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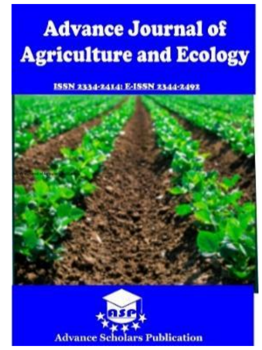

AQUACULTURE'S INNOVATION QUANDARY: ADDRESSING TECHNOLOGY DEFICITS AND EMPHASIZING FISH INTESTINAL MICROBIOTA RESEARCH IN AFRICA

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Keywords: *Aquaculture Technology, Rural Innovation, Sustainable Development, Technology Adoption, Rural Empowerment.*

Abstract: *Technology, characterized as a strategic design to mitigate uncertainty in the causal relationship between action and outcome, comprises both hardware and software components (Rogers and Shoemaker, 1992). This definition encapsulates the essence of technological advancements, particularly within the aquaculture sector, where these innovations hold the promise of transformative opportunities for rural communities (Chattopadhyay, 2017). Despite the prevalence of low-tech farming practices in developing nations, the adoption of advanced technologies in aquaculture remains a formidable challenge. The effective assimilation of modern technologies into aquaculture operations not only addresses this challenge but also serves as a catalyst for industry-wide innovation (Chattopadhyay, 2017). This study delves into the intricate dynamics of technology integration in aquaculture, focusing on its potential to revolutionize rural economies and foster sustainable development. The juxtaposition of traditional farming practices and cutting-edge technologies presents a unique opportunity to bridge existing gaps and enhance the overall efficiency and productivity of aquaculture operations. The inherent challenges associated with embracing new technologies in resource-constrained environments require a nuanced understanding of the socio-economic factors influencing adoption patterns. By examining the evolving landscape of technology adoption in aquaculture, this research aims to shed light on the transformative potential of modern technologies in rural communities. The study considers the implications of technological integration for industry innovation, economic growth, and the empowerment of rural populations engaged in aquaculture activities.*

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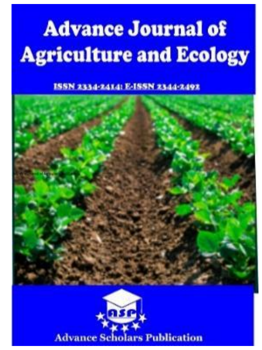

INTRODUCTION

Technology is defined as a design for instrumental action to reduce uncertainty in the relationship between cause and effect (Rogers and Shoemaker, 1992). It comprises two components: hardware and software. In the aquaculture sector, technological advancements have presented greater opportunities for rural populations (Chattopadhyay, 2017). Despite the prevalence of lowtech farming operations in developing countries, embracing advanced farming technologies remains a challenge. Effective integration of modern technologies into aquaculture production can serve as a platform for industry innovation (Chattopadhyay, 2017).

The intestinal microbiota is recognized as a vast and intricate ecosystem within the body, constituting a "superorganism" (Amenyogbe et al., 2021). As indicated by existing literature, environmental factors, physiological state, and genetic factors can induce changes in the intestinal microbiota of fishes (Yang et al., 2021; Jin et al., 2017). Variations in the feeding habits of aquatic animals contribute to differences in fish intestinal microbiota (Ma et al., 2019a). The recent deficiency of modern technology for studying fish intestinal microbiota in sub-Saharan Africa has led to subpar fish production. Furthermore, studying fish microbiota holds significant implications for human health, as many fish species are vital food sources in Africa and globally.

The literature shows that several studies have utilized various modern technologies to investigate fish intestinal microbiota (Chen et al., 2019; Liu et al., 2019; Jiang et al., 2019; Parshukov et al., 2019; Zhang et al., 2020). These modern technologies aid in the identification, visualization, and characterization of microbial communities within the fish gut. There is a compelling need for advanced technologies in Africa to facilitate the study of fish intestinal microbiota, a pivotal field of research. To provide a comprehensive overview of disruptive and emerging technologies that could revolutionize aquaculture, this review briefly outlines and discusses how the absence of these technologies impacts African aquaculture research, specifically focusing on fish intestinal microbiota research. The present study offers crucial information and opens doors for technology innovators and businesses interested in the sector to invest in Africa.

