namibia had nine operational mariculture farms each year. The number of farms has remained constant, although fluctuations were observed in productivity. Looking at the production trends of five species; Pacific oysters, European oysters, abalones, blue mussels and Mediterranean mussels in Namibia from 2008 to 2019, there is a gradual decline in production (Fig. 20.4). Annual mariculture production (oysters, mussels and abalone) averaged 411 tons from 2008 up to 2019, with the highest production in 2008 of 569.6 tons and the lowest production of 188.31 tons recorded in 2019 (Fig. 20.4). Based on data not presented here, mariculture production in 2002 was reported to be 600 tons and worth about N$6 million.

In 2004, there were 120 tons of seaweed produced and 132 tons in 2008 (Chiripanhura and Teweldemedhin 2016), but there seems to be limited progress with these seaweed species at the moment. In addition to earnings, mariculture employs a small fraction of people. The latest (2022) MFMR unpublished data records indicate that in 2018 about 185 people were employed in this industry; however, this number declined to 168 in 2020 and further reduced to 159 in 2021. The unemployment rate (which in 2018 was estimated at 33.4% in Namibia based on Trading Economics 2019) can be reduced if production is increased in the mariculture sector. The numbers of employees in this sector between 2018 and 2021 represent a minute fraction of the Namibian population, which was 2,632,885 as of 2022, based on Worldometers (https://www.worldometers.info/world-population/namibia-population/). A decline in production has domino effects on employment numbers and economic contributions. An increase in productivity might also boost local consumption of seafood (Erasmus et al. 2021).

20.4 Market and Economic Contribution of Mariculture to Namibia

The market for Namibian mariculture products is narrow; the main export markets are in South Africa (Murta and Kibria 2017) and Asian countries, mainly Hong Kong, China and Japan, with some emerging new markets in Russia (MFMR 2018). Few products are bought locally by restaurants (Chiripanhura and Teweldemedhin 2016). In 2004, it was estimated that 70% of the oyster production was destined for South Africa Market (Iitembu 2005). The most significant financial advantage was

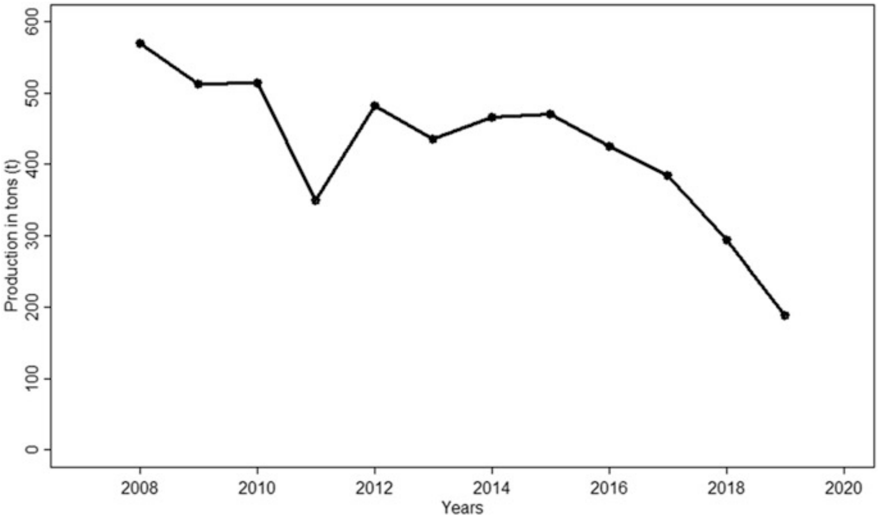

Fig. 20.4 Total production of mariculture products from Pacific oysters, European flat oysters, abalones, blue mussels and Mediterranean mussels between 2008 and 2019 off Namibia. (Data source: MFMR Unpublished data)

realised in 2016 and the lowest in 2018 when examining the final market size amounts without spats (Fig. 20.5).

20.5 Challenges Associated with Namibian Mariculture

Despite the impressive economic benefits of mariculture (Fig. 20.4), this sector is handicapped by various challenges ranging from environmental variabilities to a lack of funds and infrastructure.

20.5.1 Environmental Impacts

The influence of climate change on aquaculture has already been identified (Froehlich et al. 2018). The Namibian waters constantly experience the proliferation of harmful algae blooms (HABs), which are biotoxin-producing algae (van der Lingen et al. 2016; Murta and Kibria 2017). HABs cause mortality in fish and shellfish because they cause the environment to be anoxic by attaching to the gills. Shellfish feed on phytoplankton; some of these phytoplankton species produce toxins, which are then accumulated in the flesh of the shellfish. These accumulated toxins are not toxic to the organisms, and they are harmful to humans when they consume contaminated shellfish. The mariculture grow-out areas are monitored by

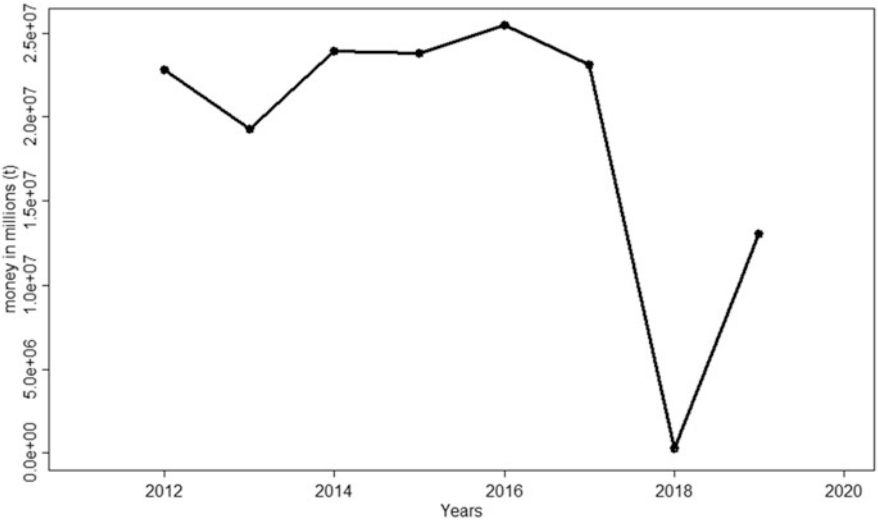

Fig. 20.5 Total production of mariculture products from Pacific oysters, European oysters, abalones, blue mussels and Mediterranean mussels between 2012 and 2019 off Namibia (Data source: MFMR Unpublished data)

the Mariculture Division under the program of water quality and disease control. The division's main focus is on water analysis for phytoplankton with the aim of monitoring the occurrence of toxin-producing species. If the presence of the toxin-producing species exceeds the set limit, flesh samples of the organisms are then sent to the Namibia Standard Institute (NSI) for analysis of the presence of the toxin associated with whatever species is present. If the species test positive for the toxins, then another retest will be conducted. Should the retest fail again, the farm will temporarily stop selling its products to the public for about 2 weeks until a negative result. The closure of the farm is to allow the organisms to self-depurate any accumulated toxins.

Other types of HABs are oxygen-depleting algae that die after the bloom, leading to decomposition, which uses up oxygen, causing an anoxic condition. This leads to fish 'walkout'. HABs can lead to measures such as closing production areas, which is detrimental to this sensitive business. Algae blooms in Namibia have been a significant constraint for years (Mapfumo 2009; Murta and Kibria 2017), still with no solution to help farmers to cope with these natural disasters. The impact of HABs on mariculture is a global concern (Brown et al. 2019).

In some areas, especially in the central region of the Namibian coast, sulphate reduction by anoxic bacteria is the source of 'sulphur eruptions' typified by a 'rotten egg' odour. This can result in mass mortalities of fish and other marine organisms, caused by these organisms being trapped against the coast by these toxic and often anoxic waters. This phenomenon only affects a limited part of the shelf, particularly the coastal waters around Walvis Bay. Higher incidences of 'sulphur eruptions' are linked to interannual scale periods of decreased upwelling intensity in the central Benguela ecosystem (Emeis et al. 2004; Monteiro et al. 2006).

Environmental variables such as sea surface temperature (SST) rise (caused by the intrusion of Angolan warm water, e.g. Benguela Niños) are thought to trigger algae blooms and sulphur eruption. Mariculture farmers who had not established themselves could not break even due to the sulphur eruption (Chiripanhura and Teweldemedhin 2016). Extreme occasional strong wind affects mariculture operations by, for instance, damaging farm structures. Sea level rise reduces processing capacity, displacement of shore-based processing plants, safety at sea issues and other impacts on infrastructure. Rough weather, extreme events and unfavourable weather conditions can damage infrastructures at the mariculture farms and processing facilities. There has been an increasing concern over ocean acidification, which is harmful, especially to organisms with shellfish, i.e. oysters (Kroeker et al. 2013).

20.5.2 Contaminants

Heavy metal contamination, mainly cadmium, in the water may cause accumulation in the shellfish. Because shellfish are filter feeders, they also filter contaminants into their bodies. For this reason, muscles, especially *Mytilus* spp., are used as biological indicators of pollution in water bodies (Azizi et al. 2018). Other heavy metals such as mercury, zinc, lead and arsenic, tested by NSI, are regularly conducted because they are a requirement before export. To export mariculture products, the concentrations of these heavy metals should be below 3.0 mg/kg for most countries such as South Africa and China. In 2014, the farmers exported mariculture products to Hong Kong without evaluating the presence of cadmium, while in Hong Kong, these products were evaluated for various contaminants, and they tested positive for cadmium. The entire consignment was sent back to Namibia, leading to irrecoverable economic and reputational losses and damages suffered by the producers.

20.5.3 Other Marine Organisms and Microbial Diseases

Other marine organisms might interfere with mariculture farming. In particular, jellyfish washout gets stuck on the oyster bags, a major concern. Mussels that grow on the oyster bags are also a significant concern; this leads to the oyster bags becoming heavy. Heavy oyster bags and ropes can break to the point of no repair.

In terms of pathogens, generally, the most prevalent disease, Pacific Oyster Mortality Syndrome (POMS), has become panzootic and represents a threat to the oyster industry (Petton et al. 2021). However, no reports of this pathogen in Namibia have been observed elsewhere. Pathogens such as *vibrio* spp., *salmonella* spp. and *cholera* spp. affect the consumers, thus, farms close temporarily when their products test positive for these pathogens. The data on major disease outbreak from microbial attacks, e.g. *Escherichia coli* on Namibian mariculture farms is insufficient to make any conclusion. However, when they occur, these diseases are described as chronic problems in this industry (Brown et al. 2019).

20.5.4 Lack of Funds and Infrastructure

The lack of specialised technical knowledge, logistical infrastructure and difficulties in access to credit and markets were listed as hindrances in the mariculture subsector (Villasante et al. 2015). Namibia only exports these goods to a small number of nations suggesting that market access is a constraint on this industry. Additionally, since running an oyster farm and the logistics involved are pretty expensive, a farmer needs to have access to a boat for regular maintenance, which should be done every 2 weeks. The production costs are intensified because oysters must be transported live or chilled and are transported mainly by flight to ensure freshness. Because of the risky nature of this business, financial institutions are primarily sceptical about loaning new entrants' funds to start mariculture businesses. Access to technology has also been previously listed as a constraint (Britz 2006). For instance, abalone production farm requires a lot of funds to set up, and requires a lengthy period of time (about 8 years) before income can be generate income, this could be a contributing factor there are few abalone farmers in Namibia and hardly any new entrants in the recent years.

20.5.5 Market

New entrant farmers are struggling to penetrate the market. The expansion and sustainability of Namibia's oysters and other mariculture products are hampered by their limited access to other export markets, such as those in the EU, the United States, Russia and other Asian markets with stricter import regulations (Murta and Kibria 2017).

20.6 Drawbacks of Mariculture

Although we are advocating for the growth of the mariculture subsector, we need to be cognisant of the possible impacts of this activity on the marine environment and its organisms. The operations might generate waste (e.g. oyster bags and ropes used to suspend bags) that might detach and settle at the sea bottom, thereby causing plastic pollution (Fig. 20.5). Plastic pollution is a critical problem globally (Galgani et al. 2021; Horton 2022). Furthermore, dead oyster shells might accumulate and be

Fig. 20.6 Oyster bags and ropes from mariculture production. Pictures were taken around mariculture farms in Lüderitz, Namibia, in March 2022. (Picture credit: Saima Kapia)

a nuisance (Fig. 20.6). Oyster shells are also sharp and potentially dangerous for those near the beach or processing plants. However, these by-products can be recycled to ensure that they contribute to the circular economy.

Depending on the farming system used, wastewater from mariculture activities in Namibia is pumped back into the ocean, which might change the chemistry of the water in the vicinity. Additionally, nutrients, particularly those from the feeding and cage systems, tend to accumulate around bags. Moreover, farm escapees might alter species composition, which would disrupt food chains and food webs. This, in turn, can change the biodiversity's genetic diversity pool. Mariculture has few adverse side effects beyond those already mentioned.

20.7 Opportunities in Mariculture

20.7.1 Culturing Marine Finfishes

Marine finfishes such as silver kob (*Argyrosomus inodorus*), although not currently farmed have the potential to be farmed through mariculture based on extensive research on these species (Tjipute 2011). The potential for finfish mariculture off Namibia was also identified by (Akegbejo-Samsons 2022). Many African countries involved in mariculture are culturing finfish such as flat-head grey mullet (*Mugil cephalus*) and European *sea bass* (*Dicentrarchus labrax*) in Egypt (Adeleke et al. 2021). Since finfish are not currently a part of Namibian mariculture, there is an urgent need to diversify this industry's focus in order to make it more commercially viable and boost food production. There is a need for a rigorous search for potentially cultivable candidate species to supplement what is currently cultured. The Namibian waters are home to diverse species, and some might make suitable cultivable species. When productivity is increased, the employment rate and food security status will improve.

20.7.2 Capacity Building

Mariculture might be new to Namibia, but some countries have been practising this for decades. Developed countries such as China are leading players in aquaculture support and capacitate developing countries to improve their mariculture fish farms. There will be less reliance on outside expertise once the farmers and aspiring farmers are capacitated. Additionally, Namibia can strengthen regional cooperation with South Africa, which shares borders and marine species with Namibia and has thriving mariculture, and we can tap into their expertise.

20.7.3 Promotion of Both Small- and Large-Scale Mariculture

Looking at the profit made from the current production, this industry has the potential to contribute significantly to economic growth if practised on a large scale. Beginning with a high output of oyster spats. More players need to get on board to set up more mariculture farms, both small-scale and large-scale farms. The public should be engaged to get more information on how to participate in mariculture. Production quantity from mariculture is insignificant; specifically, in 2012, Namibian mariculture made up the least of the top eight leading countries in Africa; however, new analyses are needed to evaluate the current position in this regard. Additionally, mariculture can be developed as an artisanal program for coastal-based communities. When productivity becomes more significant, we do not see market opportunities as bottlenecks. Namibian seafood products such as hake are already in demand in many European countries.

20.7.4 Resilience to Climate Change

Globally, climate change has received significant attention (Gíslason et al. 2020), and Namibian waters are not exempted (Junker et al. 2017). Namibia needs to invest in rigorous research to identify species that are less sensitive to HABs outbreaks so that the economic losses during algae blooms are limited. It is common knowledge that species respond differently to changes in environmental parameters. Furthermore, they have varying optimal temperatures or oxygen tolerance, for example. If these species are unavailable, the current ones can be genetically modified to be resilient to these recurring challenges.

20.7.5 Technology

The application of technology in various fields and sectors has changed the approach and accelerated its development. This can also be true for mariculture in Namibia. Farmer and aspiring farmers can employ the use of electronic monitory systems (EMS) that can be deployed/launched to farm locations to aid the monitoring of the growth of the oysters and other farmed species. This would lessen the capital and labour invested in boats that do physical inspections on these farms. Devices that detect changes in the water chemistry can be installed on structures to alert the farmers. Additionally, if finfishes are cultured in this manner, Fish Aggregating Devices (FADs) can be installed to attract forage fishes to the farmed fish in cages, making feeding more accessible and less costly. The use of technology in mariculture can boost production.

20.7.6 Financial Investment for Start-ups

One of the critical issues facing potential mariculture farmers is a lack of start-up capital. The government and external investors can increase financial investment in the farmers and aspiring farmers to redress this problem.

20.8 Conclusion

Although there are major persistent challenges in the mariculture subsector in Namibia, Namibia's efforts to develop aquaculture have paid off, economically, for mariculture and not much for freshwater aquaculture. It is evident that mariculture farms (especially for mussels) close to Walvis Bay station experience diverse threats and stress from physical and biochemical factors, leading to the accumulation of metals in their body and shells. The narrated opportunities have the potential to improve and grow the mariculture sector in Namibia. Other countries with similar coastal characteristics, such as Angola and South Africa, can capitalise on the discussed opportunities to benefit their mariculture industry. Mariculture has an enormous potential to address social problems such as food insecurity and unemployment and, at the same time, remove pressure from wild capture fisheries. These benefits are directly proportional to an increase in production. The main strength of mariculture is that it is not limited by water, space and feed. Arid maritime countries such as Namibia can take advantage of the limitless water supply from the ocean. Therefore, it is anticipated that aspiring mariculturists would be able to realise the potential in mariculture as discussed in this chapter and that this sector will expand in the future, moving forward.

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Chapter 21
Climate SMART Best Practices in Aquaculture and Fisheries with Specific Emphasis on Sierra Leone

Olapade O. Julius

Abstract In Sierra Leone, just like in any other developing nation, the effects of climate change are perspicuous, affecting food security, social services, social cohesion, and human displacement and migration. Solar radiation received by the earth and human activities such as bush burning, charcoal burning, deforestation, intensive use of land for agriculture and other biotic activities has been implicated in causing the increase in global warming. The precarious and vulnerable conditions of many fishing and coastal communities due to climate events are glaringly evident, leading to poverty and underdevelopment. Climate change, a variation in weather pattern distribution and or average weather conditions over some time, is impacting the infrastructural base and socio-economic sectors of the country, leading to increase deforestation and a decline in agricultural productivity. Climate change has become a subject of intense public debate, especially by researchers and policymakers, and has put the government of Sierra Leone on the decision-making edge. The fisheries and aquaculture sector of the country shares in the adverse outcomes of climate incidences. The industry is regarded as high risk in the context of climate change as they are easily vulnerable to changes in environmental variables that further compound the socio-economic woes of the fishing communities, and communities that depend heavily on fish and ancillary activities for food security and income generation. This chapter reviewed the literature on the impact of climate change on the fisheries and aquaculture sector with specific emphasis on Sierra Leone to understand climate SMART best practices in the all-important sector that contribute significantly to the nation's Gross Domestic Product.

Keywords Fisheries · Aquaculture · Coastal communities · Climate events · Vulnerable · Sierra Leone

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21.1 Introduction

The role and contributions of the fisheries and aquaculture in terms of food supply, security and income generation globally have been discussed severally by researchers. About 43.5 million people are believed to work in the fisheries and aquaculture sector, many of whom come from third-world countries. In reality, it is thought that the fisheries and aquaculture sector support close to 200 million livelihoods when the processing, marketing, distribution and supply industries are added up. More than 1.5 billion people from the third-world nation benefit from aquatic foods, which supply 20 per cent or more per capita animal protein intake. According to FAO (2008), marine products are the most widely traded foodstuff globally and contribute to export earnings of Asian and most third-world countries. The small island state mainly depends on the fisheries and aquaculture sectors for about 50 per cent of animal protein needs. Whatever affects this sector, no doubt, can affect the livelihood of those who depend on it.

Climate change is one environmental factor creating severe concern for the management and productivity of the fisheries and aquaculture sectors. According to FAO (2008), climate change will pressure livelihoods and food supplies. Its effects would be felt across ecosystems, societies and economic sectors of countries, including the fisheries and aquaculture subsector. Food quality, mainly from fishing and aquaculture, is critical as a developmental issue. Compared to mainstream agriculture, the fisheries and aquaculture sectors has peculiar interactions and needs concerning climate change. Aquaculture is known to complement supply and has links with the capture fisheries, a unique subsector closely linked with global ecosystem processes. It has become glaring that changes in fishing practices, aquaculture operations, location of landing, farming and processing facilities will be influenced by changes in habitat, species composition and distribution.

The pronounced influence of climate change on the fisheries and aquaculture in Sierra Leone is worrisome, affecting the livelihoods and the food security of the people who depend on the sector (Benjamin 2015). Climate change means that many dry areas are going to get drier, wet areas are going to get wetter, and these are current realities in Sierra Leone. It is, however, important to mention that climate change will be more significant over land than over sea because land retains heat more than water. Benjamin (2015) noted increasing evidence that Sierra Leone will be particularly hit by vertical rises and falls in air currents. The author opined that the country might be caught between the devil of droughts and the deep blue seas of floods—a ‘great tragedy’ (Benjamin 2015). The Intergovernmental Panel on Climate Change (IPCC) elevated the threats of climate change to human society and the ecosystem as a top priority. Therefore, it is essential to focus on the effects of climate change on fisheries and aquaculture, a crucial economic sector in the country, and its pronounced impact on the coastal and riparian communities in Sierra Leone (Benjamin 2015). One interesting thing to note is that most artisanal fishers and coastal dwellers lack adequate knowledge of Climate Smart Practices and sustainable environmental practices. This has further increased their vulnerability and risks to fisheries and the environment. The impact of climate change on fisheries and aquaculture sector and the exposure of the people makes it urgently imperative for practical education on earth system science; the human and behavioural aspects of climate change, and the broad societal action to smart energy choices at the household level (Gardner and Stern 2008). Education should cover food production, nutrition security, and economic growth and development. This paper aims to provide relevant information on climate change adaptive strategies that will guide practical fisheries and aquaculture production in Sierra Leone. The information in this paper will provide practical starting points to actors involved in the fishing and aquaculture sector of Sierra Leone in the face of climate change events.

