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Current Status and Development Trend of Aquaculture: Prospects and Future Potentials

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Abstract:

In recent years world aquaculture production has been increased with innovative and technological developments within fisheries sector and scaled up in world total fisheries production. This increasing aquaculture production depends on innovative production systems and technologies, biotechnological developments. The advancements in these cutting-edge technologies have been focused on promoting sustainable aquaculture production, mitigating the risk of disease outbreaks, and contributing to eco-friendly environmental initiatives. This review paper highlights the cutting-edge technologies that have emerged in the field of aquaculture in recent years, up until the present time, with a focus on advancements in fish nutrition. The advancements in aquaculture technology have been instrumental in promoting the achievement of sustainable development goals. As the aquaculture industry continues to evolve, it is expected that there will be further advancements in technology, sustainability practices, and innovative approaches to meet the increasing demand for seafood while minimizing environmental impact. Overall, the future of aquaculture is likely to be characterized by a combination of technological innovation, sustainable practices, and increased focus on environmental and social responsibility. In the arena of aquaculture, this review paper has the potential to nourish the minds of aquaculturists and aquafarmers with a bountiful feast of knowledge. It unveils the latest technologies and developments in the realm of aquaculture, serving as a nutritious resource that can enhance the operation of cultures and promote a fruitful increase in production in the not-so-distant future.

Keywords: *Sustainability, Environments, Recent technologies, effective microbes.*

Introduction

Aquaculture practices are the only approach to assure an adequate supply of dietary nutrient while also ensuring the safety and sustainability of fish production (Yue and Shen, 2022).

Furthermore, aquaculture has major issues such as environmental pollution, which necessitates a large number of workers, and disease outbreaks, where new developed technology is required to boost aquaculture and fish production and ensure its sustainability (Yue and Shen, 2022).

Biotechnology development in fisheries and aquaculture is accelerating, as it has been discovered to aid in enhancing fisheries productivity in the fisheries and aquaculture sector (Lakra and Ayyappan, 2003). According to El-Gayar (2008), the use of advances in information technology (IT) such as computerized models, artificial intelligence, image processing, and geographical information systems aid in the better management of aquaculture facilities and has also become one of the regional planning in aquaculture development. Meanwhile, biotechnology advancements have included the use of synthetic hormones in fish breeding, monosex culture, polyploidy, molecular biology, transgenesis, and the introduction of marine natural products, all of which have helped to revolutionize the aquaculture industry while also playing an important role in biodiversity conservation (Lakra and Ayyappan, 2003). Furthermore, new technologies such as genome editing, offshore farming, recirculating aquaculture systems, oral immunization, and the Internet of Things (IoT) may provide a solution for more sustainable and lucrative aquaculture production (Yue and Shen, 2022).

This review paper introduced and highlighted the most current technological breakthroughs in the aquaculture business. The application of these new and mostly recent technologies contributes to increased aquaculture production and profitability, better aquaculture industry management, and future sustainable aquaculture production, as well as supporting the Sustainable Development Goals (SDGs) of no poverty and zero hunger.

Microalgae Application in Aquaculture

Microalgae play a crucial role in the aquaculture industry as they are widely employed as a dietary source of nutrition for aquatic animals (Ma et al., 2020). Microalgae have been extensively employed in the field of aquaculture as a highly nutritious feed source for the larvae of molluscs, echinoderms, crustaceans, and fish larvae, as documented by Muller-Feuga in 2000. In the realm of aquaculture, a diverse array of species is commonly employed as feed sources. These include *Chlorella* sp., *Tetraselmis* sp., *Scenedesmus* sp., *Pavlova* sp., *Phaeodactylum* sp., *Chaetoceros* sp., *Nanochloropsis* sp., *Skeletonema* sp., and *Thalassiosira* sp. These microalgae species have been found to exhibit a commendable growth rate and demonstrate stability when cultivated under varying conditions of temperature, light, and nutrient availability within the hatchery system (Sirakov et al., 2015). In the realm of fisheries science, it is worth noting that certain microalgae species, including *Dunaliella salina*, *Haematococcus pluvialis*, and *Spirulina* sp., have gained significant popularity for their natural pigmentation properties. Specifically, these microalgae are known to produce the carotenoid astaxanthin, which imparts a delightful pink hue to cultured prawns, Salmon fish, and even ornamental fish (Sirakov et al., 2015).

In recent times, there has been a notable global utilization of microalgae as a viable protein substitute for fishmeal, as evidenced by the work of Roy and Pal (2015). Numerous species of microalgae have been identified as valuable in promoting the growth of cultured organisms, enhancing feed utilization, augmenting physiological activity, mitigating stress responses, bolstering disease resistance, and improving starvation tolerance in aquaculture animals (Roy and Pal, 2015). In a recent study conducted by Zhang et al. (2022 b), it was observed that the cultivation of Whiteleg shrimp (*L. vannamei*) in the presence of two species of microalgae, namely *Nannochloropsis oculata* and *Thalassiosira pseudonana*, had several positive effects. These effects included an increase in shrimp survival rate, inhibition of pathogenic *Vibrio* sp. growth, and an overall increase in shrimp yield. The two species of microalgae were found to contain beneficial minerals and vitamins. The utilization of these two microalgae species in aquaculture have demonstrated a positive impact on the overall quality of muscle shrimp. Additionally, this approach proves to be an efficient strategy in promoting an environmentally sustainable and conducive culture environment for muscle shrimp cultivation (Zhang et al., 2022 b).

In natural ecosystems, certain species of wild micro-algae exhibit the potential to serve as valuable resources for augmenting immunostimulants and promoting growth performance in cultured animals. These species include *Haematococcus pluvialis, Arthrospira platensis* (commonly known as Spirulina), and various strains of *Chlorella* spp. (Ma et al., 2020). In the aquaculture industry, there have been notable advancements in utilising microalgae, such as *Chlamydomonas reinhardtii*, *Dunaliela salina*, and *Cyanobacteria*, for the production of oral vaccines (Ma et al., 2020). Typically, microalgae biomass is employed as a nutritional resource due to the presence of crucial amino acids, beneficial triglycerides for lipid provision, vitamins, pigments, and bioactive compounds that have the potential to enhance the survival rate of cultured animals, as well as improve the coloration and quality of the resulting fillet (Nagappan et al., 2021). The identification of microalgae with the ability to recover nutrients, release oxygen, and enhance production yield has positioned them as a promising biotechnological solution for aquaculture wastewater treatment and as a dietary supplement for fish (Li et al., 2020).