COMPOSITION OF FISH INTESTINAL MICROBIOTA

The intricate and dynamic intestinal microbial ecosystem within animals plays a crucial role in nutrient absorption. Previous studies have demonstrated the benefits of fish intestinal microbiota for the host's nutrition, physiology, and immune processes (Llewellyn et al., 2014; Ma et al., 2019b). The utilization of

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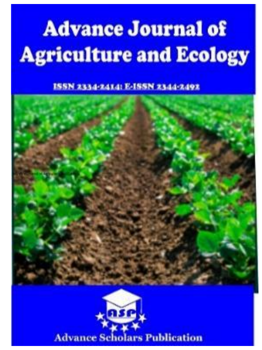

metagenomics in aquatic organisms, whole-genome sequencing of the gastrointestinal microbiome, and the analysis of information related to microbiota's abundance, species, structure, composition, and function hold immense significance. These approaches contribute not only to controlling fish growth and development and preventing diseases but also to overcoming the limitations of traditional culturing methods. In both freshwater and marine fish intestinal microbiota, major bacterial genera such as Proteus, Bacteroides, and Firmicutes have been identified (Rimoldi et al., 2018). Additionally, Vibrio, Achromobacter, Alteromonas, and Flavobacterium are prevalent in marine fish (Egerton et al., 2018). The presence of different bacterial strains in these fish classes can potentially be attributed to the more complex habitats and diverse diets associated with these environments, as suggested by Skrodenytė-Arbačiauskienė et al. (2008).

THE ROLE OF MICROORGANISMS IN THE DIGESTION OF DIET

According to literature, feed intake, metabolism and digestion in mammals are all regulated by microbes within the gastrointestinal tract (GIT) (Fetissov, 2017; Read and Holmes, 2017). The existence of interaction between GIT microbiota and neurotransmitters, such as serotonin (Yano et al., 2015), norepinephrine and catecholamines dopamine, affects the release and function of gastrointestinal hormones, motility, and feeding behaviour of the host (Strandwitz, 2018). The digestion and host diet are greatly significant when studying the functional interactions of fish diets and their intestinal microbial communities (Clements et al., 2014). Several herbivorous fishes of freshwater, such as grass carp, do not depend on the cellulolytic activity of bacteria but instead released huge amounts of plant materials swiftly via their gut and recoup the proteins and soluble sugars that are released via their pharyngeal teeth activities (Gangadhara et al., 2004). The pharyngeal apparatus helps to regulate the flow of food through the digestive system, ensuring that it is properly broken down and absorbed. The gut is responsible for the absorption of nutrients and the elimination of waste products. In grass carp, the gut is relatively long, which allows for more complete digestion of the fibrous plant material that they consume (Wu et al., 2021). Marine herbivorous fish differ from a range of freshwater herbivorous fish species in the sense that, marine herbivorous fish species depend on gut microorganisms for the transformation of inassimilable algal elements, such as mannitol, to metabolize their beneficial short chain fatty acid (White et al., 2010). On the other hand, omnivorous and herbivorous freshwater species exhibit shorter gut transit periods and minimal short chain fatty acid levels in their guts (German et al., 2010). However, only a few pieces of literature support

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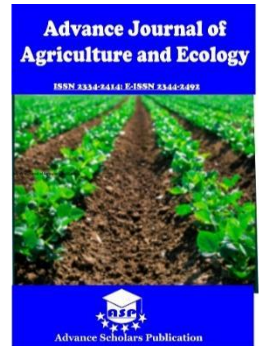

gastrointestinal fermentation, supplying the most important components of day-to-day energy requirements for freshwater fish species and cellulose as a key substrate for the gut microbiota of freshwater fish species. This does not relegate the significance of gut microorganisms for their nutritional value in fish species. The gut microbiota has been shown to facilitate the formation of lipid droplet and uptake of fatty acid in the liver and intestinal epithelium of zebrafish (Semova et al., 2012). As of now, the role of microorganisms in the digestion of diet is still not completely elucidated. More studies are still needed to completely understand the role of these microbes in the digestion of diet.

EFFECT OF FOOD FACTORS ON FISH INTESTINAL MICROBIOTA

With the continuous development of high-throughput sequencing technologies, the effects of feed components on the composition of farmed fish gut microbiota will be more precise. The structural and compositional analysis of fish intestinal microbiota can reflect the information of their habitat and diet. Currently, there are many research fields of microbial meta-genomics (Fjelheim et al., 2007). There are often marked microorganisms in the gut for different feeding habit of fish, which digest and absorb different types of nutrients (Navarrete et al., 2008). It has been indicated that there is a significant relationship between the host's food preference and the composition of intestinal microbiota (Mikaelyan et al., 2015). The composition of intestinal microbiota in different feeding habit of fish is different due to different factors such as degradation of cellulose, protein, and chitin. The fish feeding habits are categorised into three groups: herbivores, carnivorous, and omnivorous. The major nutritional sources of *herbivores* fish are plants, which are rich in cellulose and polysaccharide. The degradation of cellulose depends on various cellulases, but fish cannot produce cellulase by themselves. Therefore, cellulose utilisation only depends on the decomposition and absorption by intestinal microbiota (Bairagi et al., 2002). The diversity of intestinal microbiota of carnivorous fish is slightly lower than that of *phytophagous* and filter feeding fish, which might be due to their single feeding preference. The microorganisms involved in cellulose metabolism are also found in the intestinal microbiota of carnivorous fish species like *Bacillus thuringiensis* and *Bacillus citrate*, but they are in less abundance. The intestinal microbiota of two types of carnivorous fishes, including Mandarin fish (*Siniperca chuatsi*) and Mongolia (*Culter alburnus*), were compared to those of *phytophagous* fishes. The results showed that the protease-producing *Halomonas* and *Fusobacterium* were the predominant bacteria in both carnivorous fish. The enzymatic activity analysis showed higher activity of trypsin and lower activity of cellulase in carnivorous fishes, while the herbivorous fishes