21.2 Causes of Climate Change

Simply put, climate change is a variation in weather pattern distribution or average weather conditions over an extended period. The observed changes may be caused by so many factors, including biotic processes, the type of solar radiation by the earth and human activities that results in global warming (Carbon posting or emissions). Human activities are notoriously implicated in the warming of the globe (IPCC 2007; National Research Council 2010). Deforestation, increasing population pressure, intensive agricultural land use, overgrazing, bush burning, extraction of fuel wood and other biotic resources are believed to contribute to an increase in average global temperature. This elevated temperature, according to Benjamin (2015), is caused primarily by increases in greenhouse gases such as carbon dioxide (CO_2). According to Cunningham and Cunningham (2004) and Osborn (2010), climate change occurs when temperature increases, especially by 0.2 °C, with differences in rising in precipitation and rise in the ocean level. CO2 is the pre-eminent greenhouse gas responsible for global warming. Other gases that have been reported in studies by researchers include methane and nitrous oxide. These gases come from fossil fuels, landfills and agriculture, and industrial processes.

21.3 Climate Change Impact on Fisheries and Aquaculture

Climate change affects fisheries and the aquaculture sector in diverse ways, discussed under two categories – effects on the ecosystem and human livelihood sustenance. Climate change affects the four dimensions of food security as presented here:

1. Availability—alteration of habitats affects the stock composition and species distribution, consequently influencing aquatic food supply.

2. Stability—this will be influenced by factors such as changes in productivity of the ecosystem, seasonal and increased supply variability, and risks.
3. Access—availability and access to aquatic foods will be influenced by livelihood patterns, catching or farming opportunities.
4. Utilisation—there will be a change in the type of aquatic products readily accessed and the way they are used by people. Meaning communities will start to utilise species that were not traditionally preferred.

21.4 Climate Change and the Aquatic Ecosystem

Greenhouse gas (GHG) accumulation in the atmosphere and water is a physical phenomenon that influences changes in the physical properties of water, especially water temperature and acidification of water bodies; it also affects ocean currents and rising sea levels. The ecological functions in the aquatic systems, their frequency and intensity, are affected by climatic events (Cochrane et al. 2009). Climate change and its associated events have far-reaching effects, both direct and indirect on fisheries and aquaculture. There is a reduction in the productivity of most tropical and subtropical aquatic ecosystems. The impact of the changes on the physiological and behavioural processes of fish and their prey has been variously reported. Evidence abounds for the modification of the distribution of marine species by global warming. There are changes in the size and productivity of the habitats of warm water species that are being moved towards the pole.

21.4.1 Specific Impact of Climate Change on the Ecosystem

- Displacement of tropical fish species towards the pole, and the shrinking in the size and productivity of their habitats.
- Reduction in the productivity of both tropical and subtropical aquatic ecosystem.
- Elevated temperature with both positive and negative effect on the fisheries and aquaculture systems.
- Effects on seasonality of certain biological processes like the food webs which in turn affect fish production negatively. There is also increased spread of vector-borne disease, a result of alien species invasion.
- Differential warming between land and ocean, and between polar and tropical regions affect freshwater and marine resources stability.
  - Other consequences of this warming are:

    Floods.
    Drought.
    Storms.
    Change in climate pattern – El Nino.

Plate 21.1 Coastal erosion effect in Sierra Leone (Source: https://www.google.com.sl/search)

- A rise in sea level, glacier melting, ocean acidification and changes in precipitation.
- Ground water and river flows effect on coral reefs, wetlands, rivers, lakes and estuaries.
- Uncertain supply of freshwater (Plate 21.1).

21.5 Climate Impact on Livelihoods and Food Security

The world's aquatic ecosystem benefits many people globally as a critical component of the global food production system ensuring food security and economic prosperity. The fisheries and aquaculture sectors are particularly important in any nation's development, playing a significant role in food security and enhanced livelihood of billions of people in developing countries. FAO (2009a; b) reported the precarious and vulnerable states of many fishing and coastal communities worldwide. This sad situation results from fishery resources overexploitation, habitat degradation, poverty and underdevelopment of the rural coastal communities. The effect of climate change, according to FAO (2009a, b), is becoming pronounced in fishing and coastal communities. Climate events threaten inland fisheries and fish farming worldwide, causing adverse effects on the food supply and livelihoods of the poor population. The fisher folks in the coastal communities in Sierra Leone depend on the overfished fishery resources and inhabit areas deficient in basic social amenities and infrastructure. The vulnerability of the fisheries and aquaculture sectors to climate change is profound and affects the communities that depend on them. This vulnerability, however, depends on the potential impact (sensitivity and exposure) and adaptive capacity of the sectors. Ecological (semi-arid and coastal locations) and social (significant dependence on fish for protein, low adaptive capacity, weak economies and low human development) factors, according to WorldFish Center (2007) have made the African fisheries sector more vulnerable.

21.5.1 People, Communities and Vulnerability

Vulnerability to climate change by people and communities, according to the Intergovernmental Panel on Climate Change (2001), vulnerability to change depend to a greater extent on the degree of exposure, the sensitivity of a system to such changes and the adaptive capacity of the system. The most vulnerable to climate change are the developing nations, which are primarily limited in terms of resources to adapt: socially, technologically, and financially. Climate change is anticipated to have far-reaching effects on developing countries sustainable development, including their ability to attain the United Nations Millennium Development Goals by 2015 (UN 2007). Many developing countries' governments have given adaptation action a high, even urgent, priority. Vulnerability in fisheries and aquaculture rests on certain factors, such as identification of exposure of concern, scale and phase for adaptation planning, and the availability of data for planning. Allison et al. (2009) described the vulnerability of national economies to climate from the perspective of the potential impact on the country fisheries, while Bell et al. (2011) focused on the vulnerability of species, food webs and ecosystems and explored the issues related to tunas, their food web, coral reefs, mangroves, freshwater habitats and fisheries activities in the tropical Pacific islands.

Cinner et al. (2012), to understand the links between the human and aquatic system and coral reef-dependent fishing communities' vulnerability to climate change, build upon the IPCC model. Impacts of climate change to be experienced by fisheries and aquaculture-dependent economies, coastal and riparian communities are shifts away from traditional fishing grounds or changes in available fish species. Direct risks due to sea level rise, stronger sea surges and changes in the frequency, distribution or intensity of tropical storms may happen to fishers, farmers and coastal communities. Other risks to be experienced are those of human diseases related to increased air and water temperature. Climate change will also impact food security, social services, social cohesion, and human displacement and migration. The vulnerability of the fishing and coastal communities is perspicuous, with almost palpable poverty and underdevelopment. These communities do not have easy access to capital and lack the skills to sustainably exploit available fish stocks and other natural resources and improve the degraded ecosystems. As noted in this paper, the vulnerability of the fisheries, aquaculture and fishing communities depend significantly on the uncertain ability of individuals or systems to anticipate these changes and adapt, not just their exposure and sensitivity to change. De Silva and

Soto (2009) noted that the high population densities of the tropics, where the bulk of the world's aquaculture production is situated, make it more vulnerable.

21.6 Climate Impact on Fisheries and Aquaculture

The impact of climate change is not felt only by the diverse ecosystems but by societies, economies, livelihoods and food supplies (FAO 2008). According to WorldFish Centre (2007), ecological and social factors have made West and Central African countries the most vulnerable. The degree of vulnerability of the fisheries and aquaculture sector is dependent on either the severity or extremity of the climate elements. The solar heat energy absorbed by the aquatic habitats makes the fisheries sector particularly vulnerable. Climate change influences the physical and chemical variables of water bodies, particularly water temperature. It affects the physiological functions of fish which are cold blooded, water supplies and the populations, the normal resiliency and productivity of the aquatic ecosystems, livelihood and food security (Plate 21.2).

21.6.1 Impact on Fish Physiology and Population

The physiological and biochemical processes of most freshwater and marine fish species are dictated by the prevailing ambient water temperature. Smith (1989) observed that the breathing rates, feed consumption, enzyme activities, oxygen

Plate 21.2 Flooding of the Njala University fish farm as a result of weather variability

Table 21.1 Temperature tolerance of selected cultured species from a different ecology Modified from Ficke et al. (2007)

Climate/temperature guild/ species		Incipient lethal temperature (°C)	
Tropical	Lower	Higher	Optimal range
Redbelly tilapia (*Tilapia zilli*)	7	42	28.8–31.4
Guinean tilapia (*Tilapia guineensis*)	14	34	18–32
Warm water subtropical			
European eel (*Anguilla anguilla*)	0	39	21–23
Channel catfish (*Ictalurus punctatus*)	0	40	20–25
Temperate polar			
Arctic charr (*Salvelinus alpinus*)	0	19.7	6–15
Rain bow trout (*Oncorhynchus mykiss)*	0	27	9–14
Atlantic salmon (*Salmo salar*)	−0.5	25	13–17

consumption and feed metabolism are altered by abnormally high temperature and this, according to him, affects fish growth. An increase in fish population is influenced by how fast the fish grow and reach maturity size, the fecundity and recruitment into the exploitable phase. The number of fish available for harvesting based on the sustainable yield principle is a function of the population size. There is, however, a decline in the quantity and quality of freshwater and marine fish population because of the pressure exerted on it through overfishing and pollution. The recruitment phase (larvae, fry and fingerlings) is heavily affected by predation, competition and water quality, thus limiting survival to few that thrive in the adult phase. A decrease in fish population is exacerbated by the increase in water temperature, with a limiting effect on oxygen transport, a situation that could significantly impact aquaculture and result in changes in the distribution and abundance of both marine and freshwater species (FAO 2008) (Table 21.1).

21.6.2 Impacts on Water Flow

Climate change is causing a general increase in precipitation worldwide, and Africa is the most prone. One of the events of climate change is the flooding of rivers, lakes and reservoirs with some effects that may be severe, as often witnessed in Sierra Leone and elsewhere. It is therefore becoming increasingly necessary for countries to be well prepared to handle the devastating effects of climate change, especially flooding that has become a yearly event. The coastal zones in Africa are the most vulnerable to the severe impacts of coastal erosion, flooding and storm surges. Social wellbeing, livelihood security, water resources and critical economic sectors like tourism, agriculture and fishing are the most affected. Negative repercussions of climate change on the livelihood of the coastal communities reduced fishing productivity, ecosystem degradation and low farming outputs. Effects of climate change are not all together negative; it is good to know that inundation of adjacent land areas

Plate 21.3 Inundation of fishponds in Kenema caused by weather variability

because of increased rainfall and flooding is beneficial to fisheries. Flooding expands the littoral zones and increases the diversity of the ecotones for fish feeding, breeding and rearing of the juveniles (Plate 21.3).

21.6.3 Impact on Water Quality and Fish Distribution

Climate change influences water temperature, which shares an inverse relationship with oxygen. The solubility of oxygen in water by extreme temperature and the favour survival and multiplication of parasites and bacteria. The cumulative effects of this high temperature, according to Halls (2009), are the negative effect on fish survival, natural food availability, growth and reproductive success of wild fish population and farmed fish species. The capacity of the different water bodies to sustainably produce fish is impaired by climate change. African lakes, as reported by Anonymous (2009), are expected to experience a decrease in annual rainfall and temperature due to the atmospheric temperature on the continent that is higher than the global average. Changes in temperature and precipitation are most likely to affect the wetlands and shallow rivers. Consequently, primary productivity will be lowered, and aquatic organism distribution will be influenced because of the effect of temperature on lake and reservoirs stratification; limited or no seasonal turn over; greater deoxygenation of the bottom layers. Studies have shown that temperature is key in determining the stability of the ocean water. Temperature more than other factors like salinity and depth exerts greater influence on water stability. The result of the variation of water temperature in the different parts of the Atlantic (Ocean) is the variation in the water density, with concomitant effect on distribution of organisms and fishing. The risk associated with abnormally high temperature is the displacement of stenothermal and eurythermal species to unfavourable habitats that impair survival, growth and reproduction (Table 21.2).

21.7 Climate-Smart Approaches in Fisheries and Aquaculture

Climate SMART approaches are specific, measurable, achievable, realistic, and timely coping strategies in vulnerability to climate events. Climate-smart measures for fisheries and aquaculture are not different from that of other sectors. The strategy must consider cross-cutting themes of development and environment. For climate-smart to be useful for development, there are important issues to be resolved as outlined here.

1. It must respond to the growing daily demand for aquatic food; address specific issues of food and livelihoods across the entire supply, value, and benefit chains.
2. Be able to deploy effectively new technologies and also embrace market and socially driven changes within and around the sector.
3. It should identify specific gaps in capacity, efficiency, and system resilience for the sector, particularly those which may increase under climate stress, and identify particular action to be taken for these gaps.
4. Prescribe appropriate options for better policy and management integration within and across the sector, in terms of understanding the function and flows of goods and services from the aquatic systems as well as defining efficient use of these resources.
5. The strategies should connect well with related development objectives, such as hunger eradication, poverty alleviation, resource protection and rehabilitation, nutritional safety and health, personal and community empowerment, self-determination and vulnerability reduction.
6. Must connect with approaches that are recognisable and actionable by policy agents to work effectively with practitioners and beneficiaries at all levels – based on clear evidence of functionality and effectiveness.

21.7.1 Climate SMART Best Practices in the Fisheries of Sierra Leone

More than half (56%) of trapped green or biological carbon captured globally is captured by marine living organisms – this is called blue carbon. Thus, a crucial mitigating approach is to maintain and improve the ability of forests and oceans to absorb and bury carbon-carbon sinking. Three pathways recognised for engaging in mitigation are as follows:

Table 21.2 Ways in which climate change may directly affect production from fisheries and aquaculture

Drivers	Biophysical effects	Implications for fisheries and aquaculture
Increase in frequency and/or intensity of storms	Large waves and storm surges. Inland flooding from intense precipitation. Salinity changes. Introduction of disease or predators into aquaculture facilities during flooding episodes	Loss of aquaculture stock and damage to or loss of aquaculture facilities and fishing gear. Impacts on wild fish recruitment and stocks. Higher direct risk to fishers; capital costs needed to design cage moorings, pond walls, jetties, etc. that can withstand storms; and insurance costs
Drought	Lower water quality and availability for aquaculture. Salinity changes	Loss of wild and cultured stock. Increased production costs. Loss of opportunity as production is limited
	Changes in lake water levels and river flows	Reduced wild fish stocks, intensified competition for fishing areas and more migration by fisher folks
Changes in sea surface temperature	More frequent harmful algal blooms; Less dissolved oxygen; Increased incidence of disease and parasites; Altered local ecosystems with changes in competitors, predators and invasive species, and changes in plankton composition	For aquaculture, changes in infrastructure and operating costs from worsened infestations of fouling organisms, pests, nuisance species and/or predators. For capture fisheries, impacts on the abundance and species composition of fish stocks
	Longer growing seasons; Lower natural mortality in winter; Enhanced metabolic and growth rates	Potential for increased production and profit, especially for aquaculture
	Enhanced primary productivity	Potential benefits for aquaculture and fisheries but perhaps offset by changed species composition
	Changes in timing and success of migrations, spawning and peak abundance, as well as in sex ratios	Aquaculture opportunities both lost and gained. Potential species loss and altered species composition for capture fisheries
	Damage to coral reefs that serve as breeding habitats and may help protect the shore from wave action (the exposure to which may rise along with sea levels).	Reduced recruitment of fishery species. Worsened wave damage to infrastructure or flooding from storm surges.
El Niño-Southern oscillation	Changed location and timing of ocean currents and upwelling alters nutrient supply in surface waters and, consequently, primary productivity	Changes in the distribution and productivity of open sea fisheries
	Changed ocean temperature and bleached coral	Reduced productivity of reef fisheries
	Altered rainfall patterns bring flood and drought	See impacts for precipitation trends, drought and flooding above

(continued)

Table 21.2 (continued)

Drivers	Biophysical effects	Implications for fisheries and aquaculture
Rising sea level	Loss of land	Reduced area available for aquaculture. Loss of freshwater fisheries
	Changes to estuary systems	Shifts in species abundance, distribution and composition of fish stocks and aquaculture seed
	Salt-water infusion into groundwater	Damage to freshwater capture fisheries. Reduced freshwater availability for aquaculture and a shift to brackish water spaces
	Loss of coastal ecosystems such as mangrove forests	Reduced recruitment and stock for capture fisheries and seed for aquaculture. Worsened exposure to waves and storm surge and risk that inland aquaculture and fisheries become inundated
Higher inland water temperatures		Reductions in fish stocks
	Raised metabolic rates increase feeding rates and growth if water quality, dissolved oxygen levels, and food supply are adequate, otherwise possibly reducing feeding and growth. Potential for enhanced primary productivity	Possibly enhanced fish stocks for capture fisheries or else reduced growth where the food supply does not increase sufficiently in line with temperature. Possible benefits for aquaculture, especially intensive and semi-intensive pond systems
	Shift in the location and size of the potential range for a given species	Aquaculture opportunities both lost and gained. Potential loss of species and alteration of species composition for capture fisheries
	Reduced water quality, especially in terms of dissolved oxygen; Changes in the range and abundance of pathogens, predators and competitors; Invasive species introduced	Altered stocks and species composition in capture fisheries; For aquaculture, altered culture species and possibly worsened losses to disease (and so higher operating costs) and possibly higher capital costs for aeration equipment or deeper ponds
	Changes in timing and success of migrations, spawning and peak abundance	Potential loss of species or shift in composition for capture fisheries; Impacts on seed availability for aquaculture
Changes in precipitation and water availability	Changes in fish migration and recruitment patterns and so in recruitment success	Altered abundance and composition of wild stock. Impacts on seed availability for aquaculture
	Lower water availability for aquaculture. Lower water quality causing more disease. Increased competition with other water users Altered and reduced freshwater supplies with greater risk of drought	Higher costs of maintaining pond water levels and from stock loss. Reduced production capacity. Conflict with other water users. Change of culture species

(continued)

Table 21.2 (continued)

Drivers	Biophysical effects	Implications for fisheries and aquaculture
	Changes in lake and river levels and the overall extent and movement patterns of surface water	Altered distribution, composition and abundance of fish stocks. Fishers forced to migrate more and expend more effort

Excerpted from WorldFish Policy Brief (http://pubs.iclarm.net/resource_centre/ClimateChange2.pdf)

1. Improve knowledge of water–climate interactions and how aquatic ecosystems function at various levels to take up and sequester CO_2.
2. Prevent the further loss and degradation of coastal and other aquatic ecosystems and catalyse their recovery. It is essential to determine how much CO_2 the aquatic ecosystems can offset in a year (3–7% or 7200Tg CO_2).
3. Define how these ‘Blue Carbon’ sinks could be further managed and, in some cases, further extended.

21.7.1.1 Local Win–Win Approaches

There are win–win approaches that could sequester GHG, enhance adaption and contribute to food security, rural livelihoods, poverty reduction and environmental services. Specific interventions include but are not limited to the following.

- Invest in aquaculture of algae and seaweeds.
- Invest in microalgae production for biofuels.
- Stop forest burning.
- Avoid cutting down riparian forests especially mangrove trees.
- Engage awareness education on the impact of climate.
- Plant more trees.
- Stop sand mining and dredging.
- Invest in alternative energy options.
- Provision of alternative income-generating opportunities for coastal dwellers.

21.8 Gender Perspectives in Climate Smart Agriculture

Gender should be considered in climate smart agriculture, especially from resource access competition, risk vulnerability, livelihood shift, distribution and processing in which women take the leading role. It is certain that with variations in rainfall patterns and higher temperatures, most farmers will have to shift what they produce and how they produce it. The contribution of women to fisheries and aquaculture is often undervalued or misinterpreted, with their related dependence and vulnerability due mainly to inadequate gender awareness and involvement (FAO 2009a, b). To achieve the desired transformative changes in agriculture and food security, there is a need to tackle gender issues by recognising it as a critical component in climate-smart agricultural practices. The actions stated below will go a long way to integrate gender into CSA in Sierra Leone and elsewhere.

1. **Invest** in ‘action research’ initiatives that test new farming practices and value-added activities with women and men. We need to learn together what works best and how to support all those producing food in different environments in a wide range of farming systems.
2. **Catalyse** and support strategic and structured partner engagement efforts with local governments, private sector and civil society organisations working closely with women, as well as men and other food system actors.
3. **Strengthen** the capacity of these partners in gender-disaggregated data collection and analysis and forward-looking and inclusive, evidence-based local adaptation planning efforts.
4. **Test** innovative communication strategies, together with private and public sector partners in many countries, to reach more women and youth with much-needed information on exciting new options and opportunities in agriculture.

21.9 How to Respond to Climate Change Impact

- Awareness-raising through the synthesis of observations on the mechanisms behind climate change and its potential impact on fisheries, aquaculture and aquatic ecosystems; the development of relevant guidelines ensuring that climate change impact assessment covers aquatic ecosystems and fisheries and aquaculture adequately.
- Knowledge improvements through a better understanding of risks—who and what is affected – and the role and implications of vulnerability (different areas, regions, and scales); harmonisation of indicators databases; strengthening and/or creating working groups to access impacts and consequences; and development of guidelines.
- Implementation of activities through targeting ongoing planning and development processes, lobbying regional fisheries and other organisations and non-governmental organisations (NGOs) regarding guidelines, capacity building, and encouraging relevant organisations to include climate change in their action plans and to identify leaders and key players.