Through the strategic incorporation of microalgae within the recirculated aquaculture system (RAS), the potential for optimising nutrient recycling processes is heightened. Notably, the utilization of microalgae has been observed to effectively eliminate NH_4^+ - N by an impressive range of 95.49% to 100%. Furthermore, microalgae exhibit a commendable capacity for phosphate removal, with removal rates surpassing 80% (Duan et al., 2022). Microalgae species, including *Chlorella marina, Tetraselmis suecica,* and *Picochlorum maculatum*, have demonstrated potential in the remediation of nutrients present in aquaculture wastewater. These particular microalgae species have been observed to effectively remove significant quantities of NH_3-N, NO_2-N, total nitrogen (TN), and total phosphorus (TP) from such wastewater sources (Meril et al., 2022). The assimilation of nutrients derived from the wastewater of aquaculture systems has the potential to be harnessed for the cultivation of microalgae biomass, subsequently serving as a valuable source of biologically-derived fertilizer (Meril et al., 2022).

In a recent investigation carried out by Soto-Rodriguez et al. (2021), it was discovered that *Chaetoceros calcitrans*, a species of marine microalgae, exhibits antibiotic properties within the hydrophilic compound of its cells. These properties were observed to be effective against Vp M0904, a highly virulent strain of *Vibrio parahaemolyticus* bacteria. This strain is known to be responsible for causing acute hepatopancreatic necrosis disease (AHPND). The co-cultivation of microalgae, specifically *Isochrysis galbana*, with bacteria such as *Alteromonas* sp. and *Labrezia* sp., along with *Marinobacter* sp., has been found to yield improved outcomes in terms of total length, survival, and metamorphosis of *P. vannamei* larvae, as reported by Sandhya et al. (2020).

Vaccines Application in Aquaculture

Over the course of the previous decade, significant advancements have been observed in the field of aquaculture. In the present day, the establishment of a sustainable aquaculture business holds notable significance in terms of global food supply and economic stability. This sector plays a pivotal role in offering and contributing a substantial portion of high-quality protein sources for human consumption. Nevertheless, the rapid growth of aquaculture has resulted in elevated populations of farmed species, hence amplifying the potential for outbreaks of aquatic diseases. In addition to causing economic losses, these diseases also pose ecological risks by facilitating the transmission of pathogens to marine habitats, so infecting wild fish and contributing to environmental pollution. Hence, ensuring the well-being of fish is crucial for the aquaculture sector to achieve environmental sustainability and serve as a fundamental requirement for intensive production on a worldwide scale. According to a recent study conducted by Assefa & Abunna (2018), the practice of intense and large-scale fish farming has resulted in the emergence and widespread occurrence of many infectious fish diseases. The aquaculture sector largely adopted the ongoing use of antibiotics and drug residues as a means to address the challenges at hand. Nevertheless, the utilization of antibiotics and the presence of drug residues have resulted in adverse consequences, including extensive contamination, potential threats to food safety, and an indirect exacerbation of antimicrobial resistance (Su et al., 2021). Hence, the utilization of vaccination is often regarded as the most efficacious and ecologically sustainable strategy for combating viral diseases, with negligible ecological repercussions and broad applicability across many farmed fish species.

A vaccination is a biologically derived product designed to enhance immunity against a particular disease or a set of diseases (Mondal & Thomas, 2022). Vaccines, sometimes known as biological agents, are capable of inducing an immune response specific to a particular antigen derived from a disease-causing infectious pathogen. Currently, vaccination plays a significant role in the field of aquaculture and has gained widespread adoption globally as an effective measure for mitigating a diverse range of viral diseases and bacterial infections (Ma et al., 2019). Nevertheless, the current worldwide market only offers a total of 34 commercially available fish vaccines as of the year 2021, as indicated by Su et al. (2021). This scarcity underscores the pressing necessity for additional vaccine development in order to effectively address the existing challenges in ensuring food safety. In their study, Snieszko et al. (1938) employed vaccinations as a preventive measure against disease in carps. Specifically, they immunized the carps with the bacteria *Aeromonas punctate*, which was identified as the initial instance of protective immunity in the field of aquaculture. The initial documentation in the English language regarding the safeguarding of Rainbow trout, *Oncorhynchus mykiss*, against *Aeromonas salmonicida* through oral administration and parenteral inoculation was presented in a study conducted by Duff in 1942.

Since the 1940s, with the introduction of the first fish vaccine aimed at diseases prevention (Snieszko and Friddle, 1949), numerous vaccines have been developed that significantly contribute to the reduction of bacterial and viral harmful diseases (Gudding and Goodrich, 2014). Numerous vaccines have been documented for various fish species, including Tilapia (*Oreochromis niloticus/mossambicus*), Atlantic Salmon (*Salmo salar*), Rainbow Trout (*Oncorhynchus mykiss*), Sea bass (*Dicentrarchus labrax*), Sea Bream (*Sparus aurata*), Amberjack (*Seriola dumerili*), Yellowtail (*Seriola quinqueradiata*), Catfish (*Ictalurus punctatus*), and Vietnamese Catfish (*Pangasianodon hypophthalmus*) (Clarke et al., 2013; Assefa and Abunna, 2018; Su et al., 2021). According to Shefat (2018), there is currently a wide range of commercially available vaccines targeting major infectious bacterial and viral diseases in fish. These include vaccines such as the Arthrobacter vaccine, *Vibrio anguillarum-ordalii*, *A. salmonicida* bacterin, *Yersinia ruckeri* bacterin, and other vaccines designed to combat bacterial infections in salmonids. Additionally, there are vaccines available for *Flavobacterium columnare, E. ictaluri* bacterin, and other bacterial infections in Grouper. For viral infections, there are vaccines against infectious pancreatic necrosis virus (IPNV), infectious salmon anaemia, nodavirus, and other viruses affecting salmonids and seabass. Furthermore, vaccines have been developed to address *Streptococcus agalactiae* and *Streptococcus iniae*, which cause Tilapia Streptococcosis. Lastly, vaccines are available for spring viremia of Carp, Koi herpes virus (KHV), Grass Carp haemorrhage disease, and other viral infections in Carps.