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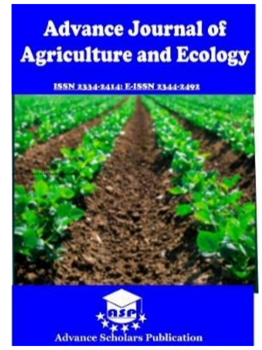

showed opposite results. Furthermore, another study reported predominant cellulase-producing *Paenibacillus* in herbivorous fish but not in carnivorous fish (Liu et al., 2016). This may be because the filter-feeding omnivorous fish feed on the common young plants and filters out the individual microphytoplankton, organic debris, and bacterial aggregates expanding the feeding species, requiring complex intestinal microbiota for decomposition and absorption.

EFFECTS OF FATS, PROTEINS AND CARBOHYDRATES ON FISH INTESTINAL MICROBIOTA

Due to the shortage of animal protein sources, especially that of fish meal, the fish industry generally improves the fat contents in feed to play "protein-saving effect" and replaces fish oil with vegetable oil to reduce costs to promote the rapid growth of fish. At the same time, it has many adverse effects, such as excessive accumulation of fat and immune damage to fish (Xing et al., 2013), and affects the composition and structure of intestinal microbiota (Sheng et al., 2018). In the formation of lipid droplets, sclerenchyma tissues play a crucial role, while *Bacteroides* and *Proteus* cannot increase the number of lipid droplets. When the Salmon (*Salmonidae*) were fed with polyunsaturated fatty acids (linoleic acid and linolenic acid) or high unsaturated fatty acids (HUFAs) in diet, the number of *Lactobacilli* in the intestine and faeces among the fish in the linolenic acid group and HUFA group increased significantly (Bagi et al., 2018; Falcinelli et al., 2017; Ringø et al., 2016).

The problem of substitution for protein sources in aquatic feeds, especially the replacement of fish meal with plants-based protein sources, animal by-products, as a protein source, has become a hot topic for scientists worldwide (Acar et al., 2019, 2018). The effect of replacing fish meals on their intestinal health, primarily intestinal microbial balance, needs to be studied.

Sphingomonas was the dominant bacterial group when soybean proteins were used as a substitution for the protein source (Ringø et al., 2016). To sum up, the current studies, based on pure culturing technology, show that the use of soybean proteins as a substitution for protein source does not significantly alter the microecological balance of fish intestine, and to a certain extent, leads to the formation of the anaerobic state in the intestine, thereby providing resistance to the invasion of pathogenic bacteria (Ringø et al., 2016). Therefore, it can be utilised as a good substitution for protein source in a fish meal (Ringø et al., 2016).

In terms of glucose metabolism, the fish are considered to be born with "diabetes" and are intolerant to high glucose concentrations (Jiang et al., 2011). Scientists try to explain this from the perspective of evolution (Jiang et al., 2011) and molecular biology (Jiang et al., 2011). The

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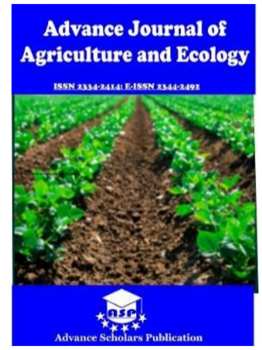

fish industries also try to reduce the feed cost by increasing carbohydrates content or adding different sugar sources in fish feed (Sulaiman et al., 2020; Zhou et al., 2013). However, the interactions of different carbohydrates sources with intestinal microbiota in the fish gut and their effects on the metabolism of fish carbohydrates are still not known (Sulaiman et al., 2020; Jiang et al., 2011). The use of different carbohydrates sources for energy metabolism by intestinal microbiota, critical roles of different bacterial groups in intestinal microbiota, and the low ability of fish to utilise carbohydrates as an energy source due to the lack of some bacterial groups are not clear, which are needed to be studied in detail.