21.9.1 Strategies for Climate Change Adaptation

- Awareness raising through targeted communication strategies, synthesising current knowledge, and identifying and targeting community leaders and movers.

- Knowledge improvements through identifying benefits of well-managed fisheries and aquaculture systems; training in key themes, use of ecosystem approaches, pilot projects, monitoring and impact assessments; identification and targeting of vulnerable communities and enhancement of systems for monitoring and assessing risk from natural hazards.
- Implementation of activities such as dissemination of key messages, convening multilevel meetings, capacity building and empowerment of policymakers; promotion of diversified livelihoods for vulnerable communities, insurance schemes, disaster relief funds and the integration of fisheries and aquaculture into the climate change mitigation and adaptation strategies of other sectors.
- Identification of resources and partners to ensure financing is available for fisheries and aquaculture adaptation strategies; development of resource mobilisation teams and strategies; entering strategic partnerships and exploring the possibilities for funding at the community level.

21.9.2 Climate Change Mitigation and Policy Actions

- Awareness raising through the development and dissemination of key policy messages, development of best practices brochures and integration action in ongoing mitigation processes.
- Knowledge improvement through workshops and specific technical reviews and case studies; better understanding and use of the potential of aquatic environments (and aquatic food production systems).
- Implementation of activities such as testing approaches to emission reduction; the role of certification and labelling in marketing products; technical guidelines; linking fleet decommissioning and efficiency improvements with carbon markets; mainstreaming mitigation into policies; development of national frameworks and setting emission reduction targets for the sector.
- Identify resources and partners to ensure short-term to long-term financing through various donors from the private sector, national governments, and multilateral and bilateral agencies.

21.10 Conclusion

There is no gainsaying that the fisheries and aquaculture sector of Sierra Leone is a significant revenue generation sector that contributes to the national gross domestic product (GDP). It is also important to mention that the fisheries and aquaculture sector plays a significant role in world food security, providing nutritious food and contributing to economic growth, development, income and livelihood of millions of people, especially in Africa. The sector contributes to the livelihood of the fishing and fish farming-dependent inhabitants of the coastal and riparian communities.

Unfortunately, the sector is being impacted by climate change, making the fishing and coastal communities more vulnerable. Climate change influences the rise in sea temperatures and migration of fish stocks from equatorial latitudes towards the colder waters; it also affects the sizes of fish, migratory patterns and mortality rates of wild fish stocks. The challenges confronting the fisheries and aquaculture sector demean its sustainability and productivity. The influences of climate change on the fishing and coastal communities of Sierra Leone are becoming alarming. Annual flooding and coastal erosion have become an issue of grave concern that renders the fisheries sector and coastal communities at high risk and vulnerability. The resilience, sustainability and productivity of this sector would depend on the appropriation of appropriate management strategies. The use of climate SMART approaches has been proposed to enhance the sustainable production of the fisheries sector and to make the fisher folks and coastal communities more resilient to the vagaries of climate change. This paper espouses important climate SMART practices that would help enhance the capacity of the fisher folks to deal with climate events.

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Chapter 22
The Potential of Small-Scale Freshwater Aquaculture for Household Nutritional Security and Malnutrition Alleviation in Namibia

Rebekka Ndatolewe Gabriel, Ndakalimwe Naftal Gabriel, and Ottilie Nameya Shikesho

Abstract Malnutrition is a widespread problem, especially in sub-Saharan Africa, of which Namibia is part. This chapter aims to discourse on small-scale freshwater aquaculture, its contribution to improving food security at the household level and its potential to relieve the malnutrition burden in Namibia. Fish is an excellent source of nutrients essential for human health and is part of the solution to building solid food systems and maintainable quality diets. Although it is still in its infancy, Namibia's aquaculture industry has the potential to grow. In the same vein, small-scale freshwater aquaculture has the potential to improve food security and thus reduce malnutrition prevalence, particularly in rural Namibia, where the majority of the poor live. However, there is a need to differentiate small scale from commercial farming to ease the regulatory problems on farmers potentially farming for household consumption. The government still has a long way to go to fully exploit the potential of small-scale aquaculture. Among others, there is a need for aquaculture promotion, education, technical knowledge and support, financial support, policy reviews and intersectoral collaborations with sister sectors such as agriculture.

Keywords Aquaculture · Namibia · Malnutrition · Freshwater · Nutrition

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22.1 Introduction

By 2020, roughly 768 million people worldwide were estimated to be undernourished. Of those, more than half (418 million) live in Asia and more than one-third (282 million) in Africa (FAO et al. 2021). This loosely means that one in five people was facing hunger in Africa in 2020. Malnutrition has been linked to approximately 45 percent of childhood deaths globally (Ndivelao et al. 2016; Onyango et al. 2018). Defined by the World Food Programme (WFP) as 'a state in which the physical function of an individual is impaired to the point where he or she can no longer maintain adequate bodily performance process such as growth, pregnancy, lactation, physical work and resisting and recovering from disease' (Bain et al. 2013), malnutrition is an ill much too common in many limited resources countries, including sub-Saharan Africa, where some of the highest rates have been reported (Akombi et al. 2017). Malnutrition includes both undernourishment/undernutrition and over nourishment/overnutrition. Of those, undernourishment is the most common form of malnutrition experienced. The Food and Agriculture Organization of the United Nations (FAO) defines undernourishment as the inability of an individual to acquire enough food to meet the daily minimum dietary energy requirements over a year (FAO et al. 2021). The World Health Organization (WHO) recommends 0.66 g/kg body weight/day protein intake, a recommendation numerous developing countries fall short of (Schönfeldt and Hall 2012). Coincidentally, poverty has been nominated as one of the major contributing factors to malnutrition (Adeyeye et al. 2017). Some major poverty influences in Africa have been attributed to economic depressions, bad governance, unemployment, war, environmental factors such as drought/ famine, climate change, and population growth (Otekunrin et al. 2019) (Fig. 22.1).

Namibia is not exempted from elevated malnutrition rates. In fact, Namibia has continued to report elevated malnutrition rates since it gained its independence in 1990 (Henghono, R N, Nghitanwa E M 2019; Bauleth et al. 2020). Thirty years later,

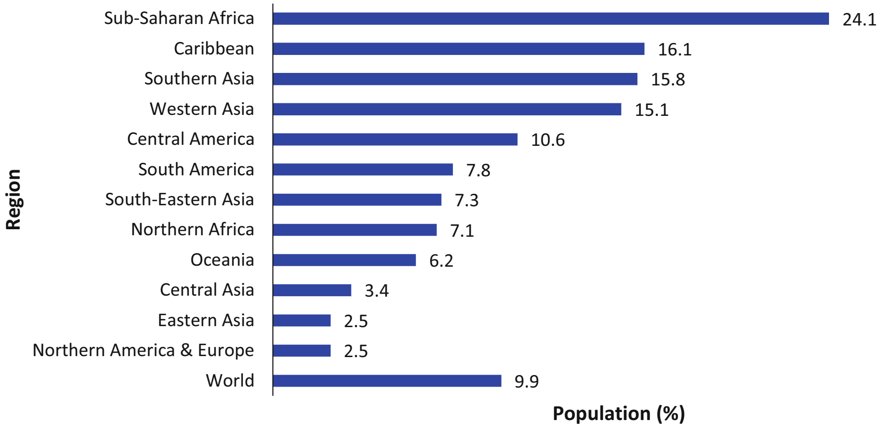

Fig. 22.1 Prevalence of undernourishment by Region, 2020, Source:(Statistica 2021)

not much has changed as the country was ranked 19th on the Global Hunger Index (GHI) in 2019 (Otekunrin et al. 2019, 2020a, b). According to WHO's global nutrition report, Namibia has made no progress towers lowering childhood wasting with 7.1% of children under 5 years still wasted and has achieved small progress towards lowering childhood stunting with 22.7% of children under 5 years still stunted (WHO 2021). Albeit the saddening statistics, there is hope. Generally, hunger indicates a lack of food security in any country. The United Nations General Assembly (UN-GA) and Sustainable Development Goal (SDG) two makes it a priority to end hunger and malnutrition by the year 2030 (Thilsted et al. 2016; Otekunrin et al. 2019). This prompts governments to implement measures towards becoming more self-sustainable in terms of achieving food security. Some measures that could be a possible solution to malnutrition and a step closer to attaining food security are backyard gardening and small-scale fish farming/aquaculture. It is estimated that more than 200 million people in Africa depend on fish consumption for high-quality yet low costing protein (Obiero et al. 2019). Despite this, compared to the rest of the world, African aquaculture production has remained insignificant on a global scale (Jamu and Ayinla 2003).

Many Africans depend on rainfall, they generally depend on inland fisheries, dams, rivers, lakes and other freshwater ecosystems for constant food supply and income (Nasr-Allah et al. 2020; Simmance et al. 2021). This is also the case in Asia and Latin American fields (Nasr-Allah et al. 2020). There is limited information on the potential of fish consumption to overcome the ill of malnutrition which is detrimental to overall health (Herman-Roloff et al. 2011; Roy et al. 2020). Moreover, the critical role that fish consumption play towards good nutrition, in particular in poor households, has vaguely been recognised and sometimes ignored altogether to date (Thilsted et al. 2016). Moreover, small-scale fisheries remain undocumented and overlooked in fisheries and food system development, limiting the assessment of household fisheries contribution to the quality of household diets (Lynch et al. 2016; Funge-Smith and Bennett 2019). This chapter will focus on the importance of small-scale aquaculture in alleviating malnutrition and promoting food security in Namibia.

22.2 Climate Change and its Influences on Food Production in Namibia

Climate change has been among the most significant pressures on food production and health the world has faced in recent years. The concentration of greenhouse gases has been increasing at exhilarating rates since the 1700s due to human activities transforming the composition of the global atmosphere (Mohanty 2021). It is projected that climate change will worsen the dry conditions experienced in Namibia, coupled with soil erosion and flood, when it eventually rains (Reid et al. 2008). Being the driest country in the Saharan desert, Namibia is and has been experiencing evidence of climate change prolonged, and drought conditions have been recorded in the country over the past recent years. This is terrible news, especially such that over half the population of the country depend on subsistence farming. This renders the country vulnerable to climate change. There is increased pressure on land resources to upsurge food production and better the livelihood of those living in absurd poverty, especially in rural areas (Taapopi et al. 2018). This translates to the need for initiatives to improve food availability while taking pressure off the land.

22.3 Important Inland Aquaculture Fish Species

Marine and freshwater aquaculture are the two types of aquaculture sectors in Namibia, with the latter having the most species variety. Private fish farmers, who raise highly valuable species, dominate the marine aquaculture industry. Freshwater aquaculture, on the other hand, involves communities, and this is the sector in which the government has committed a significant amount of money to empower communities to create their food, income and jobs. Although it has been primarily agreed that aquaculture increases access to food, there are deliberations on whether it has been able to mitigate the reduction in dietary diversity and micronutrient intake as it focuses on a few selected species (Belton et al. 2014; Bogard et al. 2015). Deliberations that in no way dispute that generally, fish provide more protein and macronutrients than other animal protein sources.

Three spotted tilapia (*Oreochromis andersonii),* tilapia Mozambicus (*Oreochromis mossambicus)*, red tilapia (hybrid tilapia), redbreast (*Tilapia rendalli*), African catfish (*Clarias gariepinus*), and common carp (*Cyprinus carpio*) dominate Namibian freshwater farming. After carps, Tilapia is the second farmed fish in the world and is expected to take over from carps in the near future (Eknath and Hulata 2009; Menaga and Fitzsimmons 2017; Mtaki et al. 2021). Several attribute this fish variety popular in aquaculture. These include ease to breed in captivity, having a short production cycle because of fast growth rate, acceptability of artificial feeds after yolk-sac absorption, and marketability and stable market prices (Wang and Lu 2016; Prabu et al. 2019; Abaho et al. 2021). Apart from the latter, the foremost crucially can be a determining factor when selecting species for small-scale aquaculture. Tilapias are also considered hardy fish that can tolerate varying degrees of physical and chemical environmental factors, making them suitable for farmers with limited technical knowledge (Kapinga et al. 2019).

Carps, which is the most important farmed aquatic animal, comes from the Cyprinidae family. They are the longest farmed fish, dating back as far as 2500 years (Miao and Wang 2020). Grass carps translate plant proteins into animal proteins by direct digestion and absorption of plant material. In addition, they are well known for their delicious and nutrient-dense meat, extensive adaptability to a large range of environmental conditions, and wide temperature tolerance and are one of the inexpensive fish in the aquaculture (Lu et al. 2020). Catfish is the most common cultured fish in Africa and is considered a traditional fish in the northern Namibia (Haimene 2018; Amponsah et al. 2021). This fish is very hardy, can feed on a wide variety of feeds, grows rapidly, and has a high survival rate in poorly oxygenated water as well as high market demand (Dauda et al. 2018; Tesfahun 2018; Abdul Kari et al. 2021). Aside from the latter, these characteristics are essential in small-scale aquaculture, where farmers may struggle to abide by the high cost of feed and maintain good water quality regularly. Overall, the most important aquaculture species pose specific characteristics that make them suitable for small-scale farming.

22.4 Nutritional Value of Fish and Importance of Fish Consumption

Alleviating malnutrition by 2030 will require a significant change not only in everyday diets but also through the consumption of nutrient-rich food inclusive for people in poor and middle-income countries. When focusing on the nutritional value of food supplies, it is agreed that fish is a major nutrient-dense animal source of food for a substantial percentage of the nutritionally susceptible people. Fish delivers a healthier food source overshadowing other terrestrial animals consumed as meat products (Bene et al. 2016; Xie et al. 2021). However, even with so many benefits, some people remain uneducated about the importance of fish consumption. Fish is composed of 18–20% protein and provides high biological value easily digestible protein that is essential for body growth and development, maintenance and repair of tissues, and for construction of essential enzymes and hormones (Tacon et al. 2020; Maulu et al. 2021). The lack of high-quality protein has been linked to stunting in children (Kwasek et al. 2020). Fish also contain less fat than red meat (Tacon et al. 2020) (Table 22.1).

The main health benefits of fish are attributed to their high content of n-3 long-chain polyunsaturated fatty acids (FAs) (n-3 LC-PUFA). These are linked to numerous health benefits, including positive cardiovascular health, improved nervous system and increased metabolism. They are also associated with decreased preterm birth, lower risk of infant low birth weight, improved visual health in infants, enablement of early neurodevelopment in children, prevention of dementia and cognitive decline and a decreased risk for developing age-related macular degeneration, particularly eicosapentaenoic (EPA) and docosahexaenoic acid (DHA) when

Table 22.1 WHO n-3 LC-PUFA recommended intakes, Source: (Maulu et al. 2021)

World Health Organization	Age	AI (Adequate Intake; per day)
Eicosapentaenoic + Docosahexaenoic acid	2–4 years	
	4–6 years	150–200 mg
	6–10 years	200–250 mg
	Adults	200–250 mg

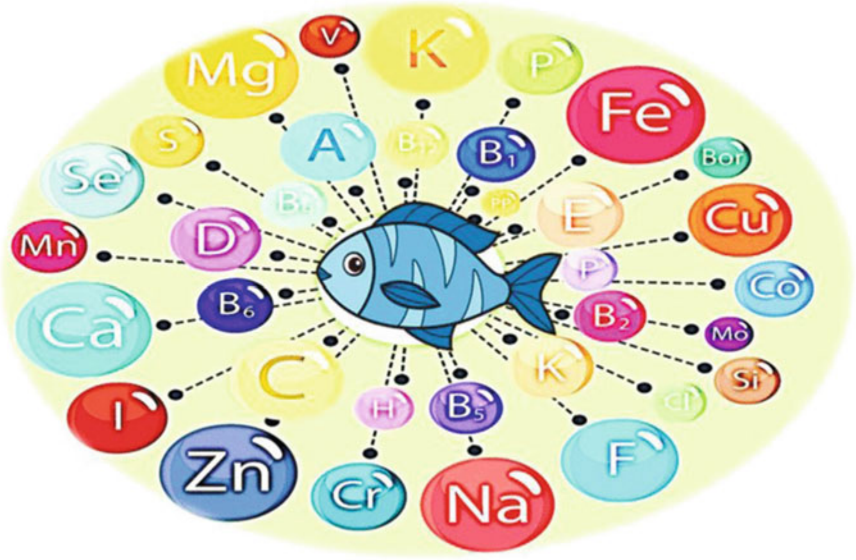

Fig. 22.2 Fish is a source of vital vitamins and minerals for human growth, Source: (Maulu et al. 2021)

consumed in sufficient amount (Monroig et al. 2018; Muhlhausler et al. 2018; Cave et al. 2020). In addition, fish is rich in most essential amino acids particularly methionine, lysine, taurine, which are limited in other kinds of muscle food (Calder 2018). The compounds found in fish are often not readily available in other diets (crops and animals), despite their massive physical benefits and cognitive development to both adults and children (Bene et al. 2016).

It is agreed that the nutritional value of fish depends on the diet to a higher degree (Sobczak et al. 2020); however, the nutritional value of fish, especially for human optimum growth, cannot be denied. Fish is an important source of vitamins A, D, and some vitamins from group B. Vitamin A is essential for numerous physiological processes, including maintenance of surface tissues, healthy immune system, good vision, bone development and reproduction, among many others (Gilbert 2013; Maulu et al. 2021). The vitamin A in fish is more readily available in the body than in plant food (Maulu et al. 2021). Deficiency of vitamin A results in an increased risk of severe infection, this makes the deficiency worse as infection increases the body's demand for vitamin A (Chea et al. 2021). Children are especially at risk if they are malnourished (Chea et al. 2021). Certain fish species are rich in vitamin A, particularly those eaten whole with the head and viscera (Kwasek et al. 2020) (Fig. 22.2).

The vitamin D in humans is mainly acquired from the sun as many foods do not contain enough vitamin D for human growth and development (Balami et al. 2019). Vitamin D stored in the fish liver is essential for bone growth as well as for the prevention of rickets, low bone-mineral density, osteoporosis and other calcium

Table 22.2 Some essential minerals found in fish muscles, Source, (Pal et al. 2018)

Element	Average value (mg/100 g)
Sodium (Na)	72
Potassium(K)	278
Calcium (Ca)	79
Magnesium (Mg)	38
Phosphorus (P)	190

metabolism disorders, including malnutrition (Reddy et al. 2010; Mishra 2019). It is necessary for thyroid function and regulates blood pressure (de la Guía-Galipienso et al. 2021; Pardabaevna 2022) (Table 22.2).

Fish contains numerous high bioavailability minerals that are important for the human body. These include: iron, calcium, zinc, phosphorus, selenium fluorine, and iodine (Maulu et al. 2021). An excellent source of these are small fish that are eaten whole, including heads and bones. Iron is critical in the formation of haemoglobin, which is responsible for oxygen transportation in the body (Kwasek et al. 2020; Maulu et al. 2021). Iron deficiency may lead to impaired brain function and anaemia (Balami et al. 2019; Maulu et al. 2021). It also result in poor learning abilities and poor cognitive development in infants and children (Balami et al. 2019). In pregnancy, iron deficiency has been linked to maternal mortality, increased risk of sepsis and low birth weight (Abbaspour et al. 2014). In large doses, selenium is toxic to the human (Balami et al. 2019). It is an essential antioxidant trace element that is essential for the normal function of the thyroid (Mojadadi et al. 2021). Regrettably, selenium deficiency is far too common globally and often requires supplementation (Gorini et al. 2021). Calcium plays a role in various metabolic processes and is responsible for bone density, normal functioning of tissues and the nervous system (Balami et al. 2019; Mishra 2019; Maulu et al. 2021). Given the abundance of nutrients that fish provide, it can be agreed that they provide more than just protein to our diets and are crucial for human health.

22.5 The Role of Small-Scale Aquaculture in Increasing Food Security and Alleviating Malnutrition in Namibia

Sub-Saharan Africa has the highest malnutrition prevalence in the world. Undernourishment, a significant health problem, has been increasing over recent years (Onyango et al. 2019). With malnutrition rates this high, it is projected that poor diet and insufficient food consumption are directly and indirectly responsible for more than half of children's deaths in sub-Saharan Africa (Drammeh et al. 2019). This is a strong indicator of the lack of food security in this region. Moreover, it was estimated that the number of food insecure individuals in the same region has increased to about 17 million people by 2021(Drammeh et al. 2019). For decades, continuing food insecurity, malnutrition and hunger have continuously been

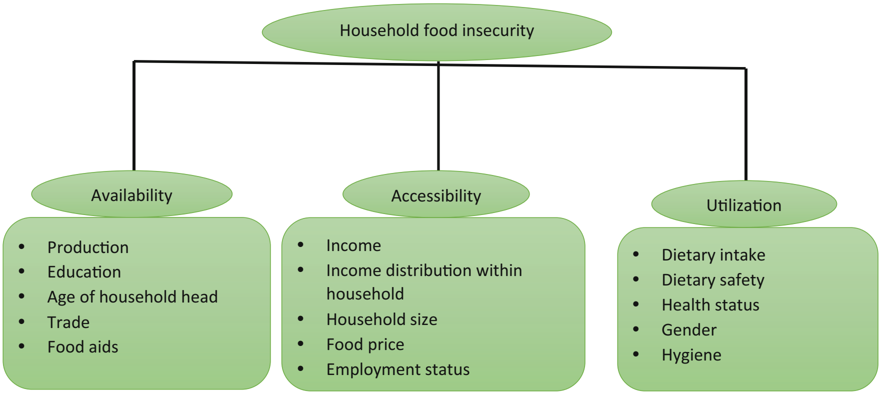

Fig. 22.3 Conceptual model of household food insecurity, Source: (WFP)

discussed as a global issue exacerbated by lack of access and poor redistribution at household level (Drammeh et al. 2019).