In general, vaccinations can be categorized into three distinct forms, mostly determined by their methods of preparation. These types include live vaccines, inactivated vaccines, and genetically modified vaccines (Ma et al., 2019; Su et al., 2021). Live vaccines are formulated using microorganisms that have been attenuated or altered for the purpose of management. Inactivated vaccines are comprised of pathogenic microorganisms that have been rendered inactive, yet nevertheless retain their immunogenic properties and capacity to elicit particular resistance in aquatic animals upon inoculation. The third category, known as genetically modified vaccinations, encompasses several varieties such as recombinant subunit vaccines, DNA vaccines, gene deletion or mutant vaccines, and live-vector vaccines. Currently, the most commonly utilized vaccinations are those that are live attenuated and inactivated (Ma et al., 2019). The potential utilization of plant-produced vaccines, which involve the application of plant biotechnological techniques, is now under investigation and remains in the developmental phase (Su et al., 2021). Vaccine delivery methods encompass three primary modalities: injection, immersion (water bathing), and oral administration. Different types of vaccines include distinct advantages and disadvantages. Typically, the selection of a vaccine and its administration method is mostly contingent upon many aspects of the cultivated fish species, including but not limited to size, eating habits, economic worth, and water quality. The consideration of economic costs, pathogens, and necessary protection is crucial when selecting and implementing appropriate vaccines. Su et al. (2021) argued that forthcoming fish vaccines targeting infectious pathogens ought to possess cost-effectiveness and environmental sustainability, while also being amenable to large-scale production. This would ensure their accessibility and suitability for both intensive aquaculture operations and smaller-scale fish farming enterprises. The use of vaccines has emerged as a viable strategy in mitigating the spread of disease in prawn populations (Shreedharan et al., 2022). The utilization of a polyvalent vaccine in prawns has been shown to augment the efficacy of the vaccine. This is achieved by supplementing the vaccine with adjuvants, nutritional additives, and immunostimulants (Shreedharan et al., 2022).

Biofloc Technology

The utilization of biofloc technology has gained significant global recognition in the field of aquaculture due to its environmentally sustainable nature. This technology facilitates zero water exchange and effectively reduces the frequency of water exchange within the culture system (Avnimelech, 2007). Bio-floc technology is a cutting-edge method that contributes to the sustainability of aquaculture production by enhancing prawn yield, providing supplementary nutrition for animals, facilitating bioremediation and biodegradation processes to maintain water quality, and reducing the need for frequent water exchange (Khanjani et al., 2022 c). The biofloc technology encompasses a diverse array of microorganisms, each with distinct functions that contribute to various aspects of the aquatic farm system. These microorganisms play a crucial role in enhancing water quality, serving as a supplementary food source, imparting probiotic properties, and ultimately ensuring the overall success of the system (Khanjani et al., 2022 c). Biofloc is composed of a diverse range of microorganisms, including heterotrophic bacteria, algae, fungi, protozoa, nematodes, and detritus. These microorganisms form a symbiotic relationship, working together to maintain water quality and support the high density of prawn production (Manan et al., 2017). In the biofloc system, it was shown that heterotrophic bacteria exhibited more dominance in comparison to nitrifying bacteria. This can be attributed to their higher growth rate and microbial biomass yield, as supported by studies conducted by Manan et al. (2017) and Hargreaves (2006). In the biofloc system, the conversion of uneaten feed and faeces into microbial protein is facilitated by heterotrophic bacteria. This process is supported by the introduction of carbon sources and a robust aeration system. It is important to maintain a C/N ratio within the range of 10:1 to 20:1, as suggested by Yuvarajan (2020).

There exist multiple carbon sources that can be utilized within the biofloc system, including wheat flour, corn flour, tapioca flour, rice bran, sweet potato, jaggery, and molasses. The selection of carbon sources should prioritize affordability and cost-effectiveness, as well as their ready availability in the market (Avnimelech, 2007; Yuvarajan, 2020). Additionally, it has been observed that biofloc exhibits advantageous characteristics, such as favourable nutritional properties, facilitation of exogenous digestive enzyme activity, possible pathogen control, and immunostimulant effects (El-Sayed, 2021). Biofloc has been proposed as a novel alternative for the production of sustainable aquaculture, with potential contributions to the achievement of the Food and Agriculture Organization's (FAO) sustainable development goal (SDG) 2, which aims to end hunger and improve food security (El-Sayed, 2021).

According to Che Hashim et al. (2021), the introduction of *Bacillus infantis* bacteria through inoculation facilitated the enhanced proliferation of advantageous heterotrophic bacteria and resulted in an increase in the volume of biofloc. This increase in biofloc volume played a crucial role in preserving the favorable water quality inside the culture system. In a recent study conducted by Kasan et al. (2021 a), the researchers investigated the impact of sedimentable solids on water quality and survival rates of *Scylla paramamosa* larvae in crab culture. The findings revealed a decrease in the presence of pathogenic bacteria when the dominant bacteria in the biofloc culture tank were heterotrophic. Additionally, the study observed a depletion of nutrient levels from the early stages of larval culture until the end of the culture stage. It is recommended to utilize a sedimentable solid concentration of 2 ml/L in the cultivation of *S. paramamosain* crabs within the bio-floc system. This application had shown effective in preserving water quality and enhancing the survival rate and overall performance of crab larvae culture. In their study, Manan et al. (2022) utilised 16S rRNA gene sequencing to investigate the bacterial community present in a biofloc shrimp culture pond inhabited by *P. vannamei*. Their analysis revealed the presence of various bacterial species within the biofloc, including *Exiguobacterium aestuarii*, *E. profundum, E. aurantiacum*, *Bacillus pumilus*, *velezensis*, *B. cereus*, *B. safensis*, *B. subtilis*, *Vibrio diazotrophicus, V. diabolicus*, *V. natriegens*, *Rheinheimera aquimaris*, *Acinetobacter junii*, According to Kasan et al. (2022), the utilization of a commercial pellet in conjunction with quick biofloc aggregation as a dietary strategy has been found to enhance the survival rate of *S. olivacea* crablet culture. Additionally, this approach aids in the maintenance of favorable water quality and nutrient levels within the crab culture system.

Integrated Multi Trophic Aquaculture (IMTA)

Aquaculture, on a global scale, has emerged as the most rapidly expanding industry in agricultural food production, with an average annual growth rate of 5.3% between the years 2001 and 2018, as reported by the Food and Agriculture Organization (FAO, 2020). Moreover, aquaculture has garnered global recognition as a highly sustainable approach to mitigating poverty and improving food security (Barrange et al., 2018). The demand for seafood is increasing in tandem with the growth of world populations (Goh et al., 2022). The exponential growth in the expansion of aquaculture reliant on formulated feed, also known as fed species, has been accompanied by a multitude of adverse effects on the surrounding ecosystems (Bergqvist and Gunnarsson, 2011). The release of aquaculture effluents into natural water bodies presents a challenge due to their high concentrations of organic and inorganic nutrients, which can lead to environmental degradation (Herath and Satoh, 2015).