Effects of additives on fish intestinal microbiota and host nutrition metabolism

Amino acids, vitamins, and minerals are essential nutrients for the body's metabolism. Most bony fish cannot synthesise these nutrients by themselves. They rely on exogenous factors to meet the body's growth, development, and metabolism needs (Zhai et al., 2017). In recent years, the influence of probiotics and prebiotics on the intestinal microbiota of fish has changed the developmental direction of aquaculture from an increase in quantity to an improvement of quality (Nyman et al., 2017). Meanwhile, there has been rapid development in scientific research and industry related to probiotics and prebiotics. At present, probiotics, which are mainly used in aquatic fish feed, include *Lactobacillus, Bacillus, Clostridium bifermentans*, and yeast. The common prebiotics includes fructo-oligosaccharide, galactooligosaccharides, dextran, mannan and xylooligosaccharides. The lactic acid bacteria and yeast are currently the most widely used probiotics in aquaculture (Merrifield et al., 2013; Ahire et al., 2019; Abdelrahman et al., 2017; Giorgia et al., 2018).

A couple of studies showed that the addition of shortchain fructooligosaccharides and xylooligosaccharides to fish feed did not alter the diversity of intestinal microbiota in Norwegian sea bass (*Sparus aurata*) and European sea bass, but significantly increased the abundance of lactic acid bacteria (Guerreiro et al., 2018; Dawood et al., 2016). Therefore, it is of great significance for the aquaculture industry to isolate fish-derived probiotics from the intestines of fish, fed with different diets and different environmental conditions, and carry out relevant taxonomy and basic biology studies. The active components in plant extracts include glycosides, acids, polyphenols, polysaccharides, terpenes, flavonoids and alkaloids. A study on Rainbow trout showed that the addition of cresol or thymol decreased the abundance of anaerobic bacteria in the fish intestine, along with the decrease in the abundance of lactic acid bacteria (Hagi et al., 2004).

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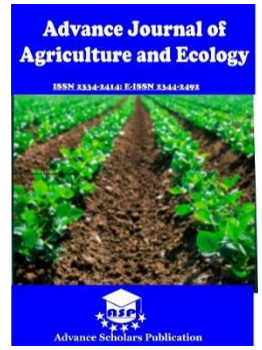

INTESTINAL MICROBIOTA AND GUT IMMUNITY IN FISH

The gut microbiota of fish plays a vital role in the inhibition of pathogenic microorganisms. The dominant microbial species in their intestinal tract protect the host from infection and invasion of environmental pathogens. Some intestinal microbial species also promote the proliferation of intestinal epithelial cells and immune system response (Stagaman et al., 2017). Environmental pressures, such as pollution, hypoxia, and sudden temperature variations, can damage the host's immune system, which can lead to the invasion of pathogens, thereby altering the composition of intestinal microbiota. The changes in the structure of the intestinal microbiota of fish are not the only factors for adapting and improving their immune ability, but also some chemical elements (antibiotics, pollutants, pesticides, insecticides) entering the digestive tract of animals have a significant impact on the composition of intestinal microbiota (Navarrete et al. 2008).

Even though a symbiotic relationship exists between the host's metabolism and gut microbiota, the interactions of host-microbiota at the functional level, particularly in the wild species, are still not precise (Tarnecki et al., 2017). Most of the studies regarding the assembly practices and interactions of host-microbiota are laboratory-based studies that typically use model species that have been tamed in laboratory environments for generations (Tarnecki et al., 2017; Eichmiller et al., 2016). Nonetheless, the interactions of fish gut microbiota and other organisms have many features, and these laboratory-based studies might not satisfactorily represent these interactions in wild-type animals. Therefore, the enhanced understanding and knowledge of the natural microbiota of healthy animals and their mode of interaction with hosts and other environmental factors are still of utmost significance.

OTHER TECHNOLOGIES, RESEARCH METHODS AND STRATEGIES IN AQUACULTURE

The rapid development of aquaculture has been promoted by applying science and introducing cuttingedge technologies (Figure 1) over the past five to six decades (Yue and Shen, 2021). Scientific and technological advances have benefited almost every aspect of aquaculture. Aquaculture species can now be diversified due to improved reproductive technologies (Yue and Shen, 2021; Weber and Lee, 2014).

Using quantitative genetics, selective breeding has resulted in significant improvements in more than 60 culture species of aquaculture (Gjedrem and Robinson, 2014). The cost of feed has been reduced and the feed conversion rate (FCR) has been improved when feed formulations are optimised depending on the species of fish and their nutritional needs (Yue

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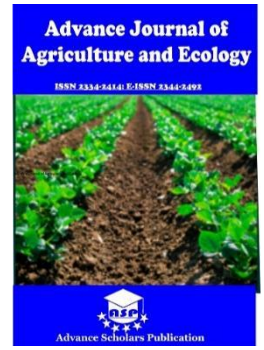

and Shen, 2021). Kelly and Renukdas (2020) noted that disease management technologies Aquaculture has grown

had reduced disease occurrence in aquaculture.