Although Namibia has one of the highest GDPs in Africa, it also suffers from major income disparities. More than 80% of Namibia's population live in rural areas and are dependent of subsistence farming as a source of food. However, climate change rendered the country prone to prolonged flooding and recurrent droughts amongst others. Floods and recurrent drought meant that subsistence farmers were left vulnerable to hunger as conditions made it impossible to produce food for themselves. Household food insecurity has been termed a prominent risk factor of malnutrition. Similarly, it jeopardizes dietary intake. Food security was termed to exist by the World Food Programme (WFP) when 'all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life' (Crush et al. 2019). Even though there has been a debate on how best to measure food security, there is no doubt that Namibia as a sub-Saharan country has a long way to go as far as food security is concerned. In the rise of the COVID-19 pandemic, like other numerous countries, Namibia has suffered major food access disruptions in forms of supply chains, lockdowns and increases in food prices, a situation which has further worsened the already existing food insecurity (Fig. 22.3).

Various studies have reported that, similar to many other African countries, Namibia has a high prevalence of stunted and underweight/undernourished population, specifically in children under 5 years (Akombi et al. 2017; Drammeh et al. 2019; UNICEF 2020). This has placed pressure on the government to implement solutions that will not only yield fast results but are also cost-effective and sustainable to increase food production and end hunger in the country. Historically, home food procurement has been how people secure food for household consumption (Niles et al. 2021). This included but was not limited to hunting, gardening, fishing, foraging and livestock. Over the years, some of these activities have received significant interest and have picked up more than others. To date, numerous countries have embraced backyard and community gardens as part of the efforts to increase food security (Dorado et al. 2018; Nkrumah 2018; Fehr and Moseley 2019). However, the same cannot be said for small-scale aquaculture.

Small-scale aquaculture is defined as 'low-production medium-scale aquaculture, based on increasing natural water productivity, polycultures, and using alternative feed prepared with local or waste supplies' (Villasante et al. 2015). Millions of people look up to fish as a source of income and food. In the same vein, it was found that people in rural areas depend on fishing for improved access to food (Villasante et al. 2015). In the wake of global food shortages, aquaculture can foster the bridge to seal the gap in food insecurity. Small-scale aquaculture practised at the household level may be the answer to food supply chains and accessibility issues. This is specifically significant in females comprising households as researchers have found that women's catch is mainly aimed at family consumption, unlike men's catch which is usually aimed at market sales (Lauria et al. 2018).

Contrary to studies found that Namibians do not consume fish regularly (Erasmus et al. 2021), others have found that, since engagement in fish farming, fish consumption increased in rural households as well as fish consumption frequency (Villasante et al. 2015). Seeing that most of Namibia's population lives inland in rural areas, the introduction of subsistence small-scale rural aquaculture may see an upsurge in food availability which will subsequently curb malnutrition (Hlophe-Ginindza and Mpandeli 2020; Arthur et al. 2022). This was supported by a study that constructed a village computable general equilibrium (CGE) model to examine whether aquaculture improves local livelihoods in the Zambezi region, Namibia. This study found that not only did aquaculture improve households' income, but it also increased fish availability and consumption, which in turn meant a reduction in malnutrition cases (Gronau et al. 2020). Recommendations to increase small-scale fish farming might include increasing up farming and agricultural activities plus encouraging interministerial and stakeholders' collaboration.

22.6 The Potential of Small-Scale Aquaculture Development in Namibia

Despite being highly recommended as a source of food and income at a household level and is the fastest growing food-producing factor worldwide, aquaculture has seen a slow take-off in Namibia. Aquaculture in Namibia can be traced back to the 1800s, but it only took off in the 1990s in Namibia (Iitembu et al. 2022). To date, the country contributes a minor fraction to global aquaculture production. The Ministry of Fish and Marine Resources (MFMR), in conjunction with the Namibian government, donors and international agencies, made great efforts to develop the aquaculture sector in Namibia. This was due to aquaculture being identified as a high-priority area of development. The main legal framework that guided the administration of aquaculture in the country is the aquaculture act, which was,

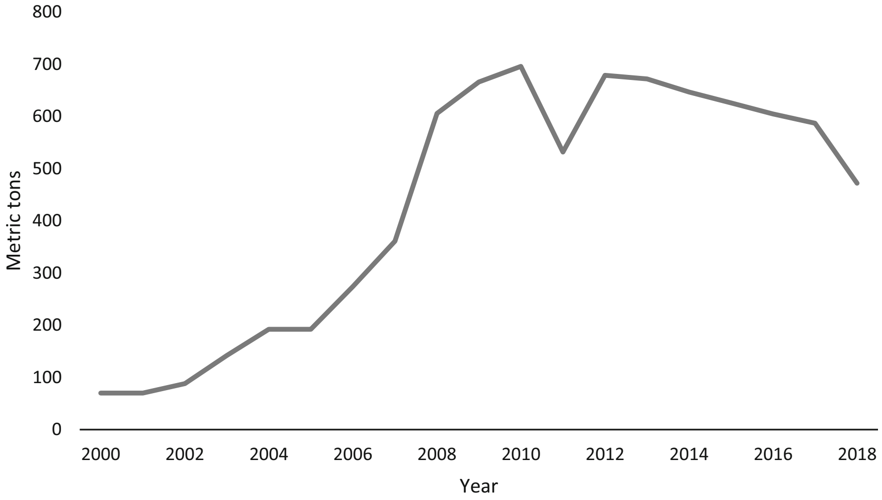

Fig. 22.4 Aquaculture production in Namibia, 2000–2018, Source: (World Bank)

however, only adopted in 2002 (Moyo and Rapatsa 2021). Despite the slow take-off, aquaculture has a promising future in the country that has the potential to contribute significantly towards attaining self-reliance and food security.

Namibia has a western coastline on the Atlantic Ocean. The Namibian coastal waters are some of the richest fishing grounds in the world (Tall and Failler 2015). However, the country has no notable natural freshwater bodies that would be excellent for large-scale/ commercial fish farming. There also are no big lakes known on an international level. The country has significant rivers that form borders with neighbouring countries such as Angola, Zimbabwe, Zambia, Botswana, and South Africa, where little fishing for local markets takes place. They are comprised mainly of Tilapia, catfish, and tiger fish. However, the country enjoys permanent water bodies in dams and sinkhole lakes. It also has non-perennial rivers that mostly flow during the rainy season. Marine aquaculture in the country is, however, trivial and limited to the waters of the Benguela ecosystem. Traditionally, subsistence small-scale freshwater aquaculture is not a norm in the country; thus, current activities are government and donor-led (Iitembu et al. 2022) (Fig. 22.4).

Notwithstanding the framework in place to support aquaculture development in the country, the development of rural small-scale aquaculture may suffer a setback as there is no distinction between community-based and commercial farming. This generates regulatory problems which cannot be easily met by potential small-scale fish farmers willing to farm fish for household consumption.

22.7 Conclusion and Recommendations

The aquaculture industry has a promising future in Namibia, especially with support from the ministry of fisheries and development partners. Moreover, small-scale aquaculture can increase food security and improve the quality of diets in Namibian households, thereby reducing the prevalence of malnutrition, especially in rural areas where poverty is far too common. Because fish is far more consumed than other animal proteins in many countries, this sector can also be an alternative in increasing protein supply to meet the demand of the growing population. However, for small-scale aquaculture to take off, we recommend the following be implemented:

- Invest more energy in aquaculture production education.
- Consolidation through fish farming development policies.
- Promotion of aquaculture production at the household level.
- Financial support for prospective farmers.
- Technical knowledge and support to prospect farmers.
- Intersectoral collaboration and engagement of stakeholders.

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Chapter 23
The Southern Mullet (*Chelon richardsonii*) as a Potential Candidate Species for Aquaculture in the Southern African Region

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Abstract This study investigated the potential of the southern mullet (*Chelon richardsonii*) as an aquaculture candidate. The southern mullet lives in marine, brackish, and freshwater environments. It is a low-trophic level species with a diet primarily comprised of detritus and plankton. The species is also a target species of a small-scale fishery off Namibia. The fish's biology makes it an ideal aquaculture candidate that can contribute to food security. This species has the possibility to be cultured with other fish species and feed on leftover feed as well as wastes acting. Moreover, it can be cultured in single-culture conditions. The culturing of this species will reduce pressure on wild stocks in both Namibia and South Africa, in which the latter is reported to be regionally overexploited. However, more biological studies will be needed to identify a specific method that can be used to culture the southern mullet optimally. Economic feasibility studies will also be required to address issues related to mass production, markets, and profitability.

Keywords Aquaculture · Food Security · Low Trophic · Southern Mullet · Sustainability

23.1 Introduction

Global fish production was predicted to exceed 179 million tonnes in 2018, with a total first-sale value of USD 401 billion, with aquaculture accounting for 82 million tonnes for USD 250 billion (FAO 2020). Aquaculture was responsible for 46% of overall production and 52% of fish for human consumption (FAO 2020). China

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continued as the major fish producer in 2018, accounting for 35% globally (FAO 2020). A substantial share of output in 2018 came from Asia (34%), excluding China, followed by the Americas (14%), Europe (10%), Africa (7%), and Oceania (1%) (FAO 2020). Captured fisheries have mainly remained steady since the late 1980s, with annual harvests ranging between 86 million and 93 million tonnes (FAO 2020). Captured fisheries are thought to have reached a plateau, and no further expansion is envisaged (Maani 2017). The aquaculture industry serves as a vital source of nutrition in some of the world's fastest developing countries and will be critical in meeting future global fish demand (Kamalii et al. 2022). In 2001–2018, global aquaculture production of farmed aquatic animals increased at a rate of 5.3% per year on average (FAO 2020). Aquaculture has been a promising industry, with a faster growth rate than any other food-producing industry in the world (Subasinghe et al. 2009; Pandey & Kumar 2021).

Aquaculture contributed between 16 and 18% to the total fish production in Africa (FAO 2020). Many African countries are far below their targets (Golden et al. 2016; FAO 2020). Africa only contributes around 2.7%, with Egypt being the major producer and Nigeria significantly increasing its aquaculture production to become Africa's second-largest producer (FAO 2020). However, this cannot be said for Southern African countries, whose production remains significantly low (El-Sayed 2013). Southern Africa can potentially increase aquaculture production (Brummett et al. 2008).

Low-trophic level fish species are considered more environmentally friendly to farm than high-trophic level fish species (Pauly et al. 2001). This is because they have a low demand for animal protein (Tacon et al. 2011). In contrast to carnivorous fish species, which rely heavily on fish meal and oils, low-trophic level fish species may be given a diet rich in plant-based proteins. Fish meal has recently been the dominant protein ingredient in fish feed, considered a golden standard protein source (Daniel 2018; Hodar et al. 2020). However, its production from wild-caught fish has reached a plateau over the years, making it difficult to obtain, very expensive, and unsustainable (Naylor et al. 2009; Nunes et al. 2014; Egerton et al. 2020). Fish meals and oils have received much attention because they are mainly derived from wild-caught fish (Naylor et al. 2009; Cao et al. 2013; Jones et al. 2015). Wild-caught fish could be used for direct human consumption, but the supply to the fish meal industry is more preferred given its demand and profits, which dampens efforts to increase direct human consumption (Delgado 2003; Naylor et al. 2009). As a result, using fishmeal and oil in aquafeeds has raised concerns about the environmental sustainability of farming carnivorous fish species such as salmon (Naylor et al. 2009; Ytrestøyl et al. 2015). In reality, humans consume more fish than the fishmeal industry; this has been demonstrated by many researchers (Byelashov and Griffin 2014). However, the fishmeal industry does contribute to pressure on wild-caught fish (Naylor et al. 2000, 2009). Reduced reliance on wild-caught fish in aquafeed is widely acknowledged as a critical long-term strategy for aquaculture growth (Rust et al. 2011). Research has indicated that fish feed can be supplemented with plant-derived protein, reducing the need for fish meals and oils (Rust et al. 2011). This has been primarily achievable in low-trophic level fish species, which are better equipped to digest plant proteins than high-trophic level fish species (Turchini et al. 2019).

Concerns about the environment have prompted widespread calls to refocus fish farming on low trophic level species fed non-fish natural diets. In addition, Olsen (2011) believes that one of the solutions to sustainable aquaculture is to introduce lower trophic level fish species that do not require fish meal in their diet and can entirely rely on proteins derived from alternative sources. Reports from higher institutions such as the World Resources Institute, World Wildlife Fund, and Asia Pacific Fisheries Commission acknowledge this and advocate for aquaculture production and sustainability goals to be met by farming fish low in trophic level (Waite et al. 2014). The 2019 Californian Ocean Resiliency Act (SB-69) of the United States requires producers to focus on low-trophic level fish species (BigeLow et al. 2020). Africa needs to expand on this and introduce new aquaculture candidate species that feed at a low-trophic level to promote security while utilising resources in a sustainable way.

Mullets are fish species from the Mugilidae family distributed worldwide that feed at a low trophic level (Whitfield 2016). They are distinguished by their tolerance to a wide variety of salinities and temperatures (Whitfield 2016). A distinctive mullet, the Southern mullet (*Chelon richardsonii,* previously *Liza richardsonii*) (Durand and Borsa 2015) is found in the southern African region (Whitfield 2016). It is an important fish species that have a significant contribution to the socioeconomic of small-scale fishers in Namibia and South Africa. However, Horton (2018) and Horton et al. (2019) reported the species exhibiting signs of overexploitation in South Africa. No population studies are available from Angola and Namibia; thus, this study refers to reports from South Africa. The Sothern mullet is commercially important (de Villiers 1976; Horton 2018; Horton et al. 2019). Due to its tolerance to various salinities, it could be a valuable species in brackish and freshwater aquaculture (Bok 1983). The biology and economic value of the southern mullet make it an excellent aquaculture fish species that can be introduced into the southern African region to promote sustainable aquaculture, which will contribute to food security. This chapter discusses the biology, ecology, reproductive traits, and aquaculture prospects of the southern mullet in the southern African region.

23.2 Geographical Distributions

Southern mullets are distributed along coastal waters and estuaries from Lobito, Angola to KwaZulu-Natal, South Africa (DAFF 2014). The juveniles and adults are common in Eastern and Western Cape estuaries; however, this species is usually more abundant in the nearshore marine environment (Bennett 1989). The distribution of this species along coastal waters might be attributed to the high natural productivity of the Benguela system that happens near shore (Fig. 23.1).

Fig. 23.1 The red solid line shows the geographical distribution of the southern mullet (*Chelon richardsonii*) as described by Branch (2017) (map adapted from Google maps)

23.2.1 *Biological and Feeding Ecology of Southern Mullet*

Southern mullet (*Chelon richardsonii*) is a fish species from the Mugilidae family (Whitfield 2016). It can be identified with a silvery sheen that is usually darker above and white below, with gill covers that have a blotch and an elongated and pointed snout (Branch 2017). It is euryhaline species that can tolerate a wide range of salinities (Branch et al. 1985; Branch 2017; Whitfield 1996, 2016). It can also tolerate a wide range of temperatures (Whitfield 2016) recorded within its distribution area, from slightly below 9 °C to slightly above 20 °C. The southern mullet reaches a maximum length of 400 mm (Branch 2017). It is marine-estuarine dependent, reproducing in the marine environment, and the hatched fry migrate toward the shore where they spend their juvenile phase before moving into estuaries as adult fish (Branch 2017; Whitfield 2016; Whitfield 2019).

Mugilids are characterised by a 'cardiac' stomach and a long alimentary canal for the digestion of diatoms and detrital material (Marais 1980). However, all species have distinctive feeding patterns that minimise interspecific competition. Generally, mullets are oligophagous, having a diet dominated by benthic floc, detritus, meiofauna, microphytobenthos, and smaller epifauna (Whitfield 2016). Large quantities of inorganic particles are found ingested within most mullet's food items. Blaber and Whitfield (1977), Masson and Marais (1975), and Whitfield (1988) showed that primary dietary items ingested by juvenile and adult mugilids in local estuaries are particulate organic debris, pennate diatoms, unicellular and filamentous algae, flagellates, macrophytic plant material, blue-green algae, ostracods, foraminiferans, and small invertebrates, e.g., gastropods and harpacticoid copepods. In addition to food, the estuarine population of mullets ingest a significant amount of silt and fine sand compared to the environment population that feeds on planktons (De Villiers 1987; Marais 1980; Romer and McLachlan 1986). Mullets obtain their food mostly in shallow waters that are associated with high organic content (Whitfield 2019).

Southern mullets travel in schools and mainly feed on phytoplankton, fine algae, benthic diatoms, detritus of bottom sediments, and other marine invertebrates (Branch 2017). The estuarine populations of *C. richardsonii* appear to reach physiological conditions more than marine populations because they do not lose significant energy to reproduction compared to the marine population (De Decker and Bennett 1985). Southern mullets larger than 20 mm SL feed on a regular mullet diet, while postlarval less than 20 mm SL ingests copepods and macruran larvae (Whitfield 1985) predominantly. An early study by Marais (1980) indicates that *C. richardsonii* found in Swartkops estuary feed mainly during the day and rarely at night.

23.2.2 The Reproductive Characteristics of Southern Mullet

Mullets are documented to spawn and reproduce in several temperatures (Abraham et al. 1966; Van der Horst and Erasmus 1981). Southern mullet matures at 180 mm SL (de Villiers 1987). However, Branch (2017) reported different results that this species attains sexual maturity at 230 mm. This difference in results could be from different populations. Southern mullets found in Algoa Bay are reported to have a noticeable gonadal development that happens between September and April and spawns during spring and summer, while in the Swartkops estuary, they are reported to be summer spawners. In addition, Van der Horst and Erasmus (1978) reported *Liza dumerili,* a closely related species, to spawn during the summer period in the Swartkops estuary. According to Lasiak (1983) and van der Horst and Erasmus (1981), *C. richardsonii* found in the Eastern Cape waters spawn often close inshore between September and March. Lamberth and Whitfield (2013) reported spawning during early and late summer peaks. It appears that *C. richardsonii* spawns during summer; however, Bennett (1989) and Whitfield and Kok (1992) reported continuous recruitment into Western Cape estuaries that takes place all year. This species has a greater sexual development that takes place between September and March with spawning taking place inshore (Lasiak 1983). It lays eggs in the marine environment, and hatched fry migrates nearshore, where they develop into the next stage (Cambray and Sok 1989).

23.2.3 Environmental Preferences of Southern Mullet

The southern mullets are found in marine, brackish, and freshwater environments (Branch 2017).

Most mugilids occupy predominantly estuarine nursery areas; however, the juvenile *C. richardsonii* inhabit both the marine and estuary environment (Beckley 1984; Romer and McLachlan 1986; Wallace et al. 1984). Estuarine juvenile mullets prefer water less than 1 m to capture zooplankton from the benthos found near the bottom during the day. At this juvenile stage, the number of sand grains increases microbenthic foods associated with sand grains become overwhelmingly dominant. Estuaries have excessive nutrient concentration and low oxygen levels; thus, southern mullets are adapted to a low oxygen environment.

23.3 Mullet Fishery

The southern mullet is the main target species of the inshore net fishery on the west coast of Namibia and the east coast of South Africa. Small-scale fishers sell this fish in coastal towns and inland towns. The southern mullet is managed under a combination of gear restrictions, total allowable effort (TAE), and closed areas in South Africa. In Namibia, it is managed through an input control scheme. There is no documentation of the exact amount that is specific to the southern mullet; however, half of the 1500 tonnes (t) per annum allocated to the net fisheries in South Africa are estimated to be the southern mullet species (Horton 2018). In Namibia, there are 10 individuals permitted to catch mullets, who have reported catching a combined amount of 10 tonnes per month and approximately 120 tonnes per annum (W. de Klerk, personal communication, 18 July 2022).

23.4 The Aquaculture Potential of Southern Mullet

Flathead grey mullet (*Mugil cephalus*) has been well studied and understood in cultured conditions. It is an essential species in aquaculture that is reared in both single and polyculture (Mires 1969; Katz et al. 2002; Lupatsch et al. 2003; Israel et al. 2017). Grey mullets can be used as cleaner fish feeding on waste particles from other fish ponds and cages (Katz et al. 2002; Lupatsch et al. 2003). This method of culture is used to maximise production. Southern mullet is closely related to *M. cephalus* (Durand and Borsa 2015), inhibiting the same environment in southern Africa. Southern mullet has not been introduced into aquaculture; however, it has as potential to be cultured, which will contribute to food security in the southern African region. An early study has successfully artificially hatched eggs of *C. richardsonii* collected from the wild (Cambray and Sok 1989).

Furthermore, mature females have also been collected from the wild and artificially spawned in captivity (Bok and Jongbloed 1987). The larvae development of *C. Richardsonii* is similar to that of *M. Cephalus* (Brownell 1979; Cambray and Sok 1989). This shows that the southern mullet can be cultured in captivity. However, more research is necessary, with special emphasis on developing suitable feeds for fry. Bok (1989) reported many mortalities in newly hatched fry. The study highlighted a challenge in supplying suitable feed for the newly hatched fry. The diet was changed to live feed rotifer, *Brachionus plicatilis*, and fewer mortalities were recorded. This has also been reported in *M. cephalus*, which had experienced a similar challenge. Watanabe et al. (1983) fed *M. cephalus* fry with *B. plicatilis* and *Artemia nauplii* which improved the survival of the fry. The growth rate of *C. richardsonii* reported by Bok (1989) was similar to that of *M. cephalus* reported by Kuo et al. (1973). With advancements in technology and better methods of culturing aquatic animals, *C. richardsonii* can be cultured in captivity from broodstock to the next generation.