Prior research has demonstrated the impact of nutrient discharge into the aquatic ecosystem, specifically the phenomenon of eutrophication, on diverse organisms. These studies have revealed that the release of nitrogen (N) at rates ranging from 52% to 95%, aquafeed at 60%, carbon (C) at 80% to 88%, and phosphorus (P) at 85% into aquaculture systems results in the retention of these nutrients in particulate, dissolved, or gaseous forms. Consequently, these nutrients subsequently serve as essential resources for the proliferation of phytoplankton and bacteria (Perdikaris et al., 2016; Tom et al., 2021). However, it should be noted that dissolved and particulate forms of heavy metals and drug residues, which have harmful effects on aquatic organisms, can also be detected (Sharifinia et al., 2022). Consequently, there have been endeavors to build an aquaculture system that is environmentally sustainable, together with the implementation of a dedicated treatment facility, in order to mitigate the discharge of excessive nutrients and pollutants that are known to contribute to eutrophication, particularly in marine ecosystems (Perdikaris et al., 2016; Thomas et al., 2021).

One of the established systems in the field is an integrated multi-trophic aquaculture (IMTA) system (Khanjani et al., 2022b). IMTA, or Integrated Multi-Trophic Aquaculture, represents a novel approach in the field of aquaculture aimed at improving economic viability, reducing environmental impacts, expanding commercial production, and enhancing sustainability within intensive aquaculture systems. This innovative technique adopts an ecosystem-oriented framework, as highlighted by Troell et al. (2009) and Sanz-Lazaro and Sanchez-Jerez (2020). The IMTA (Integrated Multi-Trophic Aquaculture) system derives economic advantages from the concurrent cultivation of multiple species, thereby generating revenue from various marine products. These products include crustaceans (such as Shrimps, Crabs, and Lobsters), gastropods (including Abalones and Snails), bivalves (such as Oysters, Scallops, Mussels, and Clams), as well as certain species of Sea cucumbers, Sea urchins, Jellyfish, Finfish, and Algae (Barrington et al., 2009; Zamora et al., 2018). The IMTA system facilitates the retrieval and transformation of nutrients and by-products, such as uneaten feed and waste, into fertilizer, feed, and energy for other crops. Additionally, it harnesses the synergistic interactions among different species (Neori et al., 2004; Chopin et al., 2008).

The study identified three distinct groups of extractive species that consume varying proportions of waste released by fed fish, such as prawns and finfish. These groups include: an autotrophic species that absorbs inorganic nutrients and helps reoxygenate the water, a filter feeder that aids in the removal of excessive particulate organic matter (POM) suspended in the water column, and a deposit feeder that acts as a scavenger for POM that settles on the bottom. In the context of Integrated Multi-Trophic Aquaculture (IMTA) systems, the presence of both organic and inorganic extractive species is of utmost importance. This is due to their ability to utilize suspended organic materials for the purpose of retaining and minimizing the quantity of waste generated by the feeding species (Alexander and Hughes, 2017; Rosa et al., 2020).

The IMTA system posited that including a greater proportion of feed derived from high-trophic animal cultures might enhance the production of low-trophic species and mitigate the adverse impacts within the culture systems by effectively managing organic matter present in wastewater (Soto, 2009; Khanjani et al., 2022 b). IMTA has the capacity to both introduce and eliminate inorganic nutrients, as seaweeds have the ability to assimilate nitrogen generated by animal IMTA species (DFO, 2013). The IMTA (Integrated Multi-Trophic Aquaculture) system derives economic advantages from the concurrent cultivation of multiple species, resulting in the generation of income through the production of various marine organisms. These organisms include crustaceans (such as Shrimps, Crabs, and Lobsters), Gastropods (including Abalones and Snails), Bivalves (such as Oysters, Scallops, Mussels, and Clams), as well as certain species of Sea cucumbers, Sea urchins, Jellyfish, Finfish, and Algae (Barrington et al., 2009; Zamora et al., 2018).

The development of the Integrated Multi-Trophic Aquaculture (IMTA) system involved a limited number of significant phases. For instance, the careful selection of appropriate species combinations and population sizes plays a crucial role in ensuring the sustainability of the ecosystem and enhancing overall yield. Additionally, the implementation of suitable technologies that are compatible with the specific environmental conditions, the establishment of effective laws and regulations, the exploration of new markets, the promotion of awareness and education, the establishment of a robust production chain, and the ongoing pursuit of research are all essential factors in achieving these goals (Barrington et al., 2009; Rosa et al., 2020). All the aforementioned phases must be integrated in order to achieve the development of the IMTA system. In order for the Integrated Multi-Trophic Aquaculture (IMTA) to be established effectively, it is imperative to foster collaboration among various stakeholders, including aquaculture engineers, biologists, economists, natural and social scientists, and commercial investors. This interdisciplinary approach, as emphasized by Chopin (2008), is essential for the successful implementation of IMTA.

Internet of Things (IoT)

Water quality monitoring is an essential aspect that necessitates careful consideration in the operation of aquaculture. The constant monitoring of water quality could be achieved through the implementation and advancement of the Internet of Things (IoT). This could be facilitated by the utilization of specially designed sensors, which play a crucial role in ensuring the successful growth and survival of animals (Raju & Varma, 2017). The utilization of Internet of Things (IoT) technology in the field of aquaculture has experienced significant advancements in recent years, particularly in the area of water quality monitoring (Dupont et al., 2018). The aquaculture sector has been significantly impacted by the implementation of the Internet of Things (IoT), as seen by the utilization of real-time monitoring solutions to minimize human intervention and enhance monitoring processes (Gupta et al., 2022). The implementation of the Internet of Things (IoT) enabled the transfer of sensor-collected data to the farmer's mobile device through cloud technology. This initiative allows for timely preventive measures to be taken in order to mitigate potential losses (Raju and Varma, 2017), such as power outages during the farming process. According to Dupont et al. (2018), for the use of IoT in aquaculture to be effective, it is crucial that the technology is intelligent, user-friendly, dependable, exceptionally efficient, and economically accessible to aquafarmers. In their study, Lim and Majid (2021) devised a wireless Internet of Things (IoT) system for the purpose of remotely monitoring aquaculture farms. They recognized the potential for enhancing this system by integrating an autonomous farming system. According to Lim and Majid (2021), the implementation of an IoT monitoring system enabled farmers to utilize smartphones for water monitoring, hence potentially reducing death rates and enhancing profitability.