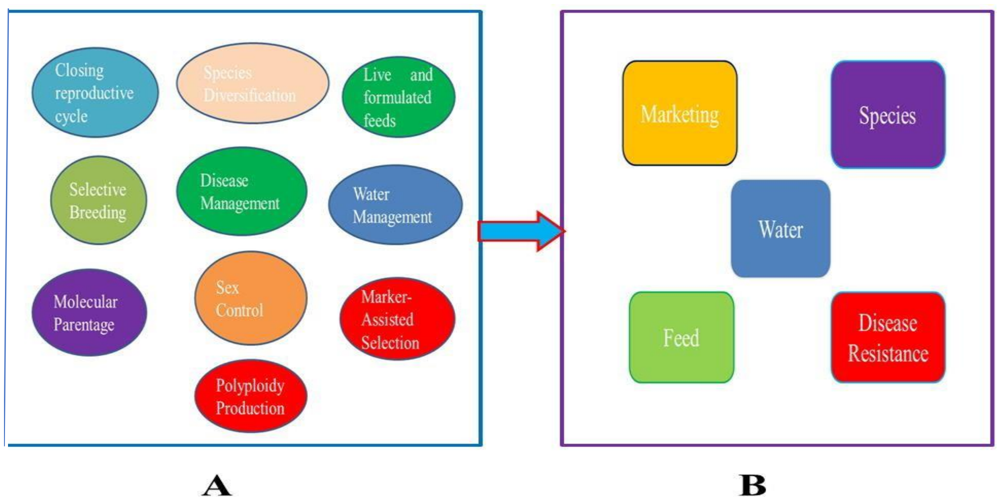

Figure 1. *As a result of aquaculture technologies, aquaculture production have increased rapidly (A) Technologies applied to aquaculture. Different technologies are used in different parts of the world with different methods (B) A key component of increasing aquaculture production.*

Source: Yue and Shen (2021). Tremendously as a result of these early innovations, but the challenges are formidable as the world population continues to grow (FAO, 2020).

Aquaculture can be further developed sustainably and profitably (FAO, 2020). The aquaculture industry is experiencing rapid growth through the development and introduction of cutting-edge technologies (Ab Rahman et al., 2017). Global seafood production and profitability will be significantly enhanced by emerging and disruptive technologies. Among these technologies are digital technology, genome editing, genomic selection, offshore farming, recirculating aquaculture systems, solar energy, and oral vaccines (Yue and Shen, 2021; Aich et al., 2020; Houston et al., 2020). Africa is lagging behind due to unavailability of most of these technologies. Hence there is an urgent need for inventors, investors and governments to quickly invest in these areas in the continent.

Several characteristics of aquaculture species that are economically significant can be

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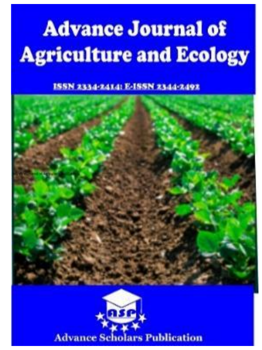

improved through genomic selection (GS) and genome editing (GE). Aquaculture genetic improvement will be substantially accelerated if GS and GE are combined with advanced conventional breeding strategies and matured biotechnologies (Yue and Shen, 2021). In another vain, increasing feed consumption and reducing feed loss can substantially reduce total production costs when the feeds are fed in accordance with hunger status (Su et al., 2020; Li et al., 2020). There is an ongoing effort in Europe to develop a platform that can detect and monitor chemicals, harmful algae bloom, pathogens, and toxins, using an automated and integrated system (Johnston, 2018). The aquaculture industry in the African continent will be able to maintain an ideal environment for fish through sensors in water collaborating with cloud management and mobile connectivity to ensure optimal feeding for growth and feed conversion. Real-time sensors will be crucial to detect pathogens in water; measure stress levels in individual fish in the future (Yue and Shen, 2021). It is possible to draw inspiration from Stanford researchers' studies on measuring stress and overall health using wearables that detect cortisol (Parlak et al., 2018).