23.4.1 Economic and Market Characterisation of Southern Mullet

The mullets are sold at a price starting from N$ 10 per/kg in Namibia. Their price is highly variable; it depends on the amounts caught in that season (W. de Klerk, personal communication, 18 July 2022). They are sold as frozen or salted and dried into a form called bokkoms (Branch 2017; W. de Klerk, personal communication, 18 July 2022). The market for mullets can only be expanded if this species is introduced in aquaculture and farmed to complement captured stocks. The southern mullet has the potential to be farmed as it has an established market in both Namibia and South Africa. However, further studies are required to examine this species' economic feasibility. The market is very crucial in aquaculture.

23.5 Conclusions

Southern mullet feed at a low trophic level with a diet primarily comprised of detritus. This makes it a potential candidate that can contribute to food security while also addressing the issue of trophic levels in aquaculture. It has the potential to be cultured with other fish species to feed on their wastes and act as biological control. Moreover, it has the potential to be cultured successfully in single-culture conditions in both intensive and extensive systems. With the awareness that the stock of *C. richardsonii* has been overexploited in South Africa, culturing this species will reduce pressure on wild stocks while maintaining stable consumption levels. However, more studies are recommended to identify a specific method that can be used to farm the southern mullet to maximise production and profits. Economic feasibility studies on tor mass production of this species are recommended.

Fishers in Namibia claim that the catches have drastically decreased over the years. Unlike in South Africa, it is difficult to determine the cause of the decline in the wild population; however, concerning the over-exploitation reported in South Africa, it could be the same happening in Namibia. Population studies are recommended to provide specific information on possible causes of the decline of catches in Namibia, which can be used to assist in managing the stock.

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Part IV
Aquaculture Animal Welfare

Chapter 24
Some Significant Parasites in Aquaculture and Their Potential Impact on the Development of Aquaculture in Africa

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Abstract Many African countries have experienced significant growth in aquaculture development in the last two decades. This growth may have been brought about by the realisation of aquaculture as a viable vehicle for development, the understanding of the biology of indigenous species with good traits for culture, the adoption of new farming technology and the adoption of enabling legislative frameworks by governments that encourage the development of this sector. The development of aquaculture in Africa was initially established to provide additional protein sources of food to cater for the growing population, improve food security, provide employment and generates income (to reduce poverty). The potential for further growth is vast as the continent has many positive attributes. Various diseases, including parasitic infections, however, pose threats to the development of the aquaculture sector as the disease can lead to mortality, reduce growth and reproduction rates and fitness of the culture fish stock and render the infected fish not marketable. Some fish diseases are zoonotic (can be transferred from animals to

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humans). For this reason, various studies globally (including histopathology, Health Assessment Index (HAI) and molecular work) have addressed parasites of cultured fishes and how they affect and/or influence the productivity of aquaculture organisms. Many of such studies aimed to understand the behaviour and life cycles of these parasites and determine the nature of pathology to the fish host. This would help in finding ways to prevent and control parasite epidemics, when necessary, in aquaculture set-ups and improve the productivity of this sector. This chapter discusses the importance of studying parasites and their effects in an aquaculture set-up.

Keywords Aquaculture · Mariculture · Fish · Fish health · Fish diseases · Fish parasites

24.1 Introduction

A parasite is an organism that lives in or on another larger organism of a different species, referred to as host species, upon which it depends for food and/or shelter (Rohde and Rohde 2005). Parasites are often small, short-lived and commonly hidden within organisms during their parasitic phase. Their effects on their hosts may be evident and profound or subtler (Rohde and Rohde 2005). Typically, they attract attention only when they cause pathology and disease (effects on host behaviour, decreased fish growth, reduced host total body weight, decreased fecundity and increased mortality) or somehow degrade biological products; thus, production, yields and economic benefits consequently increase healthcare costs (Marcogliese 2002; Stewart 2005; Hutson et al. 2011; Iwanowicz 2011; Khalil et al. 2014). For example, Merella et al. (2009) reported an outbreak of *Sciaenacotyle panceri* Sonsino, 1891, on cage-reared meagre (*Argyrosomus regius* Asso, 1801) from the western Mediterranean Sea after the fish started showing non-specific disease signs such as lethargy, emaciation, gill anaemia and mortality.

It is important to distinguish between ectoparasites and endoparasites in finfish, defined by which organs of the fish they infest or infect, external or internal organs, respectively (Poulin 2004). The main differences between ecto- and endoparasites are four-fold: Firstly, ectoparasites have direct life cycles including only one fish host and infest fish via free-swimming infective larvae (Poulin 2004). Unlike endoparasites, ectoparasites do not need different hosts to complete their life-cycle, so it is easier to multiply within a short period of time on the host (Poulin 2004; Reed et al. 2009; Whittington and Kearn 2011). Endoparasites living mostly in the gastrointestinal tract, on the other hand, have complex life cycles involving at least two host species. They are acquired by fish hosts via ingestion and could be prevented by controlling fish feed (Poulin 2004).

Secondly, the species richness of ectoparasites per host is typically greater than that of endoparasites. Gill parasites, especially, attach to the host as a result of the gaseous exchange between water and the gills. As the water passes through the gills during this gaseous exchange process, the gills accumulate most free-living parasite species in the water column. Gills hence accommodate more parasite species compared to all other host organs (e.g. Amakali 2019). Fish hosts with a broad diet, for instance *Clarias* spp. Scopoli, 1777, which feed on a wide variety of food items including detritus, fishes, zooplankton, macrophytes, insects, phytoplankton and gastropods, however, may have greater endoparasites species richness than ectoparasites.

Thirdly, endoparasites often occur at much higher abundances than ectoparasites (Poulin 2004), as they are acquired from a daily diet of the fish host and are not exposed to external environmental changes. Endoparasites are also affected by changes in the immune response of fish (Aydoğdu et al. 2015), which plays an important protective role for the fish host (Rubio-Godoy 2007). Some immune responses are activated when the parasites are in abundance. Some parasites, cestodes for instance, have less tolerance to these immune responses compered to others such as digenean trematodes. This depends on the mode of feeding associated with the parasites (Rubio-Godoy 2007; Aydoğdu et al. 2015).

Lastly, there is an effect of the external environment on the parasite, where the ectoparasites are subjected to water quality variations that influence their well-being (Poulin 2004). Monogeneans and copepods living on the external surfaces of fishes are exposed to water currents and changes in their physical and chemical environment that make robust attachment structures and copulation organs necessary. When fish die due to parasitic infections, deaths can often be associated with changes in parasite densities and community composition (Iwanowicz 2011). Frequently, the damage associated with these dead fish is relative to the rate of parasite infestation, i.e. the state of the fish being invaded by parasites (Bruno et al. 2013). A lightly infected fish will show few or no symptoms, while a heavily infected fish may become physiologically harmed and die (Iwanowicz 2011; Mumba 2014).

Parasites generally do not kill their hosts, but some severely stress the affected fish to the point of biological and economical concern (Bruno et al. 2013). High intensities of ectoparasites cause excess mucus secretion, loose scales, dermis injuries such as haemorrhages, open sores, ulcers exposing connective and muscle tissues, inflict reproductive damage (Deaton 2009) or osmotic problems affecting respiratory functions (Bruno et al. 2013). Consequently, damaged skin and gills make the fish host more susceptible to secondary infections, possibly from viruses, bacteria or other microorganisms that may also contribute to mortalities (Rohde and Rohde 2005). Martins et al. (2015) and Kotob et al. (2017) reviewed the impacts of different secondary infections, also called co-infections, on fish species.

Parasites use the nutrition from the host they invade. However, the severity of diseases and the resulting mortality is usually greater in cultured fish than in wild fish (Scholz 1999; Ternengo et al. 2010; Labella et al. 2011). In the wild, fish can get enough nutrition for their own needs and the needs of the parasites. Sufficient intake of readily and naturally available nutrients also satisfies the pathogens and hence decreases fish stress while simultaneously increasing the fish resistance to disease (Bruno et al. 2013). In farmed fish, however, natural feeds are not always readily available. In addition, feed is neither usually increased nor altered with the presence of demanding pathogens or parasites in the fish (Scholz 1999). This may lead to an increased number of parasites that cause stress to the fish, giving rise to diseases and further leading to pathological changes, a decrease in fitness and a reduction of the market value of the fish (Scholz 1999).

Aquaculture, both freshwater and marine, has been increasing in many African countries as a means to provide food to cater to the growing populations to generate foreign investment and earnings and also increase the rate of employment, and hence reduce poverty (e.g. Tjipute 2011). Despite this increased effort, the contribution from Africa to the world's aquaculture is still insignificant (from a mere 0.4% in 1996 (FAO 2016) to approximately 2.7% in 2019 (Halwart 2020)). This growth is, however, expected to increase.

Various diseases, including parasitic infections, pose a threat to the development of the aquaculture sector as it leads to loss of biological fitness (reduced growth, reproduction and survival rates) and reduced product marketability (poor quality, unattractive and undesired size). Diseases can also negatively impact the people who depend on aquaculture for a basic income (Mumba 2014). In addition, diseases emanating from aquaculture can be transferred to wild fishes and cause ecological damage (Thieltges et al. 2020).

Parasites that infect fish species are ubiquitous, primarily surviving in a dynamic equilibrium with their host(s) and they are often overlooked, but any changes in the environment, both anthropogenic and natural, can alter the parasite-host equilibrium and cause disease or mortality in fish (Iwanowicz 2011; Justine et al. 2012). Fish parasite infections arise from poor aquaculture management, high-density conditions and increased fish stress. It has been established that the interaction among these pathogens, hosts and their environment results in the development of fish diseases (Labella et al. 2011). In addition to the biological, economical and economic losses caused by parasites, some of the parasites are zoonotic. This means that they can be transmitted to humans through the consumption of infected fish that is either undercooked or consumed raw (Mumba 2014). Millions of people globally are infected by parasites, and many more are at risk of infection.

The economic loss experienced due to parasite infection is usually in the event of an intense parasite occurrence in an aquaculture set-up when the cost of production is increased because of the investment loss in dead fish, the cost of treatment incurred and decreased growth during convalescence that leads to loss of income. Mortality often occurs when there is a change in parasite density and community composition and when a stage is reached when a heavily infected fish become physiologically impaired and die. Labella et al. (2011) highlighted that to apply measures to control parasites and diseases limiting the production of cultured fish, studies involving factors of pathogenic organisms and aspects of the parasite life cycle and a better understanding of environmental conditions affecting fish cultures are a prerequisite.

The intensification of aquaculture and the introduction of new aquaculture species into environments create situations where parasite burdens increase exponentially in high-density cultures (Woo and Leatherland 2006) and emerging infectious diseases (EID). EID can be defined as previously unknown diseases, or the spread of an existing disease into a new host or geographic area (Krkošek 2010). EID causes much ecological damage, especially in some aquaculture systems such as cage systems where the barriers are weak or non-existent.

Disease management mechanisms in Africa are not well developed, and there exists a porous and, in some instances, not harmonised biosecurity system. In many instances, fish health is not prioritised until extreme impacts are observed, so the opportunity to manage and control parasites and diseases at the source is missed. Most farmers react to large outbreaks rather than preventing or managing infections, most likely because of insufficient information on the ecology of pathogenic parasites, their prevention and control (Iwanowicz 2011). The diseases and specific identity of the parasites infecting cultured fish are rarely known, and very few parasite species, classified only to their genera, are recorded (Woo and Gregory 2014). This chapter is a summary of some of the known ecto- and endoparasites affecting marine and freshwater fish species to identify and bridge the knowledge gaps.

24.2 Potential Aquaculture Parasites

24.2.1 Monogenea

Monogeneans are a group of ectoparasite flatworms (phylum Platyhelminthes) found in freshwater, brackish and marine habitats. They are associated with a one-host life cycle, shed their eggs straight into the water column, and after which hatching, the free-swimming larvae infect a new host directly and are highly host-specific (Paperna 1980; Stewart 2005; Amakali 2019). Some are viviparous such as *Gyrodactylus salaris* Malmberg, 1957, and give birth to individuals almost the same size as the adult, with another embryo ready to be born. Monogeneans have caused worldwide chaos in intensive culture facilities primarily due to their ability to reproduce rapidly (Stewart 2005). Monogeneans are also organ-specific. This characteristic has led to interesting models for evolutionary research into host–parasite relations with specific haptoral make-up suitable for the organ they inhabit. They are commonly found on the fish skin, fins and gills and feed on epidermal cells, mucus or blood. In heavily infected fish, this leads to emaciation, lethargy and anaemia. Gill epithelial hyperplasia, excess mucous production and mechanical damage to the gills causing respiratory difficulties in fish have been reported because of monogenean flukes in captivity (Stewart 2005). There are, however, some studies that have found monogeneans in the internal organs of the fish with specialised organs for attachments. This includes dactylogyrid monogeneans such as *Enterogyrus* Paperna, 1963, documented from the stomach of freshwater fish by Bayoumy and El-Monem (2012). Luus-Powell et al. (2020) also reported other species of *Enterogyrus* from the stomachs of cichlid hosts documented from Africa, including two new species of *Enterogyrus* found in the stomach of the Mozambique tilapia, *Oreochromis mossambicus* in South Africa. A monogenean parasite from the species of the *Amphibdella* Chatin, 1874, represented the most interesting monogenean parasitic adaptation, parasitising the blood system of electric rays from the family

Torpedinidae (Luus-Powell et al. 2020). In addition, Amakali et al. (2022) found and described monogenean *Calceostoma* sp. in the stomach of marine fish.

Monogeneans have been reported to cause severe fish mortalities in hatcheries all over Africa. *Diplectanum oliveri* Williams, 1989, a monogenean gill parasite of marine fish both *Argyrosomus japonicus* (dusky kob) and silver kob, *A. inodorus* (Griffiths & Heemstra 1995) is currently regarded in South Africa as the most persistent ectoparasite associated with the culture of both *Argyrosomus* species, causing pathological tissue changes in the areas associated with attachment and feeding, which can result in stock losses (Joubert 2012). Diplectanids have been reported several times in marine aquaculture from Africa and worldwide (e.g. Amakali et al. 2022), increasing mortality in sciaenid. Cultured fish (e.g. in tanks) are usually held in more crowded environmental conditions than fish in the natural environment. This promotes infestation and makes it easier for monogeneans to find a host fish in capture aquaculture (Hecht and Endermann 1998). Additionally, captive environments may have stressful effects on cultured fish, which may stem from aggressive behaviour by the tank mates, poor or insufficient nutrition, handling injury and poor water quality (e.g. Hecht and Endermann 1998; Stewart 2005; O'Rourke and Rosenbaum 2015; Mogorosi 2019). This may consequently weaken the immune system of the fish and how it responds to and fight the present parasites, thereby allowing for the rapid proliferation of parasites.

Risk assessment of parasitic helminths on cage- or pond-cultured Nile tilapia in Uganda and Kenya revealed that monogeneans (*Cichlidogyrus tilapiae* Paperna, 1960 and *C. sclerosus* Paperna & Thurston, 1969) are high-risk parasites, particularly in pond-raised fish (O'Rourke and Rosenbaum 2015). *Cichlidogyrus* and *Gyrodactylus* have also been reported to infect tilapia in several fish farms in the

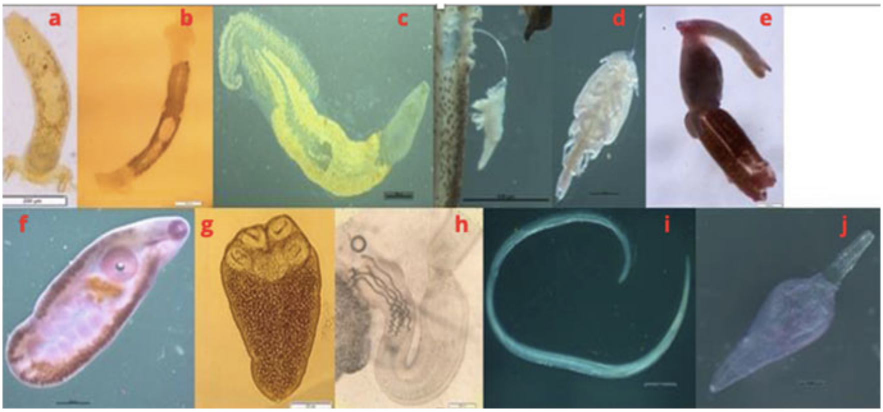

Fig. 24.1 Some marine parasites infecting fishes from Africa, ectoparasitic monogeneans: *Diplactunum* sp. (**a**), *Calceostoma* sp. (**b**), *Sciaenocotyle* sp. (**c**), Copepods Caligus sp. (**d**) and Brachiella sp. (**e**). Endoparasitic digenean trematode Helicometrina sp. (**f**), cestode tetraphyllidean plerocercoids (metacestodes) (**g**) and Callitetrarhynchus sp. larvae (**h**), nematode Anisakis sp. larvae (**i**) and acanthocephalan hook worm Corynosoma sp. (**j**)

eastern region of Saudi Arabia. Infected fish suffered from respiration difficulties due to the damage to gills, haemorrhage, fin rot and increased mucus secretion.

Diseases and damages caused by monogeneans in aquaculture set-ups have resulted in the need for trials to be conducted to assess the effects of anthelmintics on the flukes. Although fish farming contributes more than 10% of fish produced worldwide, no anthelmintics have been developed to precisely control or treat monogenean flukes in aquaculture (Stewart 2005; Mo 2020; Norbury et al. 2022). Monogeneans are challenging to eliminate, as most treatments are not 100% effective, merely reducing parasite numbers. The natural life cycle allows for the recovery of parasite numbers in days. Furthermore, some treatments that may be effective on the parasite may be harmful to the host or the environment and thus cannot be used. For this reason, it is imperative to identify a chemical/treatment that is safe to use on the host and can effectively eliminate the monogeneans to control disease outbreaks in culture environments.

Stewart (2005) studied the effect of praziquantel (10, 20 and 40 mg/l), hydrogen peroxide (30 mg/l), copper sulphate (0.2 mg/l), formalin (100 and 200 mg/l) and freshwater and observed that praziquantel (40 mg/l) and freshwater were significantly effective at eradication of *Calceostoma* sp. Freshwater successfully eradicated 100% of the parasites after an hour and praziquantel after 6 h of exposure to the treatment. Norbury et al. (2022) also reviewed and reported on PZQ's current use in aquaculture and discussed its effectiveness against various flatworm parasites of fish and issues that may arise after administration.

According to Mo (2020), *Gyrodactylus salaris*, a freshwater monogenean, is sensitive to changes in the chemical composition of the water. It is sensitive to the most used chemicals for bath treatment of farmed salmon parr and salmon eggs (e.g. high salinity salt water, formaldehyde and compounds containing chlorine and

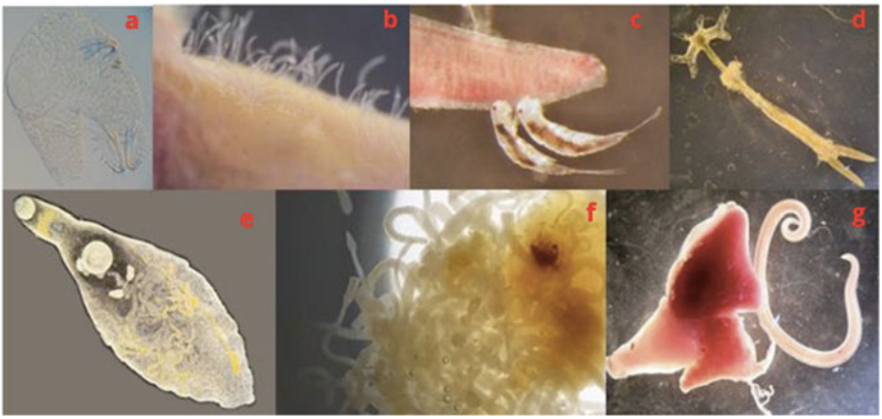

Fig. 24.2 Some freshwater parasites infecting fishes from Africa: gyrodactylus sp. (**a, b**), copepodid larvae (**c**) and copepod Lernaea sp. (**d**), digenean trematode (**e**), adult cestode (**f**) and nematode larvae (**g**)

iodine). In addition, *G. salaris* is sensitive to slightly acidic solutions of aluminium sulphate ([Al_2 $(SO_4)_3$]; AlS). AlS is less toxic to fish than *G. salaris* in moderately acidified waters. Furthermore, disinfecting fish eggs from infected farms (iodine-containing compounds have been used) was reported to be another way of eradicating the *G. salaris* parasite that may have contaminated the eggs.

24.2.2 Digenea

The digenean trematodes are flatworms (phylum Platyhelminthes) and represent the largest group of parasites and comprise approximately 18,000 families (Bannai 2017). They have been reported and described throughout a broad geographical range from multiple fish hosts across broad taxonomic ranks. Adult-stage digeneans usually have a dorso-ventrally flattened, oval body with a smooth, spiny or corrugated surface, a sucker around the antero-ventral mouth, and an additional ventral sucker or acetabulum. Both suckers are used for attachment and locomotion. The digestive system consists of a pharynx connected to the mouth opening, a short oesophagus and two blind intestinal caeca. Most trematodes are hermaphrodite, containing both male organs (testes, ducts and copulatory system) and female organs (ovary, vitelline glands, ducts and uterus). Some also contain a specialised copulatory organ which is used for differential diagnosis. Eggs are evacuated to the genital opening and are usually oval and operculated.