Prapti et al. (2021) asserted that within the context of water quality, the most crucial metrics in IoT-based aquaculture systems are temperature, dissolved oxygen, and pH. These parameters are often accompanied by an alarm system for prompt action. The IoT-based aquaculture offers several approaches, including real-time monitoring, remote monitoring, automated monitoring, early warning monitoring, online monitoring, and autonomous monitoring (Prapti et al., 2021). The application of IoT in smart aquaculture operations is a technologically advanced approach to sustainable food production. It has emerged as one of the latest ICT technologies utilized in the context of the Industrial Revolution 4.0 (IR4.0) within the aquaculture industry (Prapti et al., 2021). Furthermore, the advancement in computer technology, exemplified by the Arduino and Raspberry Pi platforms, has facilitated innovation in the realm of Internet of Things (IoT). This progress has significant implications for the application of IoT in aquafarming and aquaculture operations (Saha et al., 2018). In their study, Huan et al. (2020) devised a water quality monitoring system for aquaculture that utilized narrow band Internet of Things (NB-IoT) technology. This technology enabled the remote collection and storage of data from multiple sensors, including temperature, dissolved oxygen (DO), and pH. Additionally, the system facilitates centralized management of breeding ponds. According to Huan et al. (2020), the integration of the Internet of Things (IoT) into aquaculture operations has the potential to facilitate the advancement of aquaculture informatization. Additionally, it can offer farmers improved accuracy and convenience in monitoring their aquaculture ponds. Additional factors that need consideration are the expenses associated with deploying the Internet of Things (IoT), such as the initial setup costs, the expenditure required to enable the water quality sensor, the cost of mobile data for real-time monitoring, the expenses related to cloud storage, and the establishment of remote centers for analysis (Karimanzira & Rauschenbach, 2019). The expenses associated with maintaining the IoT system, particularly in relation to the water sensors, are significant due to the high sensitivity of these sensors and the requirement for effective maintenance in order to ensure optimal functionality.

Monosex Culture and Application of Neo-Female Technology

Monosex culture refers to a specialized technique within the realm of aquaculture biotechnology, wherein the aim is to generate populations of a cultured species that consist solely of either males or females. However, it should be noted that the suitability of species for monosex culture is contingent upon their sexual dimorphism characteristics. Sexual dimorphism pertains to the phenomenon observed in certain species wherein the individuals of different sexes exhibit discernible variations in various aspects, encompassing secondary sexual characteristics, coloration, dimensions (both length and weight), morphology, or behavioral patterns (including cognitive traits). As a result of the phenomenon known as sexual dimorphism, certain species have exhibited pronounced variations in size, which have subsequently become influential factors in the process of sexual selection.

In the context of fish species, it was observed that females tend to exhibit greater prominence compared to males. This particular characteristic holds significance in the field of aquaculture, where the optimization of large-scale production of all-female populations was considered more advantageous than mixed-sex culture (Ventura, 2018). The observed variation in sizes among individuals of the studied species may be attributed to various factors related to the environment. These factors include the ecological habitat in which the species resides (Laporte et al., 2018), the geographical distribution of the population (Jiménez et al., 1998), as well as the specific developmental and growth rates that differ between males and females (Kelly et al., 1999; Hüssy et al., 2012). Additionally, the patterns of migration exhibited by the species (Eltink, 1987) and the variations in spawning behavior (Jakobsen and Ajiad, 1999) could also contribute to the observed differences in sizes.

While monosex culture is primarily applicable for selecting commercially valuable species based on sexual dimorphism characteristics, it is a highly effective technique for enhancing production yields and meeting market demands. A case study examining the growth patterns of Freshwater crayfish, specifically Yabbies (*Cherax albidus*), revealed interesting findings. The study observed that in a monosex culture, where only males or females were present, the growth rate of males increased by 17%, while females experienced a growth rate increase of 31%, in comparison to a mixed-sex population. Additionally, the study found that an all-male population in a monosex culture demonstrated a higher gross value of production, specifically at 70%, when compared to a normal mixed-sex population (Lawrence et al., 2000). In the initial investigation conducted by Nair et al. (2006), it was observed that the production of all-male Giant Freshwater Prawn, which exhibited enhanced growth and size compared to females (Sagi et al., 1986), using the hand segregation technique yielded a notable increase in production income of approximately 60% (Nair et al., 2006). The enhancement in production rate of a cultured species was observed when directing efforts towards cultivating a single-sex population. This approach priorities the gender that exhibited faster growth and superior growth performance, while mitigating concerns related to expending energy on unwanted reproduction. It is important to note that in the absence of both sexes, breeding activities couldn't take place (Roderick, 2004). Currently, the prevailing species utilized for monosex culture encompass the all-male Nile Tilapia, scientifically known as *Oreochromis niloticus* (Felix et al., 2019). Additionally, the all-male Giant Freshwater Prawn, referred to as *Macrobrachium rosenbergii* (Sagi and Afalo, 2005), the all-male Whiteleg

Prawn, scientifically classified as L*itopenaeus vannamei* (Sagi, 2013), and the all-male Red-Claw Crayfish, known as *Cherax quadricarinatus* (Rosen et al., 2010).

Aquamimicry

Aquamimicry is an emerging system that necessitates the introduction of organic carbon, without specifying a particular carbon-to-nitrogen (C: N) ratio. This method facilitates a conducive environment for the proliferation of phytoplankton and zooplankton, particularly copepods (Khanjani et al., 2022 a). The presence of these planktonic organisms serves as additional nourishment for the shrimp. Additionally, the proliferation of beneficial bacteria in the aquamimicry system contributes to the stabilization of water conditions and enhances the growing performance of the shrimp (Khanjani et al., 2022 a). Aquamimicry is a technique that enhances the ecological state of shrimp farming by promoting the growth of beneficial microorganisms. This, in turn, leads to the proliferation of planktonic organisms, including phytoplankton and zooplankton, particularly copepods. These organisms serve as supplementary food sources in shrimp culture and contribute to the maintenance of optimal water quality conditions (Romano, 2017). Aquamimicry is a methodology that seeks to replicate the conditions seen in natural settings, with the aim of promoting environmental stability and minimizing feeding costs (Panigrahi et al., 2019). The efficacy of the aquamimicry system is contingent upon the utilization of carbon sources, such as Rice bran, Soybean, and meal, in conjunction with probiotic bacteria typically derived from *Bacillus* sp. These bacteria play a crucial role in promoting the proliferation of zooplankton, particularly copepods (Khanjani et al., 2022 a). The utilization of fermented carbon sources, which serve as a precursor for prebiotic derivatives like oligosaccharides, in conjunction with probiotic bacteria (specifically *Bacillus* sp.), has been found to contribute to the preservation of favorable water quality conditions. Additionally, this approach aids in the efficient recycling of nitrogenous waste within aquaculture systems by the action of *Bacillus* sp. bacteria. Consequently, the implementation of this strategy offers potential benefits such as reduced reliance on therapeutic interventions and the promotion of environmentally sustainable aquaculture practices (Deepak et al., 2020; Zeng et al., 2020).