By combining drones with artificial intelligence (AI) and cloud computing, the aquaculture industry can reduce costs and improve operations (Yue and Shen, 2021;
Chen et al., 2020). The use of artificial intelligence (AI) in aquaculture is increasingly being studied and applied by science-based research institutes and start-ups (Razman et al., 2020; Evensen, 2020). A shorter period of time can be devoted to increasing aquaculture production using AI since it reduces labour-intensive aspects of aquaculture (Yue and Shen, 2021). The use of feeders, monitoring water quality, and harvesting and processing of fish are just a few examples (Jothiswaran et al., 2020). It is critical that aquaculture production and marketing data be shared between fish farms and big aquaculture companies (Yue and Shen, 2021).

Virtual Reality (VR) can be applied to teaching and education in the aquaculture industry (Ferreira et al., 2012). The use of VR has been used, for instance, to inspire young people to become more interested in aquaculture in Norway (Prasolova-Førland et al., 2019). As social media have becomes more relevant to the food industry, the aquaculture industry can hook onto this platform to increase its production (Dupont et al., 2018). Predictive models can be generated using internet of things (IoT) and machine learning with data collected over time. Making better and more precise decisions using these predictive models will enable early warnings of potential risks. In the African aquaculture industry, the

IoT and big data solutions can revolutionize productivity, sustainability, and profitability and make it simpler and safer to manage risks.

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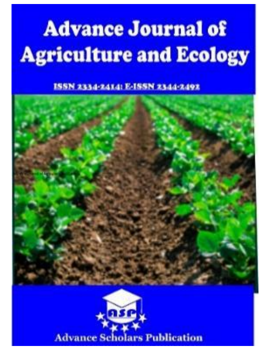

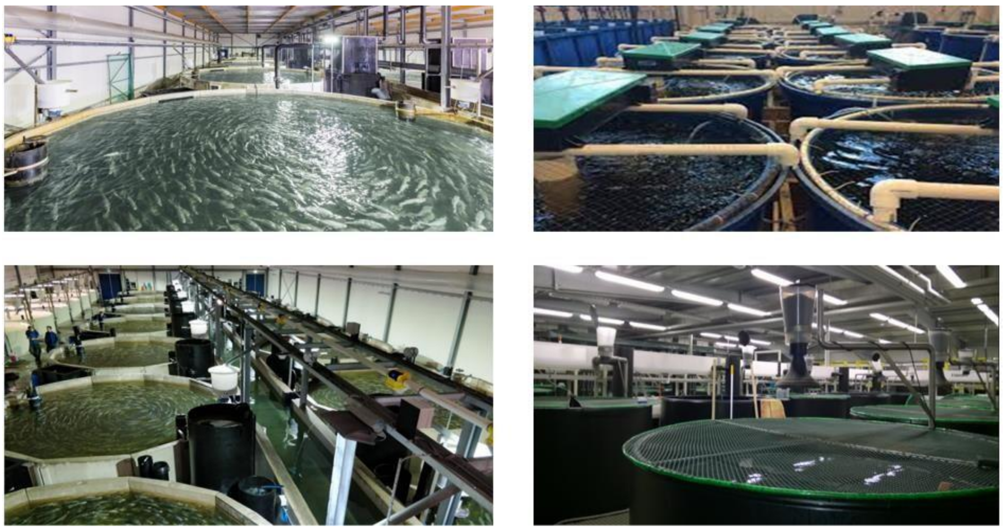

Figure 2. An image of a recirculating aquaculture system (RAS). Several offshore aquaculture systems exist, including cage aquaculture, submersible cages, vessel aquaculture, and fish farms permanently moored in deep water. Additionally, tank-based recirculating aquaculture systems, vertical aquaponics, multistory vertical tanks, and desert tanks are among recirculating aquaculture systems (RAS).
Sources: https://www.aquacultureid.com/recirculating-aquaculture-system/

Figure 2 shows a recirculating aquaculture system (RAS) in which fish are farmed in controlled conditions (Badiola et al., 2018). As a result of RAS, less water is used, biosecurity is improved, and yield is higher or enhanced. However, the technology faces several challenges, including insufficient knowledge, high energy requirements, high initial investments, and difficulty removing bacteria from the RAS once they enter (Xiao et al., 2019; Badiola et al., 2018). Several research projects have been conducted on improving recirculating loops and waste treatment, as well as using renewable energy to reduce energy costs (Badiola et al., 2018). On RAS farms, however, only high-value product species will likely be profitable due to current knowledge and technologies (Yue and Shen, 2021). Fish farmers should work with fish scientists and engineers to effectively design each RAS system component to reduce costs.