The general life cycle of digenean trematodes involves multiple hosts (which make them heteroxenous), and they usually require (with some exceptions) a mollusc as their first host (e.g. Amakali 2019). The development of rediae and cercariae takes place in the snails and crustaceans. Small fish serve as the second intermediate host, and adult trematodes develop in big fish, piscivorous birds and mammals that feed on infected small fish, serving as definitive or final hosts. Digeneans are common in wild fish, where infections are usually asymptomatic, while unless the intermediate host, commonly aquatic snails, or fish, is present, they are uncommon in cultured fish (Norbury et al. 2022). Adult parasites in fish are usually found in the intestine, though some, such as Aporocotylids (blood flukes) reside in the cardiovascular system. In the life cycle of blood digeneans, the cercaria emerges from the intermediate invertebrate host and penetrates and matures in the definitive fish host, and the resulting adult releases eggs into the fish's vascular system (Bullard and Overstreet 2002). These eggs may be sequestered in the gill, heart, kidney, liver, spleen, pancreas or other organs, where they cause inflammation and decrease the physiological and mechanical efficiency of these organs. In some cases, they kill the host. In addition to internal digeneans, Mele et al. (2022) studied a digenean trematode *Didymodiclinus marginati* from the gills of *Epinephelus marginatus*.

Adult trematodes, infecting the digestive tract of fishes, are considered harmless, even when their numbers are high. Extraintestinal trematode infections, on the other hand, are potentially pathogenic. Pathological data on blood flukes (sanguinicolids which can cause considerable damage to the gills and impair respiration) are relevant to African fish. Adult worms and trapped eggs can physically obstruct the passage of blood, causing clotting and subsequent necrosis, while escape of miracidia through the gill epithelium causes blood loss and may lead to anaemia (Hecht and Endermann 1998). The proliferation of the arterial endothelium was reported in common carp infected with *Sanguinicola inermis* Plehn, 1905. The *S. inermis* hosts experience loss of blood that causes a pale colour of the gills and a decline in packed cell volumes and oxyhaemoglobin levels. Heavy infection compromises the host's ability to withstand stressful conditions, for example, heavily infected cultured carp suffocated during transportation (Hecht and Endermann 1998). In chronic infections, adult worms scatter and become stranded in the heart, kidneys and caudal vessels. Dispersed eggs become encapsulated and may also become surrounded by a focal granuloma.

Treatment of fishes debilitated by digenean parasites is difficult, and only the combination of stock destruction and facility disinfection is a realistic option for managing cases in freshwater systems. However, because this is usually not possible in marine systems, early detection and identification of the parasite, careful site selection and construction of culture facilities, and elimination of infected hosts (definitive or intermediate) are important (Bullard and Overstreet 2002).

24.2.3 Cestoda

Cestodes or tapeworms (phylum Platyhelminthes) infect fish in adult and larval forms. They are known worldwide for fish of the families Cyprinidae, Poecilidae, Cichlidae and Centrarchidae. Records of African hosts, all from southern Africa, include the common carp, *Labeobarbus kimberleyensis* Gilchrist and Thompson, 1913, *Enteromius trimaculatus* Peters, 1852 and *Oreochromis mossambicus* Peters, 1852 (Paperna 1996). The most important tapeworms in Africa that infect fish in the adult form is the Asian tapeworm *Bothriocephalus acheilognathi* Yamaguti, 1934 (Paperna 1996). Infections with *Ligula* Bloch, 1782 plerocercoids in the body cavity and by encysted cyclophyllidean cysticercoids are widespread in Central and Southern African fish. *Ligula* infections are very common in *Enteromius* spp. and in the open water cyprinid *Rastrineobola (Engraulicypris) argenteus* Pellegrin, 1904 of Lake Victoria. It also occurs occasionally in cichlids (*Haplochromis* spp. from Lake Victoria, and *Oreochromis* spp. from Israel).

Cyclophyllidean cysticercoids are common in viscera of siluriformes, *Clarias* and *Bagrus* spp., and in cichlids; they have also been reported from *Enteromius* spp. Infections have been reported in the Sudan, in Lake Victoria and the lesser Rift Valley lakes, in Lake Kariba, Zambia, the Niger and in Ghana (Paperna 1996). In recent years, there have been several reports of the non-native *Atractolytocestus* in Africa (Scholz et al. 2015). Although seems it should not be considered a serious pathogen of cultured common carp (Gjurčević et al. 2012) but quick movements of this cestode and potential spillovers, like recent reports in a native fish in

South Africa (Dos Santos and Avenant-Oldewage 2022), are alarming and need more attention and investigations.

Amakali (2019) reported cysts of *Callitetrarhynchus* sp. larvae as well as unidentified tetraphyllidean plerocercoids (metacestodes) from the stomach of marine fish silver kob from Namibia. Larval *Callitetrarhynchus* sp. has been recorded from other fish hosts such as the red grouper (*Epinephelus morio* Valenciennes, 1828, Pisces: Sarranidae) and hake (*Merluccius gayi peruanus* Ginsburg 1954).

24.2.4 Nematoda

Adult and larval nematodes (roundworms) potentially infect all fresh and brackish water fish, with heavier infections occurring in fish occupying higher positions in the food chain, e.g. predatory fish. Nematodes are very distinctive in shape, with a solid cuticle. Because of their resistant cuticle, these worms last longer than flatworms in post-mortem conditions. Most adult forms are large enough to be visible to the naked eye. Khalil (1971) reports 40 species of adult nematodes, representatives of nine families of fish in Africa. The majority occurs in the alimentary system, and only a few enter tissues or inner cavities. The most common nematodes in an aquaculture set-up are *Contracaecum* spp. (in freshwater aquaculture) and *Anisakis* spp. (in Mariculture) both from the family Anisakidae.

The life cycle of nematodes involves crustaceans as transport or first intermediate hosts, fish and cephalopods as secondary intermediate or paratenic hosts and cetaceans, pinnipeds and fish-eating birds as final or definitive hosts (Molina-García and Sanz 2002; Fuentes et al. 2022). Their occurrence can cause a deterioration of fish quality and can be of great concern to human health if ingested in raw or undercooked fish. *Anisakis simplex* parasite species, for example, cause human anisakiasis, a food-borne disease, through the consumption of raw, salted, marinated, undercooked, previously not frozen or conveniently treated fish (Fuentes et al. 2022). Food-borne parasitic infections have been identified as one of the most significant public health problems (Khalil et al. 2014). In addition, inhalation of nematode antigens could also put handlers at risk of developing asthma (Fuentes et al. 2022). Larval nematodes occur either encysted in tissues or free in body cavities, most often in the abdominal or pericardial cavity. Larvae of *Contracaecum* Railliet and Henry, 1912 tend to escape from their cysts and crawl out of their host body after death. Larvae usually emerge from isolated cysts if incubated in 0.9% saline solution at 37 °C. Anisakid larvae are variable in size, often very large and thick, up to 60 mm long and 3 mm in diameter, with characteristic outgrowths (appendices) of either the anterior end of the intestine or the posterior end of the oesophagus (the ventriculum) or both: in members of *Contracaecum* appendices are formed (in opposite directions) from both the ventriculum and the intestine.

24.2.5 Class Hexanauplia, Sub-class Copepoda

Copepods are a group of crustaceans (phylum Arthropoda, subphylum Crustacea). Their life cycle involves a series of nauplius and copepodid stages (Hogans and Trudeau 1989). The time it takes to complete the life cycle depends on water temperature. High temperatures reduce the time it takes to complete the life cycle when compared to low temperatures. Copepods have been reported on cultured and wild fish (Johnson et al. 2004). Some species could be a vector for viruses, bacteria and protozoans and are responsible for most disease outbreaks in cultured systems, having the potential to affect growth, fecundity, the market value of fish products and the survival of their host (Johnson et al. 2004). They are also intermediate hosts for important fish parasites, including tapeworms and nematodes and parasites that infect humans and can serve as vectors of serious human diseases like cholera. The most severe crustacean parasite that may become problematic under intensive aquaculture conditions in Africa is *Lernaea cyprinacea* Linnaeus, 1758, found anchored to the fish's skin *L. cyprinacea*. Infection with this parasite has been associated with reduced host weight, growth and fecundity (Welicky et al. 2017). Other copepods may also attach to gill filaments and cause epithelial hyperplasia and may be indirectly responsible for fish kills (Piasecki et al. 2004).

Members of the family Caligidae and Lernanthropidae are the most reported parasite species on marine fish (Johnson et al. 2004; Rameshkumar et al. 2014). These species are often referred to as sea lice. Caligid copepods generally have direct life cycles consisting of two free-living planktonic nauplius stages, one free-swimming infectious copepodid stage, and four to six attached chalimus stages, one or two pre-adult stages, and one adult stage (Johnson and Albright 1991). Notable exceptions include *Caligus punctatus* punctatus Shiino, 1955 and *C. elongatus* Nordmann, 1832, in which the pre-adult stage is reported not to occur (Kim 1993). With the development of various treatments and management strategies to reduce sea lice infection levels, mortality caused by sea lice has been significantly reduced. Economic losses due to sea lice are primarily from the costs of treatment, the costs of the management strategies, the costs associated with reduced growth rates that are a direct result of infection and/or treatment and the costs of carcass downgrading at harvest (Johnson et al. 2004). The other collected copepod families, such as Lernaeopodidae, Pennellidae, Siphonostomatoida and Tetraodontidae, are also known marine fish parasites (Rameshkumar et al. 2014).

Parasitic copepods feed on host mucous, tissues, and blood and their attachment can become secondarily infected by bacteria and fungi and increase susceptibility to primary diseases. The relationship of the number of parasitic copepods to the severity of the disease is dependent on the size and age of the fish, the general state of health of the fish, the species of copepod and the developmental stages present. The infection rate can become severe and prolonged under poor water quality or crowded conditions (Hecht and Endermann 1998). Copepod parasitic infections are predominantly fatal to early juvenile fish. Infection by parasitic copepods of the mouth has been documented and reported to impair mouth breeding in *Oreochromis* species.

24.2.6 Acanthocephala

Acanthocephala is a phylum closely associated with the Cestoda phylum (Amin 2013). They are an integral component of the parasite fauna of pinnipeds. Acanthocephala is readily recognised by their evaginable thorny anterior proboscis crowned with several rows of recurved hooks that serve as an attachment organ and 'drills' firmly into the walls of the intestines and stomach of the host. In the encased larval stage, in tissues, the spiny proboscis is retracted (Amakali et al. 2022). The attachment with the proboscis causes damage and changes to the tissues exposing the tissues to other secondary infections and increasing the host's susceptibility to diseases and infection (Silva et al. 2014). The number and arrangement of the hooks on the proboscis are the main criteria for the differentiation of species. A wider range of anatomical details determines higher taxa (Kabata 1985). Acanthocephalans lack a mouth and digestive tract. They absorb their nutrients directly through their body surface. Adult acanthocephalans usually live in the lumen of the digestive tract only, but sometimes they bore through the walls of the digestive tract and come to lie in the abdominal cavity (Hayunga 1991). The worms are sac-like, containing lemnisci connected to the proboscis and genital organs opening posteriorly. The sexes are separate, and the male opening is within a membranous bursa. An alimentary canal is absent.

All acanthocephalans develop via one or more intermediate hosts (heteroxenous). Adult acanthocephalans are all gut parasites. Eggs are laid into the intestinal lumen and evacuated with faeces. The first intermediate hosts of piscine acanthocephala are amphipods, isopods, copepods or ostracods. The first larvae, the acanthella (acanthor), hatch from eggs after being swallowed by a suitable invertebrate host. Some species will develop to the adult stage when their larvae in the invertebrate host are ingested by the definitive vertebrate host (Paperna 1996). Fishes can also serve as intermediate hosts, harbouring a second larval stage (the acanthor or cystacanth). Definitive hosts of such acanthocephalans are either predatory fish or piscivorous birds. Pathogenic effects of acanthocephalans are due to the attachment of the adult parasite in the digestive tract and the encapsulation of larval stages in the tissues. In low to moderate infections, pathological effects are localised around the attachment of the adult worm. The extent of damage is proportional to the depth of penetration of the proboscis. It is negligible when parasites are attached to the epithelial mucosa only and becomes extreme, with extensive granuloma and subsequent fibrosis, when the worm's proboscis is anchored in the muscle layer or entirely perforates the intestinal wall (Kabata 1985; Paperna 1996). The depth of penetration of some species may vary in different host fishes. Extensive inflammation, peritonitis due to gut perforation and systemic clinical changes (anurhersia), will occur only in massive infections, most often in farmed fish. Information on infection among fish in

Africa on acanthocephalan is minimal. Halajian et al. (2018) documented a checklist of acanthocephalan parasites in South Africa.

24.3 Control and Treatment of Parasites

Human activities have been shown to be vital in spreading pathogenic diseases in farmed fish. There are several control measures for several diseases that affect aquaculture important species. The most important approach in controlling most diseases is the preventative measures that include good husbandry practices (good water quality, appropriate stocking densities, good feeding regime, removal of predisposing factors and stressors) and vaccination against any possible disease.

There are several considerations before treatment of any type of fish disease can be undertaken:

- Whether the disease is treatable, and the prognosis for successful treatment.
- Feasibility of treating the fish where they are being kept, considering the costs, the effect of handling (stress) and the prognosis of successful treatment.
- The prescribed concentration of the active ingredient of the treatment solution.
- Established regulations related to the type of medications approved, the appropriate withdrawal periods after vaccination before harvesting the fish for human consumption.

Registrations of parasite treatments and chemicals depend on individual countries, and farmers must check what is registered and then use the products according to the labels. There are very few (if any) registered treatments for fish parasites in Africa. In fact, there is no registered treatment for aquaculture fish parasites in South Africa. Generally, the most practicable preventative method of controlling digenean infection in farmed fish is eliminating the vector snail/intermediate hosts. Available measures include the use of chemical molluscicides, environmental manipulation and use of molluscophagous fish. The environmental limits imposed on snail survival in fish farm systems can also involve regular weed control, especially in earth ponds, performed manually or with herbicides (Paperna 1980) that destroy snail populations. Experience with commercial fish farms is still insufficient. One still needs professional advice on the best environmental and stock-friendly herbicide and the best ways to use it.

Likewise, the most common way to avoid nematode infestation is by treating pondwater with an organophosphate to kill all intermediate copepod hosts (Hecht and Endermann 1998). Prevention of larval nematode infection by keeping away piscivorous birds is impractical not only in fishing areas in natural habitats or man-made impoundments but even in fish ponds. In fish ponds, preventive treatments of *Contracaecum* by eliminating copepods may be of some value if suitably timed soon after contamination. The anthelmintic praziquantel (PZQ) was reported to effectively treat a range of flatworm parasites in various fish species and has potential for broader application than its current use in the global aquaculture industry. Norbury et al. (2022) evaluated routes of PZQ administration, along with issues related to palatability, pharmacokinetics and toxicity in fish, and discussed PZQ's effects on non-target species, environmental impacts, and the development of drug-resistance. Although PZQ has been an obvious control measure for platyhelminth parasites in aquaculture, application of PZQ for the treatment of fish for human consumption is only registered for use in several jurisdictions worldwide, for only certain parasites under specific conditions.

The encouraging prospects of aquaculture growth in Africa have not been paralleled with targeted aquatic animal and plant health management and biosecurity measures designed to prevent and control the outbreak of diseases. These aquatic animal and plant health management and biosecurity measures are critical requirements for the sustainable development of the aquaculture industry (Lee and O'Bryen 2003; Delabbio et al. 2005; Eissa et al. 2016). Several African countries have actively adopted and developed aquatic animal, plant health and biosecurity strategies and are signatories to organisations tasked with animal health, such as the World Organization for Animal Health (OIE), while other countries are making strides to apply those measures (FAO 2018). The developed aquatic animal and plant health and biosecurity strategies are using the application of the Progressive Management Plan (PMP) for improving Aquaculture Biosecurity (AB) which is comprised of four progressive stages, is risk-based, proactive and collaborative, and being country-specific (FAO 2007).

24.4 Summary and Discussion

The growth and development of aquaculture (both fresh water and marine) in Africa are still slow compared to other parts of the world, so research into fish diseases and parasites is not a high priority. However, the lessons learnt in the operating aquaculture set-ups should point to the understanding of how imperatively essential it is to build the research and diagnostic capacity in Africa to deal with fish disease problems. A majority of fish losses in African aquaculture are associated with non-infectious causes and can readily be avoided by appropriate husbandry and management techniques (Hecht and Endermann 1998). Chemical therapy of fish is expensive and requires expertise to properly administer and use. There is, therefore, a need to find and investigate alternative treatment technologies and more environmentally friendly forms of treatment. Proper site selection and design of rearing structures can reduce the number of infectious stages that are transported to and/or retained within the rearing environment, as well as ensure that fish stocks remain healthy and thereby more resistant to infection (Johnson et al. 2004). Factors such as water depth, tidal range, patterns of water circulation, flow rate, temperature and salinity have been suggested as important factors concerning parasite infestation.

Control of parasite infestation and infection in culture systems can be done accordingly depending on whether the parasites have direct life cycles or there are intermediate hosts involved. A good management strategy involves keeping intermediate and definitive hosts separate. Early detection and identification of endoparasites could be essential for eliminating susceptible intermediate hosts from the area of fish in tanks, pens, ponds or raceways. Monitoring several fish from each group to assess all parasites and diseases is advised. Infected fishes such as brood stock or fingerlings should not be transported to other facilities. Regular inspection for infestations and infections in each facility could help reduce or end the spread of disease from the culture facility to the facility by fish movements. However, such an application would probably be impractical and cost-prohibitive for marine pens or cages. Moreover, the biodiversity of endemic fauna inhabiting sites below and near containments should be preserved and protected (Johnson et al. 2004). Modifying husbandry practices can be a very effective method to reduce the magnitude of infection by ectoparasites, especially copepods. Using husbandry practices to control ectoparasite abundance requires a good knowledge of parasite biology (e.g. growth rates, duration of survival of infectious stages off-host) and host range (Johnson et al. 2004). As with other infectious diseases, management activities (e.g. stocking density and water quality management) that reduce stress and maintain optimal fish health are likely to reduce the impact of ectoparasites, particularly copepods. In pond culture, overcrowding and poor water quality have been cited as factors responsible for developing ectoparasitic diseases (Hecht and Endermann 1998; Johnson et al. 2004; Stewart 2005; O'Rourke and Rosenbaum 2015; Mogorosi 2019).

Year-class separation is also a very effective technique that has been successfully used, significantly reducing the infection rate of newly introduced juveniles. Following sites prior to restocking can reduce subsequent infection rates, providing that the fallow period is long enough to ensure that all infectious stages have died due to a lack of hosts (Johnson et al. 2004). The effectiveness of these husbandry techniques depends on the absence of wild hosts and/or other infected sites within transport distance for the infectious stages. Frequent cleaning of nets or other techniques that improve water flow through the rearing habitat may result in lower rates of infection, due to improved fish health and removal of infectious stages off-site. Net fouling has been demonstrated to result in the retention of high numbers of naupliar and copepodid stages within net pens. Increased flushing rates of a land-based grow-out facility reduce the level of infection.

24.5 Conclusion and Recommendations

Disease outbreaks and subsequent mortalities caused by parasites in aquaculture set-ups are now rare due to the development of various effective treatments. However, significant economic losses still occur due to reduced feed conversion and growth, indirect mortality, loss of product value and treatment costs. Although it is well understood that parasites have a significant impact on aquaculture, there are relatively few recent published reports of disease and/or disease treatments. Careful site selection and good husbandry practices are a prerequisite to a healthy and parasite-free aquaculture set-up and to prevent parasite outbreaks. The risk of alien and invasive fish and introduction of new parasites (Tavakol et al. 2017) or spillover of already introduced parasites (Dos Santos and Avenant-Oldewage 2022) from them must be considered as potential risks to the aquaculture industry in the continent.

It is of great value that more checklists of different parasites are documented in different African regions to make a baseline of existing parasites in each region to, at a later stage, analyse which parasites can potentially cause economic loss and which cannot. Furthermore, determining which parasite species cannot cause economic loss in insignificant numbers, but if spillover or increase in prevalence and intensity occurs, then, potentially, they can cause economic loss in aquaculture set-ups.

Lastly, there are very few (if any) registered treatments for parasites in Africa. This, therefore, highlights the gap in registering some products in Africa for use in fish culture in future.

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Chapter 25

Interactions Between Pre-harvest, Post-harvest Handling and Welfare of Fish for Sustainability in the Aquaculture Sector

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Abstract Fish and other aquatic products are nutrient-dense and a relatively accessible source of animal protein that transcends various social and cultural norms. The demand for fish has been steadily rising and now significantly outweighs the supply due to the world's acceptance of fish and its products. However, because of their biological makeup and the presence of autolytic enzymes, fish are highly perishable and require careful welfare handling techniques to prevent spoilage. Furthermore, the presence of enzymes and microbes speeds up the rate of fish product spoilage, increases post-harvest waste and lowers the quality of fish products, which could result in foodborne illness if consumed. However, to make fish available for consumption, several processes must be carried out, including feed withdrawal (fasting), air exposure, crowding within the equipment, handling, sorting and loading. The quality and nutritional value of fish products are ultimately determined by these pre- and post-harvest procedures. It is interesting to note that pre- and post-harvest practices are emerging welfare concerns in fish farming that have a significant impact on the productivity of these aquatic products, their shelf life and fish sustainability in the aquaculture industry. The texture and colour of the flesh, an increase in lactic acid production and a decrease in muscular pH are all signs of compromised welfare and the beginning of spoilage during pre- and post-harvest handling activities of fish. This hastens the onset of rigor mortis and spoilage, which lowers the market value and acceptability of these fish products. Beyond pre-harvest and post-harvest, fish slaughtering procedures must be welfare-friendly and stress-free to maintain the texture, colour and appearance of the fish. It is interesting to note that the majority of fish slaughtering techniques have reportedly been found to be inhumane, which has a negative impact on the quality of fish products. Therefore, humane treatment and slaughter of fish products during pre- and post-harvest activities contribute significantly to increasing fish productivity, enhancing

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livelihood opportunities for fish farmers, boosting return on investment, reducing societal malnutrition and achieving fish sustainability along with higher foreign exchange earnings.