The aquamimicry system does not necessitate the adjustment of the carbon-to-nitrogen (C:N) ratio, as it solely relies on the incorporation of a fermented carbon source. Additionally, the introduction of additional probiotics can be undertaken throughout the prawn growth out phase, which distinguished it from the biofloc (BFT) system (Catalani, 2020). The inclusion of fermented carbon sources is a critical factor in establishing the aquamimicry environment and promoting the growth of zooplankton. In the context of aquamimicry, the presence of zooplankton, particularly copepods, plays a significant role in the development of this system (Catalani, 2020). According to Deepak et al. (2020), Rice bran is considered the most favorable choice for a fermented carbon source due to its cost-effectiveness, easy accessibility in markets, and its high content of fibre and nutritional value.

The aquamimicry technique relies heavily on natural products, particularly copepods, as live feed sources for prawns. This approach is commonly referred to as "copefloc" technology (Deepak et al., 2020). Copepods possess a greater nutritional value compared to rotifers due to their abundance in fatty acids, particularly polyunsaturated fatty acids (PUFA) such as arachidonic acid and eicosapentaenoic acid. Additionally, copepods are rich in carotenoids, peptides, vitamins, and minerals, all of which have been recognized as crucial elements for the growth and development of prawns (Satoh et al., 2009). According to (Taher et al. 2017), the inclusion of copepods in the shrimp nursery culture system has been found to have positive effects on the growth performance and immune system of post-larvae (PL) in *Penaeus vannamei.* Additionally, it has been observed that the presence of copepods enhances the feed conversion efficiency in these shrimps. In the aquamimicry system, the rice bran underwent fermentation with a probiotic, followed by the addition of water and a hydrolyzing enzyme. The fermentation process lasted for a duration of 24 hours. The fermentation process was carried out at a pace ranging from 500 to 1000 kg per hectare. Following a week of fermentation, the proliferation of live feed organisms, such as copepods, became evident (Khanjani et al., 2022a).

Generating Monosex Technique

Monosex culture can be achieved through the implementation of manual segregation or sex reversal techniques, both of which are aimed at selectively promoting the desired sex. The manual segregation method, due to its limited reliance on technological advancements, exhibits suboptimal efficacy, prolonged turnaround times for obtaining outcomes, laborious procedures, and unfavorable cost-effectiveness. The sex reversal technique involves the administration of a substantial number of hormones in order to manipulate the sex ratio within a population, ultimately resulting in the desired gender. For example, the induction of sex reversal in fish can be achieved through the manipulation of steroids, as demonstrated by Smith et al. (2009). Based on the studies conducted by Lawrence (2004) and Siddiqui et al. (1997), extensive research trials have been carried out over the past three decades to explore improved techniques for monosex culture production in specific crustacean species. These efforts have led to the successful development of various methods, including androgenic gland (AG) transplantation, androgenic gland ablation, as well as the utilisation of dsRNA and siRNA to suppress the expression of insulin-like androgenic gland hormone (IAG) (Nagamine et al., 1980; Sagi et al., 1990; Manor et al., 2004; Ventura et al., 2009, 2012; Tan et al., 2020 a).

Manual Segregation Method

In this approach, individuals of different sexes were manually segregated and subsequently reared in separate ponds or tanks. The aforementioned technique is commonly employed in the cultivation of fish, particularly tilapia, with the aim of achieving a monosex population. The process of manual sex sorting is characterized by its simplicity and ease of execution. However, it is time-consuming and requires expert personnel to accurately identify the sexes. Consequently, this method is associated with a margin of error ranging from 3% to 10% (Felix et al., 2019). The procedure is doing a visual examination to discern and segregate individuals of different genders by observing outward sexual characteristics such as genital papillae, body size, and body coloration. The practice of segregation in large-scale fish production is not seen practicable due to the substantial quantities of fish that require sorting. This necessitates a significant amount of time, resulting in a sluggish and stressful process for the fish. According to Prabu et al. (2019), manual techniques of segregating small-size Tilapia are both laborious and not very efficient due to the difficulty in accurately discerning the sexual differentiation between males and females. As a result of this factor, the practice of manual segregation is infrequently employed for commercial applications and is primarily suitable for limited-scale manufacturing (Penmann and McAndrew, 2000).

The process of hybridization plays a crucial role in facilitating biological adaptability, maintaining gene flow within populations, and driving the process of biological evolution (Xiao et al., 2011; Xu et al., 2019). Prior to commencing hybridization, it is imperative to possess a comprehensive comprehension of broodstock management, the genetic makeup of said broodstock, as well as the ongoing assessment of the viability and fertility of cultured organisms' offspring (Rahman et al., 2018). In general, it has been observed that interspecific hybrids tend to exhibit a more accelerated growth rate when compared to their respective parent species, as reported by Qin et al. (2020) and documented in Table 3. According to Jiang et al. (2022), triploids can be categorized into autotriploids and allotriploids, based on the source of their chromosome sets. Hybrid triploids, as elucidated by Yoo et al. (2018), exhibited an augmented chromosomal composition, encompassing three sets instead of the conventional two sets.

The observed survival rates of hybrid individuals were typically characterized by a relatively low probability of long-term viability. However, the potentiality could be improved through the induction of triploid genotypes through hybrid crossbreeding, as demonstrated by Bartley et al. (2000) and Yoo et al. (2018). It is worth noting that the intriguing phenomenon of triploid hybrids, resulting from the interplay of hybridization and polyploidization, holds great potential for augmenting heterosis, improving survival rates, promoting growth, and enhancing disease resistance when compared to autopolyploids, as demonstrated by Zhang et al. (2014). Furthermore, the inclusion of triploid individuals, which commonly exhibit sterility, in aquaculture operations can yield several advantages. These advantages encompass enhanced growth rates, heightened environmental tolerance, and increased resilience within culture conditions (Piferrer et al., 2009; Qin et al., 2019). The utilization of triploids in aquaculture systems can lead to enhanced growth rates, as the energy resources are primarily allocated towards growth and development rather than being diverted for gamete production and reproductive processes, owing to their sterile nature (Manan and Ikhwanuddin, 2021). While it is acknowledged that ploidy effects may indeed exist, it is worth noting that triploids exhibit physiological and behavioral similarities to diploids, as observed by Fraser et al. in 2012. Triploids are highly desirable within the aquaculture industry due to their ability to mitigate the financial burden associated with premature maturation. Additionally, they serve as an effective measure to prevent genetic intermingling between wild and cultured populations, thereby minimizing potential environmental hazards that may arise from the escape and subsequent release of hybrid individuals into natural aquatic ecosystems (Taranger et al., 2010; Wang et al., 2020).