AFRICAN PERSPECTIVES

There has been much advancement made into studying the fish gut microbiota, but there is still

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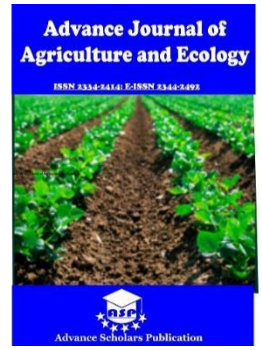

much more to be done especially on fish species from the African continent. For instance, the extent to which the microbiota is involved in feeding, immune responses, digestion, and metabolisms, thereby contributing to the sustenance and general health of fish, is still not completely elucidated (Egerton et al., 2018). One technology used in analysing the role of microorganisms in digestion is metagenomics. Metagenomics involves the direct sequencing of DNA extracted from an environmental sample, allowing for the identification and characterization of all microorganisms present in the sample, regardless of whether they can be cultured (Wu et al., 2021; Egerton et al., 2018). In the context of aquaculture, metagenomics can be used to analyse the microbial communities present in fish gut samples and to identify the functions of these communities in the digestion of feedstuffs (Wu et al., 2021). Another technology used in studying the gut microbiome of fish is microbial culturing. This involves the isolation of individual microorganisms from a sample and their subsequent identification and characterization through various biochemical and molecular techniques. This method has the advantage of allowing for the isolation and study of individual microorganisms. However, this technique is known to miss significant portion of the microbial diversity present in the sample (Wu et al., 2020). Researchers have also developed culture-independent methods, which include molecular techniques such as polymerase chain reaction (PCR), denaturing gradient gel electrophoresis (DGGE), and next-generation sequencing (NGS) (BisiJohnson et al., 2017; Sullam et al., 2012). PCR is a technique that amplifies a specific region of DNA, allowing for the identification of microorganisms through the sequencing of their DNA. DGGE is a technique that separates PCR-amplified DNA fragments based on their melting properties, allowing for the identification of different microbial populations in a sample. NGS is a high-throughput sequencing method that can identify a vast array of microorganisms in a sample (Bisi-Johnson et al., 2017). This technology involves the use of molecular probes to target specific microbial taxa within the gut microbiota. Microbiome profiling allows the identification and quantification of specific microbial groups, such as beneficial probiotic or pathogenic bacteria that may significantly impact fish health and productivity. Finally, metabolomics is another technique used in the analysis of the role of microorganisms in digestion. Metabolomics involves the analysis of the small molecules produced by the metabolic processes of microorganisms. This technique can provide insight into the metabolic pathways involved in the digestion of feedstuffs and help identify potential biomarkers for monitoring the health of fish in aquaculture (Bereded et al., 2020).

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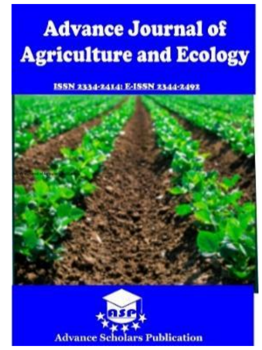

Techniques such as next-generation sequencing and metagenomics have shown promise in this regard, but they require specialised equipment and expertise that is often lacking in African research institutions. While the role of microorganisms in African aquaculture is increasingly recognised, the need for advanced technologies for analysing microbial communities remains a significant obstacle.

Additives in fish feed have been a topic of concern due to their potential impact on fish intestinal microbiota and host nutrition metabolism (Smorodinskaya et al., 2022; Sánchez-Alonso et al., 2020). Understanding these effects is crucial to improving aquaculture productivity and sustainability (Smorodinskaya et al., 2022; SánchezAlonso et al., 2020). Recent technological advancements have enabled the analysis of the fish intestinal microbiota and host metabolism at the molecular level. Advanced molecular techniques such as Next-generation sequencing, metabolomics, Metagenomic and metatranscriptomic approaches allow for identifying and quantifying microbial communities and their gene expression patterns, and host metabolism and nutrient utilization and their interactions with the diet respectively (Sánchez-Alonso et al., 2020; Liu et al., 2021). These techniques will provide insights into the functional roles of these communities in digestion, nutrient absorption, and disease resistance in African aquaculture and will provide a comprehensive understanding of the complex interactions between fish, their gut microbiota, and the feed additives. However, the African aquaculture industry still needs access to specific technologies.

Understanding how different feed ingredients and formulations impact the gut microbiota of African aquaculture species is essential for developing sustainable and cost-effective aquaculture practices. Understanding the effects of additives on fish intestinal microbiota and host metabolism is crucial to improving aquaculture productivity and sustainability in Africa. Advancements in technology will enable a better understanding of these complex interactions, providing opportunities for developing effective strategies to mitigate negative impacts and optimise fish growth and health. The intestinal microbiota and gut immunity play critical roles in fish health and production. Their analysis using various technologies can lead to the development of effective strategies for sustainable aquaculture in Africa.