Keywords Deterioration · Humane · Handling · Sector · Shelf life · Texture

25.1 Introduction

Fish and other aquatic products constitute an essential component of man's diet. Its consumption cuts across several religious and socio-cultural beliefs, and it is relatively cheaper than other animal sources of protein (Omoare et al. 2013). Rasco et al. (2015) posited that fish provides the most promising animal nutritious source of protein and is also regarded as the most traded food commodity with numerous economic benefits to several people in the world (FAO 2018). Fish and its products supply 19% of animal protein intake to Africans; it also provides several micronutrients and essential fatty acids with long-chain polyunsaturated fatty acids, which cannot be easily gotten from similar food commodities (Bene et al. 2015). Fish and its products further provide a reliable source of income to millions of fish farmers and a means of livelihood for many fish handlers and marketers (World Bank 2017). However, despite the economic, social, and nutritional benefits of fish to society, there is a great concern about the sustainability of the Aquaculture sector in bridging the ever-widening gap between fish demand and the dwindling supply from the capture fisheries (Fig. 25.1).

Interestingly, there is a continuous global increase in the human population (Fig. 25.2a) which translates to an increase in the demand for fish and its products

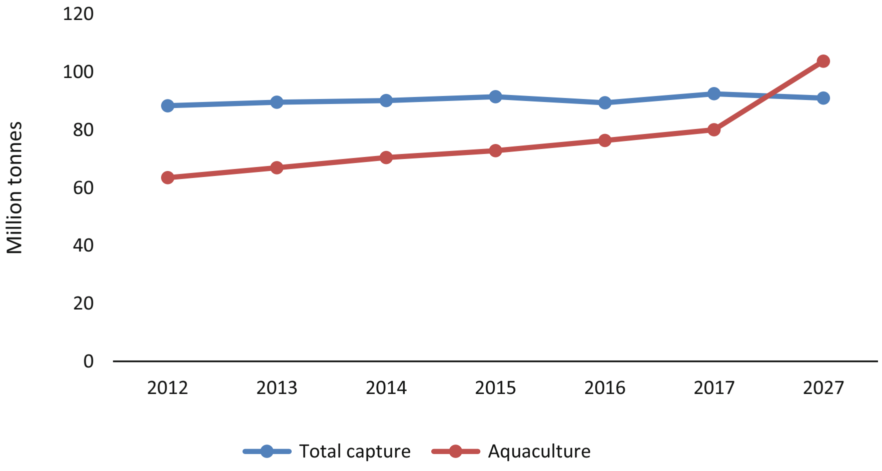

Fig. 25.1 Total fish supply from capture fisheries and aquaculture sector. Source: Food and Agricultural Organization (2020)

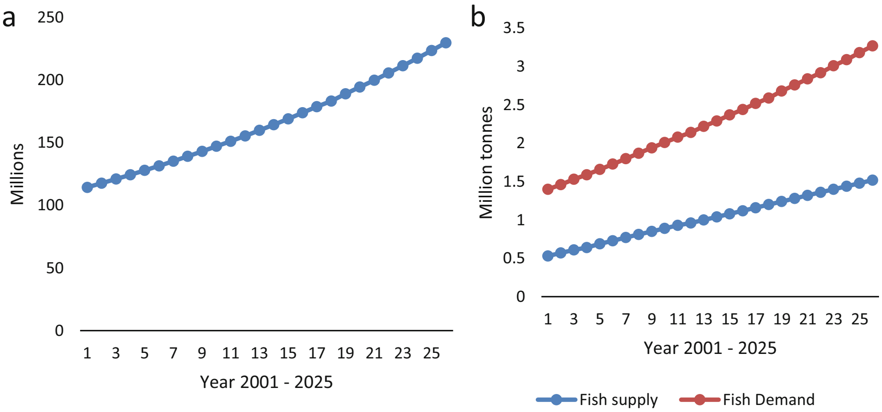

Fig. 25.2 The projected human population in millions (**a**) and global fish demand and supply in million tonnes between 2001 and 2025 (**b**) (Amosu et al. 2017)

that largely outweighs the total supply from the various fisheries sectors (Fig. 25.2b). In addition, the Food and Agriculture Organization (2010) reported that 85% of the world's capture fish stocks are either fully exploited, overfished or have collapsed. Moreover, Ayinla (2012) stated that most capture fisheries are approaching their biological limit, while the global production from the aquaculture sector has quadrupled over the last 20 years. Thus, the Aquaculture sector is considered a viable alternative to meeting the nation's need for self-sufficiency in fish production (Jerimoth et al. 2017). The sector can potentially increase the total domestic fish production for the populace to meet the ever-rising demand for fish products (Harvey 2004; FAO of the United Nations 2006, 2020; OECD/FAO 2017).

The intensive production of fish and other aquatic products in a controlled environment in the Aquaculture sector gives a favourable opportunity to carefully ascertain positive welfare for these cultured fishes for optimum production rate (Håstein 2004; Thant 2019; Martos-Sitcha et al. 2020). Fish species held in a confined environment could be given freedom from stress, discomfort, injury and other associated non-humane handling procedures for higher productivity (Lines and Spence 2012; Daskalova 2019). Ashley (2007) proposed the need to improve the wellbeing and health status of aquatic animals without compromising their welfare to boost the production and survival rate of these cultured fish species under controlled conditions. In addition, the application of welfare-friendly acts in the Aquaculture sector was asserted by Martos-Sitcha et al. (2020) to enhance fish productivity and improve the economic return on investment for the Aquaculturists toward fish food security in the sector.

However, the growing public interest in improving the welfare of fish in the Aquaculture sector stems from both ethical (welfare) and production (fish products) perspectives (Daskalova 2019; Ojelade et al. 2022). Conte (2004) stressed the need to understand the implication of improving fish welfare in the Aquaculture industry. Fish cultured in a stress-free environment will be less susceptible to disease outbreaks which will directly reduce the cost of fish maintenance practices with a reasonable survival rate for a higher return on investment (Toni et al. 2018). The relevance of good welfare in the Aquaculture sector is necessitated to increase fish output from this sector, curb malnutrition in the society, end poverty among the fisher farmers, and ascertain the quality of fish products sold to the consumers (Ashley 2007; Martos-sitcha et al. 2020; Ojelade et al. 2021). Interestingly, Brown et al. (2010) and Rasco et al. (2015) opined that maintaining positive welfare in fish farming alleviates the stressors imposed on these aquatic animals in captivity and exposes them to the freedoms of animal welfare.

Unfortunately, fish are a highly perishable food commodity that spoils soon after death which makes them prone to high post-harvest losses (Akinola et al. 2006). Yalch et al. (2020) stated that a more significant percentage of perishable foods, including fish and its products, is lost or wasted along the fish supply chain. In addition, Getu et al. (2015) categorised losses along the fish supply chain into physical, nutritional and economical to the fish stakeholders. However, over ten million tonnes of fish are lost to post-harvest wastage per year (FAO 2010); it is noteworthy to state that the volume of post-harvest wastage in the fisheries sector serves as a stumbling block to the achievement of fish sustainability. Kabahenda et al. (2009) stated that uncontrolled fish post-harvest wastage directly reduces fish supply, increases the cost of the available fish products and alters the consumers' access to nutritious fish foods.

However, many reported losses in the Aquaculture sector mainly occur during fish handling, transportation and storage activities (OIE 2008; Yalch et al. 2020). Wall (2001) corroborates the need to develop appropriate ethical fish handling, harvesting, transportation, preservation, processing and storage guidelines to boost the relevance of Aquaculture in increasing fish production. However, several welfare concerns are raised about pre-slaughtering and slaughtering procedures within the Aquaculture sector (Southgate and Wall 2001). Thus, it is essential to note that effective fish handling methods will delay fish spoilage keep the quality of fish flesh and other aquatic products and contribute positively to animal protein supply in developing countries (FAO 2010; Rasco et al. 2015).

25.1.1 Fish Spoilage

Fish spoilage is a complicated process of deterioration in the quality of fish flesh caused by bacteria, enzymes and chemical constituents of the fish (Lines and Spence 2012). Immediately fish is harvested from water; death tends to occur at any point in time, depending on the species, temperature, size, lipid content, handling method and available storage facilities (Poli et al. 2002; Ohshima 2005). Moreover, several postmortem changes occur in fish after death which could render the fish products unfit for human consumption. Thant (2019) reported that changes in fish quality are caused mainly by sensory, autolytic, bacteria and hydrolysis activities. These changes alter the odour, appearance, taste, texture and quality of the fish and, in most cases, render the fish products unfit for human consumption and thus classified as post-harvest losses in the fisheries sector. However, Rasco et al. (2015) stressed the need for the application of welfare-friendly procedures to these fish products during handling procedures as strategies for delaying the process of spoilage, deterioration and means of curbing fish post-harvest losses.

25.1.1.1 Fish Post-harvest Losses

Fish losses can be described as a decrease in the quality and quantity of edible fish products that, if permitted to manoeuvre the supply chain, could affect the utility derived by the final consumer. These losses along the supply chain could occur during fish harvest, post-harvest and transportation activities. Moreover, Getu et al. (2015) categorised these losses into nutritional, physical, quality and economic losses. It could lead to post-harvest wastage, a reduction in the prices of these fish products and a low-profit margin for the fish farmer. On the other hand, this post-harvest wastage reduces the quality and nutritional value of fish products (Kabahenda et al. 2009), which gets to the consumers and serves as a threat to curbing malnutrition in society. Thus, the welfare of these aquatic animals should be enforced at all aquaculture production levels. Ensuring stress-free and welfare-friendly harvesting and handling methods would curb the amount of post-harvest wastage of fish (Southgate and Wall 2001).

25.1.1.2 Factors Affecting Fish Spoilage

Temperature plays a significant role in the spoilage rate of fish species; most of the microflora responsible for spoilage in fish multiply rapidly with an increase in the ambient temperature. In the tropics, fish deteriorates rapidly within a few hours after harvesting if not subjected to appropriate preservation techniques (Thant 2019). Valtysdottir et al. (2010) reported that the spoilage rate in fish is directly caused by the enzymatic activities, microbial growth of the fish and lipid oxidation which could alter its nutritional and physical attributes. However, these microbial changes dictate the quality of the fish flesh, colour, appearance and ultimate acceptability of these fish products by the consumers. Thus, it becomes imperative to elongate the period for which the fish products remain safe and fit for human consumption (shelf life) while maintaining their quality until it gets to the hand of the final consumer (Wall 2001). Although fish is generally wholesome and safe, its quality could be contaminated through inappropriate handling methods. Thant (2019) stated that the quality of fish products is directly dependent on the ambient temperature, relative humidity of the air, hygiene of the handlers and technical know-how. Moreover, fish could be further contaminated through exposure to chemicals and other hazards during post-harvest handling, which accelerates the spoilage rate of these fish species (Kabahenda et al. 2009). Improper handling of fish products might cause physical damage such as injuries and loss of fins and other external appendages; this will expedite enzymatic activities and make the fish susceptible to rapid deterioration. Physiologically, a compromise in the welfare of live fish species increases the level of glucose and cortisol in the blood; this results in a rapid decrease in the energy reserve of the fish and an increase in lactic acid production (Poli et al. 2002; Rasco et al. 2015). Thus, it is essential to reiterate the adoption of good welfare by all fish handlers; this is necessitated because most fish consumers have recently indicated their concerns and interest in the slaughtering methods applied in the post-harvest sector.

25.1.2 The Concepts of Fish Welfare

Conte (2004), Broom (2014), Brown (2014) and Sneddon et al. (2018) gave various definitions that described the concept of animal welfare. The definitions of poor welfare can be summarised as the exposure of animals and fish species to stressors which exceeds the coping capacity of the animals. Good welfare could be described as the provision of the most fundamental needs of physical well-being (adequate food, comfortable rearing environments, quality and quantity of water), and the ability to express species-specific behaviours in the presence of conspecifics.

OIE (2008) and EFSA (2009) opined that fish species are sentient beings that can feel pain and distress. Thus, the sentience nature of fish could be regarded as the first prerequisite that calls for the application of good welfare in the Aquaculture sector. Subjecting these fish species to compromised welfare or handling procedures could lead to an alteration in their behaviour, stress-related physiology and ultimately death. Håstein (2004) defined the welfare of fish as the measurable traits in the objective condition of the fish (function-based), subjective experience of the fish (function-based) and the ability of the aquatic animal to live a natural life within its aquatic ecosystem (nature-based). Kristiansen and Juell (2002) further described the welfare of farmed fish as the extent to which a fish can adapt to its rearing conditions and find the same rewards. Thus, the ‘five freedoms’ approach attempts to summarise the welfare of the cultured fishes in the aquaculture production system and post-harvest sector (Webster 2001; Ashley 2007). The United Kingdom Farm Animal Welfare Council (FAWC 2012) proposed these ‘five freedoms’ as follows:

1. **Freedom from Hunger and Thirst**: Aquatic animals in a confined rearing environment should have equal and optimum access to quality and quantity diets and water to maintain health and perform all basic life activities. In addition, this freedom from hunger and thirst should be enjoyed by fish during harvesting and transportation until the point of slaughtering and death. Consequently, feed withdrawal before harvesting should be kept to the barest minimum, while live transportation of fish in containers and bowls without water, which is commonly practised by fish farmers (Plate 25.1), is a procedure that compromises the welfare of these fish species.

Plate 25.1 Fish exposure during post-harvest activities before transportation Source: Field Survey, 2022

2. **Freedom from Discomfort:** Cultured fishes should be reared in a suitable living environment, free from discomfort or aches. At harvesting, the use of inappropriate gear due to its availability and cost-effectiveness is highly discouraged to prevent exposure of the harvested fish to unnecessary discomfort (Sneddon et al. 2018). Transportation bowls and containers should not be too small for the size of fish being transported while over-stocking the fish in such small bowls during transportation puts these fish in a stressful condition and a form of discomfort that they should be free from.
3. **Freedom from Pain, Injury or Disease**: Aquatic lives kept in a captive culture environment should not be made to suffer from pain, wounds or disease. However, rapid diagnosis and treatment of fish species can be employed when a disease outbreak occurs (Chandroo et al. 2004). Over-crowding and over-stocking of fish in gears and transportation bowls during harvesting and transportation should be strictly avoided to make these aquatic animals free from pain and injury. These post-harvest procedures pose a form of pain to these fishes. Moreover, Martos-Sitcha et al. (2020) reported an increase in the stress level of fish species during transportation which could increase aggressive acts, injury and susceptibility to disease outbreaks.
4. **Freedom to Express Normal Behaviour**: Different facilities should be provided for aquatic lives to ascertain their ability to express their natural behaviour. A good rearing space equipped with adequate facilities and other conspecifics should be made available to encourage the display of their natural behaviours and eliminate stress or discomfort (Ojelade et al. 2022). On the other hand, during transportation, the provision of convenient and spacious transportation containers

filled with water will make the live fish feel at home and express normal behaviour.

5. **Freedom from Fear and Distress**: All living conditions for cultured fishes should not expose them to mental suffering or stress. Pre-harvest, harvest and post-harvest activities should not impose any form of fear on these aquatic lives. Sudden and prolonged air exposure during harvesting and transportation activities could expose the fishes to fear and distress, which might alter the behaviour and physiology of the fishes and, subsequently, the quality of the flesh of the fishes (Poli et al. 2005).

Thus, fish are considered animals that could feel pain and any other form of discomfort in their environment. Certainly, a compromise in the welfare of fish represents the most significant factor affecting fish sustainability. Therefore, aquaculturists and other fish handlers should give these aquatic animals the listed five freedoms while handling the fish, during harvesting, transportation and slaughtering to maintain good welfare, increase productivity and deliver quality fish products to the consumers.

25.1.3 Fish Harvesting

The harvesting of fish encompasses a series of activities or processes necessitated to remove cultured fishes from water with the use of several harvesting equipment and fishing gears. Poli et al. (2005) categorised the harvesting procedure as a traumatic period for fish species, affected mainly by its duration, intensity and struggle during harvesting. The fish being harvested swim continuously within the gear in an attempt to escape, which increases the production of glucose and other stress hormones in fish. However, fish harvesting is a compulsory procedure since all fin and shellfish cultured in a confined environment are ultimately removed from their rearing facilities for human consumption, either as food or for other purposes. Consequently, harvesting requires adequate technical know-how to aid the survival of the fish species, maintain their quality for the consumers and reduce the quantity of fish lost to the post-harvest sector. Unfortunately, Gustavsson et al. (2011) reported that about 35% of fish landings from the different fisheries sectors are lost to post-harvest wastage. Thus, it is essential to adhere to welfare-friendly acts during the handling, harvesting and slaughtering.

25.2 Fish Post-Harvest Activities

During harvesting, fish species are subjected to various activities such as feed withdrawal (fasting), air exposure, crowding within the gear, handling, sorting, loading, offloading, storage and transportation (EFSA 2009). These activities directly dictate the survival rate of live fish for marketing, the quality of the fish products and the final economic value derived from these fish products. Thus, it is essential to review the application of welfare procedures to these activities to increase the nutritional and socio-economic benefits derived from these sustainable aquatic products.

25.2.1 Feed Withdrawal

Fish species often have several hours of starvation or fasting before handling, harvesting or transportation procedures. This fasting is necessary to empty the fish's gut before harvesting, to reduce the activities of the bacteria in the gastrointestinal tracts and to minimise the build-up of metabolic wastes and ammonia and subsequent spoilage rate (Lines and Spence 2012) during these handling and transportation procedures. However, this entire process and period of starvation should be kept to the barest minimum to prevent a compromise in the welfare of the fish species (Ashley 2007). Lemieux et al. (2004) reported the consequence of prolonged starvation on fish growth, muscle protein and fat composition, while Martinez et al. (2003) asserted that prolonged starvation could lead to reduced nutrition, changes in metabolic activity and increased aggression. Fishes should not be starved for more than 72 h in an attempt to empty their gut content before harvesting or transportation activities (Poli et al. 2005; Robb 2008). Webster (2001) categorically stated that excessive period of feed withdrawal from fish species causes an infringement of the principles of the five freedoms of animal welfare. Moreover, feed withdrawal during harvesting poses welfare threats that could lead to weight loss, aggressiveness, cannibalism and physical injuries that lower fish quality, acceptability and risk of mass mortality (Southgate and Wall 2001). Thus, starving (feed withdrawal) of fish should be done only when there is a full assurance that harvesting will take place soonest in order not to impose continuously and repeated suffering on these aquatic animals.

25.2.2 Air Exposure

Fish and other aquatic animals are poikilothermic, and thus their body temperature is dependent on the ambient temperature. During harvesting, the water level in the rearing facilities is reduced, and fishes are exposed to air temperature, which might be prolonged due to unnecessary delay in the harvesting procedure (Plate 25.2); this has an excellent welfare implication for these animals since they are no more in their natural aquatic environment. Thus, immediately after the water level in the rearing ponds is lowered, live fish meant for transportation should be transferred to containers filled with water to prevent undue air exposure. HSA (2005) reported that all harvesting processes should be rapidly and humanely done without further stressing

Plate 25.2 Cultured fishes exposed to atmospheric air in a concrete tank prior to harvesting (Ogunsina 2017)

the fish to prevent prolonged suffering or discomfort to fish species. Poli et al. (2005) opined that exposure of fish to asphyxia is not humane since it poses a deleterious effect on the flesh, quality and shelf life of the fish. Consequently, the period of exposing fish to air during handling should be greatly reduced to limit the risk posed to the welfare and health of this aquatic fauna.

25.2.3 Crowding Within the Gear

Prolonged exposure of fishes to crowding within the harvesting equipment has several welfare implications for the fish. This unnecessary delay and exposure to poor holding conditions within harvesting gears are caused mainly by inadequate preparation by the aquaculturists and fish handlers for the harvesting process. Lines and Spence (2012) categorised fish crowding as a principal act that imperils the welfare of cultured fishes. Crowding within gear results in many fish species competing for limited dissolved oxygen within the given space, thus making breathing difficult for the fish (Plate 25.3). Brown et al. (2010) asserted that prolonged crowding of fish within gear could lead to an inflation of swim bladders in some fish species. However, an undue extended period of crowding within the gear is a dangerous post-harvest activity that makes the aquatic animals susceptible to disease, and this might lead to asphyxiation, suffocation, stress, physical damage, bruises, injuries and damage to the flesh and fins of the fish (Poli et al. 2005). All of these affect the physical and economical value of the fish products and the satisfaction derived by the consumers.

Plate 25.3 Crowding of harvested fish within the harvesting equipment. Source: Personal Survey, 2022

25.2.4 Handling

All harvested fish should be handled on clean surfaces and with clean hands and materials to prevent increased bacteria load on the flesh and skin of these aquatic animals. Any form of unhygienic handling (Plate 25.4) could reduce the shelf life of the fish and accelerate the rate of fish spoilage. Moreover, Thant (2019) noted the relevance of the hygienic handling of Aquaculture fishes during post-harvest activities. Thus, humane handling of fish requires continuous contact with uncontaminated surfaces and hands to delay the spoilage rate of these aquatic animals. Furthermore, fish species should be cleaned of all attached mud and dirt before applying either high- or low-temperature preservation techniques.