Probiotic and Prebiotic Application in Aquaculture

The aquaculture industry encompasses a diverse range of finfish, mollusks, crustaceans, and algal plants, making it a rapidly expanding sector in terms of food production. The demand for aquaculture products has been steadily increasing over the years. Nevertheless, the proliferation of disease outbreaks has emerged as a prominent impediment to the optimal growth and trade of aquaculture. This phenomenon significantly hampers the economic progress of the sector across numerous nations. In the context of the prawn and crab culture subsector, it is worth noting that the growth and development of these organisms are currently being hindered by disease-related challenges. To date, the efficacy of disinfectants and antimicrobial drugs, which are considered conventional approaches, has demonstrated restricted effectiveness in the realm of aquatic disease prevention or treatment. Furthermore, an escalating apprehension has emerged regarding the utilization, and specifically the excessive utilization, of antimicrobial agents, not solely within the realm of human medicine and agriculture, but also within the domain of aquaculture industries (Verschuere et al., 2000). The extensive utilization of antimicrobials for the purpose of promoting growth and preventing diseases in aquatic organisms has resulted in a heightened selective pressure on the microbial realm. Consequently, this practice has inadvertently fostered the natural emergence of bacterial resistance. The proliferation of antibiotic-resistant bacteria persists despite the introduction of antibiotics, and these bacteria possess the ability to horizontally transfer their resistance genes to non-exposed bacterial strains. Hence, it is imperative to conduct additional research and develop novel strategies in order to mitigate the excessive utilization of antimicrobials and address inappropriate practices.

In the realm of disease management, it is imperative to prioritize prevention strategies, as they tend to yield greater cost-effectiveness compared to curative measures. This could potentially lead to a reduced dependence on chemical interventions such as antimicrobials, disinfectants, and pesticides, as these measures primarily address the manifestations of an issue rather than its underlying root cause. Numerous strategies have been suggested for the alternative utilization of antimicrobials in the realm of disease control, showcasing promising outcomes in the field of aquaculture, as extensively documented. The reported decline in the consumption of antimicrobial agents can be attributed to various factors within the realm of fisheries science. One significant factor is the emergence of highly effective vaccines, which have proven to enhance the non-specific defence mechanisms of the host. Additionally, the utilization of immunostimulants, either alone or in conjunction with vaccines, has played a crucial role in this decrease. Furthermore, the implementation of bioaugmentation techniques, as well as the application of both probiotics and prebiotics, has contributed to the overall reduction in antimicrobial agent consumption. Based on the favorable assessments, these alternative methodologies have been recognized as pivotal factors in enhancing the quality of aquatic environments, and as significant domains for prospective investigations in disease management within the field of aquaculture.

Both probiotics and prebiotics have gained significant popularity as feed additives within the aquaculture industry. It is widely acknowledged that these organisms confer advantageous impacts on the host by actively combating diseases. Consequently, they directly enhance growth by augmenting the size and weight of the host. Additionally, in certain instances, they serve as viable alternatives to antimicrobial compounds and also stimulate the host's immune response. In the realm of fisheries science, it is commonly observed that probiotics are present within microbial feed additives that have the ability to regulate the microbial communities found in the gastrointestinal tract. On the other hand, prebiotics are substances added to forage that cannot be digested, but serve to enhance the population or functionality of beneficial bacteria or probiotics residing in the gastrointestinal tract (Akhter et al., 2015). As highlighted by Dimitroglou et al. (2011), the utilization of probiotics and prebiotics in the field of aquaculture has garnered significant interest. This is primarily attributed to their demonstrated efficacy in enhancing production outcomes, promoting the overall health, and bolstering disease resistance of aquatic organisms.

In the field of fisheries science, probiotics have traditionally been characterized as organisms or substances that play a crucial role in maintaining the equilibrium of intestinal microorganisms (Parker, 1974). As per the findings of Gismondo et al. (1999), the nomenclature of probiotic originated from the Greek term's "pro" and "bios," signifying "for life," and is commonly acknowledged as a vital aid that enhances the holistic well-being of the host organism. As per the World Health Organization (WHO) and the Food and Agriculture Organization (FAO), probiotics can be defined as viable microorganisms that, when administered or introduced in an optimal quantity to the host, confer health advantages (FAO, 2001). However, the Food and Agriculture Organization (FAO) and the World Health Organization (WHO) have broadened the scope of aquaculture to encompass a wide range of Gram-positive and Gram-negative bacteria, bacteriophages, microalgae, and yeast (as listed in Table 4). These organisms are utilized in aquaculture either through direct introduction into the water or by incorporating them into the feed in pellet form. The fundamental premise underlying the definition provided by the Food and Agriculture Organization (FAO) and the World Health Organization (WHO) is that probiotics encompass viable microorganisms that are ingested orally and exhibit discernible health benefits. The utilization of these methods has been extensively utilized for the purpose of disease management in the field of aquaculture, with a particular focus on developing nations (FAO, 2001; Irianto and Austin, 2003; Kazun and Kazun, 2014; Nayak, 2010).

Probiotic microorganisms have been recognized for their ability to stimulate the immune system and are commonly utilized for various purposes, primarily to enhance economic productivity, facilitate digestion and absorption, and mitigate the occurrence of infectious diseases (Nayak, 2010). In addition to their immunomodulatory effects, it is widely postulated that these organisms possess a wide range of mechanisms to interact with living organisms. These mechanisms include the ability to outcompete potential pathogens by releasing inhibitory molecules or engaging in direct competition for resources such as space, oxygen, and nutrients within the digestive tract of the host organism (Fuller, 1987). In certain instances, particularly in aquatic organisms, it has been observed that they exhibit an affinity for the mucosal epithelium of the gastrointestinal tract, thereby aiding in the defence against pathogens (Korkea-Aho et al., 2012; Lazado et al., 2011; Luis-Villasenor et al., 2011; Mahdhi et al., 2012). Furthermore, it has been documented that probiotics can augment the food's digestibility through the facilitation of enzymatic processes, including amylases, alginate lyases, and proteases (Zokaeifar et al., 2012; ten Doeschate and Coyne, 2008). Several studies have documented the enhancement of nutrient production, including fatty acids, vitamin B12, biotin, and others, which have been found to positively influence the overall health of the animals under investigation (Sugita et al., 1991; Zhou et al., 2010). The nutrients generated serve as a supplementary source of nourishment, aiding in the enhancement of intestinal microbial equilibrium. This, in turn, provides indirect advantages to the host organism. The utilization of live bacteria as probiotics presents a promising avenue in fisheries research, offering an alternative approach to the use of chemicals and antibiotics. Moreover, these live bacteria exhibit the ability to function as signalling molecules, thereby activating the immune system, as demonstrated by Akhter et al. (2015). To date, considerable focus has been directed towards investigating the immunomodulatory properties of probiotics in the context of aquaculture. The studies pertaining to the efficacy and verification of immune responses in aquatic organisms, specifically fish and shellfish species like prawns, have been extensively documented.