CONCLUSIONS

Utilizing the fish's gut microbiota holds unlimited potential for the fish aquaculture industry to enhance the growth and development of cultured species. Technological innovations are essential for the expansion of aquaculture. Aquaculture is on the cusp of a revolution thanks to several innovative and disruptive technologies. It is no secret that the

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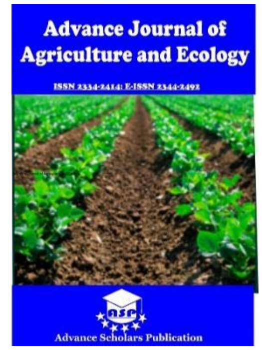

aquaculture sector tends to be slow in adopting cutting-edge technologies. However, individuals within the field are realizing that recent technological advancements could revolutionize certain aspects of aquaculture on a small scale and in a sustainable manner. Innovative and disruptive technology significantly lags behind the available technology, and the application of these technologies in aquaculture is not widespread (Yue and Shen, 2021).

Incorporating different technologies into aquaculture systems is a complex process. To make aquaculture more sustainable and profitable in Africa, these technologies must be effectively integrated. To achieve this, fish farmers, fish scientists, economists, software developers, and engineers must collaborate. In order to integrate disruptive technologies into the aquaculture sector, government agencies in Africa need to fund multidisciplinary research projects, while aquatic farming investors, venture capital firms, and extension services can support young start-ups. The aquaculture industry in Africa stands to become significantly more resourceful due to emerging and disruptive technologies. Moreover, these technologies will create new business and employment opportunities for young individuals in Africa. The sustainability of aquaculture must be enhanced through effective management to prevent these emerging technologies from undermining it (Yue and Shen, 2021; FAO, 2020). By presenting essential information, the current study enables technology inventors and businesses interested in the sector to invest on the African continent and advance aquaculture research.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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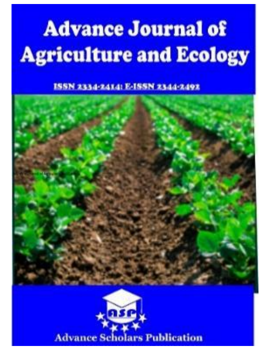

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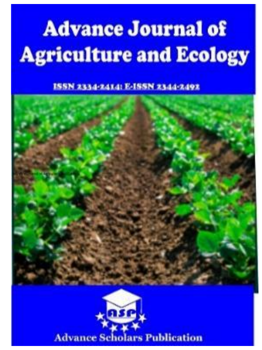

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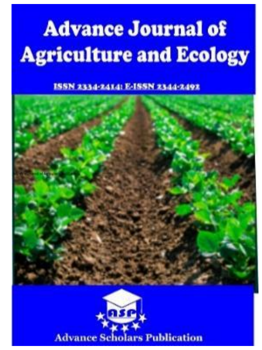

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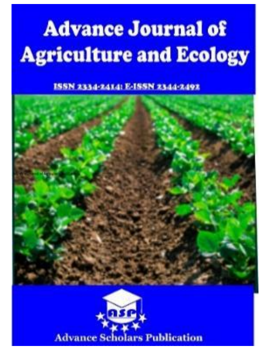

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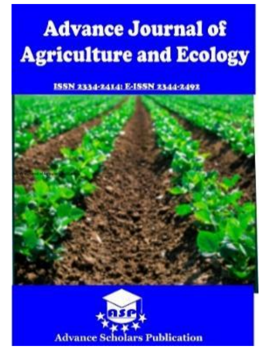

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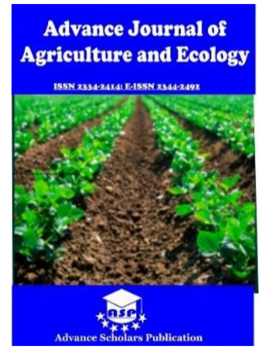

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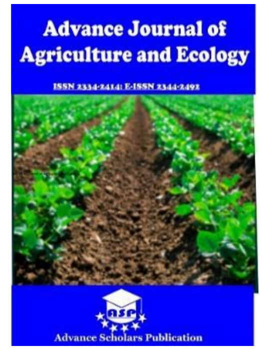

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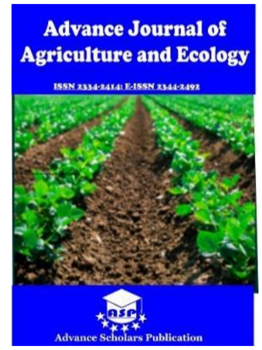

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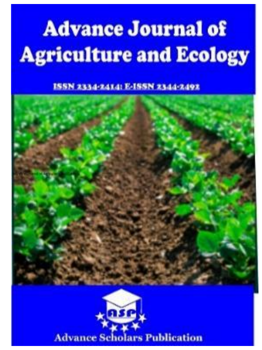

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