25.2.5 Sorting

Fish sorting during harvesting should be done rapidly to prevent additional stress on the aquatic animals. They should be sorted into species and sizes before subjecting the fish to low- and high-preservation techniques or even sold live to the marketers (Plate 25.5). Fish physically injured, with bruises and bleeding, should be rapidly removed from the harvested fish. Any delay in these activities could lead to quality deterioration and subsequent spoilage rate, causing an increase in post-harvest wastage.

Plate 25.4 A grubby cargo area of pick-up trucks used for live fish transportation. Source: Personal Survey 2022

Plate 25.5 Sorting of live fish into sizes prior to transportation

25.2.6 Loading and Off-Loading

The welfare of harvested fish should not also be compromised during loading and off-loading activities before and after the transportation procedures. Fishes have

Plate 25.6 Loading of live fish cultured in earthen ponds prior to transportation. Source: Personal survey 2022

been earlier stressed during feed withdrawal and other harvesting procedures, so it is very important to minimize the level of stress at this stage of post-harvest activities (Plate 25.6). Their welfare should be prioritized, and they should be kept in water during transportation to gain some level of energy before off-loading activities.

25.2.7 Transportation

Fishes should be transported as fast as possible to relieve the fish from the stress of confinement in bowls and other transport containers. It is essential to state that every form of delay in the transportation process could increase the level of mortality in the fish being transported. Transportation of live fish should be done with water in their transportation containers or bowls. These transportation facilities should be welfare-friendly, and they should permit water quality monitoring and an avenue to replace the water during long periods of transportation when necessary. These are ways of improving the welfare of fish and eliminating the stress that could increase mortality during fish transportation. Transportation of live fish in bowls and containers without water should be discouraged among fish handlers, this method imposes stress on the fish, and their welfare is highly compromised.

Interestingly, all pre-harvest, harvest and post-harvest activities in the Aquaculture sector can be controlled and the entire process pre-determined. Controlling the time, conditions of harvest, harvesting types of equipment and use of well-trained handlers will go a long way in ascertaining the welfare, quality of the fish flesh and invariably the consumers' acceptability, economic and market value and the return on investment to the aquaculturists.

25.3 Fish Slaughtering

Fish slaughtering is usually in three stages, and it involves pre-harvest activities which have been dealt with, the stunning and eventual killing of the fish. Stunning of fish involves activities that render the fish unconscious within the period of slaughtering or killing. Moreover, stunning fish can be achieved through immediate and gradual loss of sensibility (Rasco et al. 2015). The latter method is not welfare-friendly as the fish are exposed to slow and continuous prolonged torture until death. Fish are sentient animals that have the cognitive ability to feel pain and discomfort, which necessitates the importance of ascertaining the welfare of these fish species. Thus, their slaughtering should be humane and stress-free. At slaughter, maintaining the welfare of fish is necessary through the application of humane slaughtering procedures, which entails that fish should be carefully handled and rapidly stunned to initiate an immediate loss of sensibility before bleeding (Southgate and Wall 2001; Van de Vis et al. 2003). Interestingly, the most practised and available slaughtering methods used by fish handlers do not meet these requirements of immediate insensibility.

Although the commonly available methods of killing fish were chosen due to their ease of application and cost-effectiveness, they include asphyxiation in air or ice, depriving fishes of oxygen in a covered container, cutting live and removal of gills without stunning (evisceration), use of complex objects on the head, use of salts in a covered container and being processed alive are non-humane crude methods of fish slaughtering (Robb and Kestin 2002; Robb et al. 2000; Ogbonna et al. 2017). These listed slaughtering procedures impose immense suffering on these aquatic animals since the methods do not involve immediate loss of sensibility. Specific rules and guidelines to uphold the welfare of this aquatic fauna, such as the appropriate humane slaughtering methods, should be adopted by all fish handlers (Southgate and Wall 2001; Wall 2001; Poli et al. 2005; HSA 2005). Fish at slaughter should be stunned, and the blood drained almost immediately to improve their welfare and the quality of the fish products for the consumer. Ideally, fish should be kept in water until death; however, when this is not affordable, fishes should not be exposed to air for more than 15 s to curb aversive behaviour in these aquatic animals (HSA 2005). The use of percussive (automated flow-through system) and electrical (electrified water) stunning methods makes the fish lose its sensibility almost immediately, which is the best way to safeguard the welfare of these aquatic animals and improve their flesh quality (Kristiansen and Juell 2002). Lines and Spence (2012) stated that the quality and taste of fish flesh reduce with increased stress during pre-harvest, harvest and post-harvest activities, which often affects consumer acceptability of the products. Thus, necessary equipment for large-scale and effective stunning fish should be made available to the fish handlers in the local and regional marketing arenas.

25.4 Conclusion and Recommendation

Providing a welfare-friendly procedure in rearing, harvesting and post-harvest activities should be adopted by all because it is a two-edged sword that improves the quality of the fish while also increasing the economic benefits derived by aquaculturists. Harvesting techniques should be free of stress, with no delays, overcrowding within the gear, or asphyxiation. Aquaculturists should embrace modern harvesting techniques while slaughtering methods should render the fish insensible before stunning and bleeding. To immediately put the central nervous system to sleep, stunning should be performed quickly. In the Aquaculture sector, innovations such as an automated killing machine incorporating welfare-friendly practices to cause the fish to die before regaining consciousness from stunning are recommended. Fish handlers at the pre-harvest, harvest and post-harvest levels must be trained and retrained to fulfil their responsibilities as fish caregivers. Continuous research should identify welfare-friendly handling and slaughtering methods for cultured fish.

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Chapter 26
Alternative Fish Anaesthetics: Perspective on their Application in African Aquaculture and Fisheries Research

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Abstract This chapter reviewed herbal agents and nonchemical methods of anaesthetizing fish in aquaculture, as well as the prospects for their application in African aquaculture and fisheries operations and research. For intensive aquaculture, more handling and transportation are required. These activities may cause stress and physical harm to the fish, putting their well-being at risk. Anaesthetics are frequently used to immobilize fish during handling and transport, reducing stress, and the risk of physical injury. Anaesthesia can be either synthetic or natural. Nonchemical methods of anaesthetizing fish are also available. Synthetic anaesthetics (i.e. phenoxyethanol, benzocaine, tricaine methanesulfonate, MS-222, and quinaldine) are deemed unsustainable due to their high cost, unavailability in most African countries, and negative effects on the physiology of farmed fish and the environment. As a result, several herbal extracts example essential oils from *Eugenia aromatica*, *Aniba rosaeodora*, *Cinnamomum camphora*, and *Lippia alba* have been reported to induce anaesthesia in fish. The same was reported for nonchemical agents (such as carbon dioxide, sodium bicarbonate, electroanaesthesia, and lower temperatures). Because these alternative anaesthetics are less expensive and readily available, they may be preferable to synthetic anaesthetics in African aquaculture and fisheries research. More research is needed, however, to optimize different alternative anaesthetics in aquaculture, so that fish welfare is protected during operation and research.

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26.1 Introduction

The human population is rapidly increasing, and there is an increase in demand for animal protein to feed the growing human population (Gjedrem et al. 2012). Fish contributes significantly to the total animal protein consumed by humans worldwide. As a result, the demand for fish protein is increasing. Captured fisheries have reached their peak, and no increase in production is expected due to the overfishing of fish species (Maani 2017). Meanwhile, aquaculture has grown rapidly over the years, filling the void left by the fish protein demand (Subasinghe et al. 2009).

Aquaculture's rapid expansion has been largely attributed to increased finfish intensification and seaweed production (Kumar and Engle 2016). Intensive farming is associated with handling and transporting activities that can lead to stress (Rehman et al. 2017). Stress negatively impacts fish's immune systems, making them vulnerable to diseases (Tacchi et al. 2015). Stress is harmful to animal welfare and production and should be avoided during operations (Kibenge 2019). Fish welfare is a critical issue for the aquaculture industry because it influences production and public perception (Ashley 2007). Research into the handling and transportation of live fish for increased commercial viability is critical for protecting the welfare of farmed fish and improving production (Bodur et al. 2018). However, there are challenges between welfare and production in several areas, including handling and transportation, which appear to be associated with lower individual fish welfare when not practised ethically (Ashley 2007). In recent years, such practices have received a great deal of attention and debate.

Anaesthetics are used to reduce stress and the risk of physical injury, thereby aiding in the preservation of animal welfare during handling and transportation (Zahl et al. 2012). Anaesthesia is a recommended tool to be used during fish handling, transportation operations, and fisheries research (Hoseini et al. 2019). Anaesthesia can be defined as the biological condition in which sensation, responsiveness, and voluntary neuromotor control are lost through the application of a chemical or nonchemical agent (Summerfelt 1990). Anaesthesia reduces the stress and likelihood of physical injuries during stressful events. Reduced stress and physical injuries are a steppingstone to preserve the welfare of fish during stressful events. During anaesthesia, fish feel less pain and become more relaxed. As a result, anaesthesia can be used to safely handle, transport, and work on fish (Martins et al. 2019).

Several synthetic agents are used in aquaculture and fisheries research to anaesthetize fish. 2-phenoxyethanol, benzocaine, tricaine methanesulfonate (MS-222), and quinaldine are examples of synthetic agents commonly used to aanesthetize fish (Martins et al. 2019; Ross and Ross 2009). The United States (U. S) Food and Drug Administration (FDA) has only approved MS-222 for use in fish for human consumption (Huang et al. 2010; Topic Popovic et al. 2012). This is a similar approach taken by countries such as Spain, Italy, the United Kingdom, and

Norway. Other synthetic agents are only approved to be used for research purposes. Synthetic agents are prohibited due to safety concerns, while natural agents are more developed and are expected to have a bright future (Coyle et al. 2004). Synthetic anaesthetics have been reported to have adverse impacts on the physiology of the fish, the user, and the environment (Coyle et al. 2004). As a result, synthetic anaesthetics are termed unsustainable. Alternative methods of anaesthetizing fish, such as the use of herbal products and nonchemical methods have been studied and documented.

Several studies and reports on the efficacy of herbal products have been conducted. Several herbal products have been investigated with the aim to replace unsustainable synthetic anaesthetics. As a result, herbal products have been studied and discovered to possess anaesthetic properties in different fish species. This chapter reviewed herbal agents and nonchemical methods of anaesthetizing fish in aquaculture, as well as the prospects for their application in African aquaculture and fisheries operations and research.

26.2 Herbal Extracts as Anaesthetics in Aquaculture

Herbal extracts are gaining popularity among researchers as potential anaesthetics for fish. This is because commonly used anaesthetics such as tricaine methanesulphonate (MS-222) (Skår et al. 2017), 2-phenoxyethanol (Ghanawi et al. 2013), and etomidate (Readman et al. 2017) are either prohibitively expensive, unavailable, particularly in Africa, or have been linked to adverse side effects in fish such as stress and haemorrhagic disorders (Gressler et al. 2014). Essential oils and their constituents (such as carvone, myrcene, linalool, menthol, cineole, and eugenol) are herbal extracts that have been extensively researched as anaesthetics (Hoseini et al. 2019). These substances have been shown to have not only hypnotic or sedative effects on fish but can also be toxic (Purbosari et al. 2019). *Eugenia aromatic* clove oil is an effective herbal anaesthetic for fish (Purbosari et al. 2019). Clove oil is rarely used as an anaesthetic due to its low therapeutic index. The reason for this is that even slight changes in dosage have the potential to kill or prevent fish from recovering (Kamble et al. 2014).

The investigation of herbal extracts as potential anaesthetics in aquaculture was broadened to include other herbs. For example, essential oil extracts of rosewood (*Aniba rosaeodora*) and camphor (*Cinnamomum camphora*) at 300 lL1 were reported to have effectively anaesthetized goldfish (*Carassius auratus*) without any adverse effects. *Lippia alba* essential oils at 200–300 mg/L anaesthetized tambaqui (*Colossoma macropomum*) in less than 4 min. *Lippia alba* chemotypes (citral and linalool) were able to cause anaesthesia in silver catfish (*Rhamdia quelen*) without affecting their physiological functions (de Freitas et al. 2018). Thymol and carvacrol caused sedation at 25 mg/L and anaesthesia at 50–-100 mg/L in the same fish (Bianchini et al. 2017). *Aloysia triphylla, Ocimum americanum*, and *L. alba* have also been shown to be effective anaesthetics in Nile tilapia (*Oreochromis* *niloticus*) (Teixeira et al. 2017; Rucinque et al. 2021), citronellal, linalool, and myrcene in common carp (*Cyprinus carpio*) (Mirghaed et al. 2016; Yousefi et al. 2018), *A. triphylla in* catfish (*Lophiosilurus alexandri*) (Becker et al. 2017), *Eugenia cayrophyllata* in African catfish, (*Clarias gariepinus)* (Adeshina et al. 2016), and *Eucalyptus globulus)* and *Origanum vulgare* in silver kob (*Argyrosomus inodorus*) (Gabriel et al. 2022). This finding provides a solid foundation for African aquaculture researchers and farmers to build on as they explore the use of herbal extracts as anaesthetics in fish farming and fish management. Herbal extracts, in particular, are a better option for African aquaculture because they are effective, have few side effects, are widely available, cost less money, and may act as immune boosters, antioxidants, and anti-stress agents, and antimicrobial agents (Hoseini et al. 2019).

Furthermore, *Aloysia triphylla* (40–50 mg/L), *Lippia sidoides* (20–50 mg/L), and *Mentha piperita* (40–90 mg/L) induced anaesthesia in *C. macropomum*. However, at higher doses, these essential oils may cause severe damage to the fish, including gill fibrosis and necrosis, hypertrophy and hyperplasia of the lamellar epithelium, lamellar fusion, and chloride cell proliferation (Brandão et al. 2021). Similarly, Bianchini et al. (2017) discovered higher mortality when silver catfish were exposed to monoterpenoid (carvacrol). This is a clear indication that these products in aquaculture need to be optimized to ensure they are not harmful to the fish. Moreover, it appears that the anaesthetic mechanism of essential oils and their constituents is reasonably well understood. According to Manayi et al. (2016), essential oils induce anaesthesia due to their lipophilic nature, which allows them to easily penetrate cell membranes and influence brain functions by interacting with the gamma-aminobutyric acid receptor, GABA (inhibitory neurotransmitter) (Zahl et al. 2012; Manayi et al. 2016). In other words, essential oils may influence the swimming behaviour and state of consciousness of fish by increasing the activity of the GABA receptor, as demonstrated in *R. quelen* after exposure to carvacrol and thymol (Bianchini et al. 2017). However, more research is needed to determine how different essential oils and their chemotypes induce anaesthesia in various fish species.

26.3 Nonchemical Methods

26.3.1 Carbon Dioxide

Carbon dioxide gas (CO_2) is potentially alternative nonchemical method of anaesthetizing fish in aquaculture and research. It was first described by Fish (1943) as a potential anaesthetic for fish. Carbon dioxide can be delivered in two ways, the first method involves directly blowing carbon dioxide gas in water and the second method is dissolving sodium bicarbonate ($NaCO_3$) in water. The advantage of carbon dioxide is that it does not leave any residues in the flesh of the fish after exposure and has no secondary effects on the handler and the environment (Gilderhus and Marking 1987). Furthermore, carbon dioxide method is cheap to administer compared to chemical anaesthetics that are generally expensive (Fish 1943). However, the method of using CO_2 has some shortcomings such as the reduced efficiency to induce deep anaesthesia observed by Gilderhus and Marking (1987) and the acute and transient experience of hyperactivity in fish possibly caused by the acidification of water. Gilderhus and Marking (1987) also observed the recovery time of fish exposed to CO_2 to be long. Unbuffered CO_2 is reported to cause an increase in the stress indicators such as blood adrenaline and cortisol concentrations (Iwama et al. 1989). A range of 200 to 500 mg CO_2 concentration is recommended for anaesthetizing salmonids (at pH 6–9 and 12 °C) (Gilderhus and Marking 1987).

Sodium bicarbonate ($NaCO_3$) releases carbon dioxide (CO_2) gas in the water column which suffocates fish and make them temporarily unconscious (Gelwicks et al. 1998; Peake 1998; Opiyo et al. 2013). Sodium bicarbonate has been reported to be effective at inducing anaesthesia in various fish species such as *Oreochromis spp.* (Charo-Karisa et al. 2013; Opiyo et al. 2013; Avillanosa and Caipang 2019; Gabriel et al. 2020; Hasimuna et al. 2021; Haihambo and Gabriel 2022; Siavwapa et al. 2022), *Cyprinus carpio* (Altun et al. 2009; Bahrekazemi 2018), *Clarias gariepinus* (Githukia et al. 2016), *Liza parsia* (Sonawane and Kulkarni 2001), *Hippocampus kuda* (Pawar et al. 2013), ornamental fish (Caipang et al. 2021), *Rutilus kutum* (Babaiinezhad and Bahrekazemi 2019), and nonsalmonid fishes (Peake 1998). A recent report by Peake (1998) reported that sodium bicarbonate is more effective when combined with acetic acid (CH_3COOH). This is because, sodium bicarbonate alters the pH of water which continues to stress fish after exposure, but when combined acetic acid, it neutralizes the pH. The effectiveness of the combined method is not compromised, and it remains effective. Haihambo and Gabriel (2022) have exposed the combination of sodium bicarbonate and acetic acid to *Oreochromis andersonii* fingerlings and reported induction and recovery time within 3 min, respectively, at all concentrations used.

Carbon dioxide has a potential to be used as an anaesthetic in fish; however, best methods to administer this gas are deemed necessary in both freshwater and marine fish (Iwama et al. 1989). There are limited studies that have reported CO_2 as a possible fish anaesthetic tool. Further studies are recommended to determine other possible impacts these methods may have on fish before it can fully be advertised for large scale operations.

26.3.2 Electroanaesthesia

Electroanaesthesia is a method commonly used to immobilize and capture fish for research and broodstock purposes (Cowx and Lamarque 1990; Reynolds 1996). This method uses electricity to produce a shock that temporarily paralyses fish, making it easy to work with them. There are three types of electric currents that are utilized to immobilize fish, and these are alternating current (AC), direct current (DC), and pulsating forms of AC and DC. These methods have different mechanisms of action.

Direct current is reported to possibly cause anodotaxis, electronarcosis, and electrotetany. Alternating current is only reported to cause electronarcosis. The main advantages of electroanaesthesia are that it does not leave any resides in the flesh of the fish, it is environmentally friendly, it produces a rapid induction of anaesthesia and recovery, and has a low operating cost (Ross and Ross 2009).

This method has reduced long-term effects if the method is used appropriately. It causes minor physiological impacts in fish such as those observed in *Labeo rohita* (Chakraborty et al. 2022). Electroanaesthesia has been concluded by (Reid et al. 2022) to be as effective at inducing anaesthesia as synthetic anaesthetics such as MS-222 and thus can be used as an alternative method. However, wild fish exposed to electroanaesthesia seem to be more susceptible to predators (Schreck et al. 1976). Electroanaesthesia induces immediate elevation in plasma corticoid and lactate concentrations. This has been reported in study that exposed rainbow trout to electroanaesthesia (Madden and Houston 1976). Plasma glucose levels and cardiovascular rates were also reported to increase after exposure to electroanaesthesia. The effectiveness of electroanaesthesia depends on several factors such as the water conductivity, temperature, fish size, and species. In the past, alternating current was mostly used over direct current. It was later found that alternating current has an adverse damage to the fish compared to the direct current (Madden and Houston 1976; Ross and Ross 1984).

26.3.3 Hypothermia

Hypothermic anaesthesia uses a cooling effect to sedate fish (Erikson et al. 2006). This is because when temperatures are higher than 10 °C, hypothermic anaesthesia is less effective. However, deep induction cannot be achieved using this method of anaesthesia, unless coupled with a chemical anaesthetic (Mittal and Whitear 1978). Hypothermic anaesthesia induces light sedation characterized by an absence of motion, reduced power of exertion, and diminished nerve sensitivity (Hovda and Linley 2000). It can be achieved when temperature is changed to near 0 °C by immersing fish in crushed ice or ice water (Summerfelt & Smith 1990). This is only applicable for transporting fish but not for invasive activities such as surgery due to its inability to induce deep anaesthesia. Hypothermia provides an alternative method when chemical anaesthetics are not desirable. It has reduced impacts on the fish, the handler as well as the environment and it is relatively cheap.

26.4 Conclusion and Perspectives

Synthetic anaesthetics are being phased out in favour of more sustainable alternatives. This is to achieve the goal of preserving the welfare of the animal during operations while maintaining the aspect of sustainability and achieving maximum production. Herbal anaesthetics are inexpensive and simple to use, but they are just as effective as synthetic anaesthetics. They may be very suitable in African aquaculture and other developing countries. Nonchemical methods are also available and can be used in conjunction with other anaesthetics to achieve deep induction. However, more research on fish species using these methods is recommended in order to determine specific species safe limits. Furthermore, there have been few studies that looked at the combination of nonchemical methods such as hypothermia and carbon dioxide with herbal products. There are recommendations in the literature to combine these nonchemical methods with synthetic agents that are not sustainable. As a result, research in this field is advised. Most essential oil mechanisms of action are not fully understood, and more research is needed to address this issue. Analgesic essential oils, such as clove oil, are used in human dentistry. It is recommended that essential oils be studied for their analgesic properties, which are critical in blocking pain in fish during invasive activities.

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