In contrast, prebiotics can be defined as dietary components that are resistant to digestion and have a positive impact on the host organism by specifically fostering the proliferation or functionality of a particular group of bacteria within the colon. They have the potential to modulate the colonic microflora, thereby augmenting the abundance of beneficial bacterial consortia. As per the findings of Akhter et al. (2015), prebiotics serve as a growth stimulant for particular commensal bacteria, which in turn hinder the attachment and infiltration of pathogenic microorganisms in the epithelial lining of the colon. These organisms exhibit a tendency to engage in competition for the identical glycoconjugates present on the epithelial cells of the host. Additionally, they have the capacity to lower the pH levels within the colon, prioritize the barrier function, enhance mucus production, generate short chain fatty acids, and stimulate cytokine production. The majority of prebiotics can be classified as carbohydrates, originating from a diverse range of plant sources or the cell wall constituents of yeast. Fish can be categorized based on their molecular size or polymerization level, including monosaccharides, polysaccharides, or oligosaccharides. Some examples of prebiotics commonly studied in the field of fisheries science include inulin, fructo-oligosaccharides, mannan-oligosaccharides, galacto-oligosaccharides, arabinogalactans, and other similar compounds. These prebiotics have been investigated for their potential effects on the gut microbiota of fish species, as well as their potential to enhance nutrient utilization and overall health in aquaculture systems.

In general, prebiotics exhibit a favourable impact on the gut-associated lymphoid tissue (GALT). Prebiotics, such as inulin and fructo-oligosaccharides, are considered to be nutritional therapeutic preparations, as discussed by Akhter et al. (2015). They are frequently employed to facilitate the proliferation of indigenous bacterial communities and impede the development of pathogens, hence promoting optimal intestinal functionality. In addition to this, they were employed to hinder the initiation and spread of pathogens. The immunosaccharides mentioned in the study conducted by Akhter et al. (2015) have been found to alleviate the function and reliability of phagocytic cells, enhance bacterial activities, activate natural killer cells, complement, lysozyme, and the host's antibody response. Despite the potential benefits that prebiotics offer in terms of promoting health, enhancing growth performance, and improving quality in several terrestrial species, their Utilization in the aquaculture industry for the cultivation of fish and shellfish has been relatively neglected.

Black soldier fly (BSF) as aquatic animal feed

The utilization of animal-protein feed is favored in the poultry and aquaculture sector over plant protein due to its composition of well-balanced essential amino acids and elevated levels of vitamins, in contrast to plant sources (Saima et al., 2008; Swinscoe et al., 2018). The utilization of insects as viable food sources has gained significant traction in contemporary aquaculture practices, with one noteworthy example being the Black Soldier Fly Larvae, scientifically known as *Hermetia illucens* (BSFL). The amino acid composition of Black Soldier Fly Larvae (BSFL) closely resembles that of fish meal, making it a highly viable option for protein substitution in fish diets without compromising nutritional adequacy (Barroso et al., 2014; Lock et al., 2016). The remarkable prevalence of this particular insect species, coupled with its inherent suitability for large-scale cultivation, renders it the optimal selection for utilization as animal feed within the aquaculture sector.

According to the findings presented by Barragan-Fonseca et al. (2017) and Khairuzzaman et al. (2021), it has been established that the Black Soldier Fly Larvae (BSFL) does not exhibit characteristics of a pest insect. The aforementioned insect species exhibits a notable absence of proclivity towards engaging in biting, stinging, or disease transmission activities vis-à-vis humans. This can be attributed to their exclusive reliance on water sources and organic matter remnants for sustenance and developmental progression, as elucidated by Wang and Shelomi in their seminal work published in 2017. Indeed, this particular insect species has been observed to have a negative impact on the population of pathogenic bacteria, such as *Salmonella enteritidis* and Escherichia coli. This can be attributed to the presence of natural bacteria in the gut of the Black Soldier Fly Larvae (BSFL), which serve as prebiotics and possess the ability to eliminate these harmful bacteria (Zheng et al., 2013; Lalander et al., 2015). Furthermore, according to the findings of Park et al. (2014), it has been observed that the larvae of Black Soldier Flies (BSF) possess the ability to produce antimicrobial agents that exhibit efficacy against both gram-positive and gram-negative bacteria.

The remarkable capacity of Black Soldier Fly Larvae (BSFL) to efficiently convert organic waste into a nutrient-dense biomass containing high levels of protein, fat, and other essential nutritional elements renders them a viable alternative to fish meal and other protein sources in the formulation of aquaculture feed (Gao et al., 2019; Zozo et al., 2022). The protein content in Black Soldier Fly Larvae (BSFL) meal ranges from 40 to 60%, as reported by Al-Qazzaz et al. (2016). Similarly, the lipid content varies between 15 to 49%, which is influenced by the processing method employed and the specific substrates utilized in the meal production, as highlighted by Makkar et al. (2014). The utilization of Black Soldier Fly (BSF) larvae within the aquaculture sector is widely recognized for its environmentally advantageous attributes. This is primarily attributed to their remarkable capacity to efficiently convert organic waste materials into a valuable resource, thereby contributing to waste management efforts. Additionally, the adoption of BSF larvae in aquaculture operations is considered a cost-effective investment, further enhancing its appeal within the industry (Kim et al., 2021).

In a case study examining the utilization of Black Soldier Fly Larvae (BSFL)-based pellets as a dietary source for African Catfish fingerlings (*Clarias gariepenus*), noteworthy findings were reported. The fish that were provided with BSFL-based pellets exhibited a final weight gain of 6.45 g, surpassed the weight gain of fish fed a commercial diet consisting of fish meal-based pellets, which was only 1.9 g over a 28-day study period. These results indicated the potential for utilizing BSFL-based pellets as an excellent alternative feed option for African Catfish fingerlings, particularly due to its cost-effectiveness (Hamid et al., 2021). In contrast, the findings of Belghi et al. (2019) indicate that incorporating Black Soldier Fly Larvae (BSFL) meal as a replacement for fish meal in the diet of Atlantic salmon yields positive outcomes, as it does not adversely affect the fish's digestive processes or impede its growth performance. The utilization of Black Soldier Fly Larvae (BSFL) meal was also investigated as a potential alternative to fish meal in the diet of Yellow Catfish, with a substitution rate of 48% (Dietz and Liebert, 2018). Additionally, its efficacy as a replacement for soybean meals, at a substitution rate of 50%, was examined in the diet of Nile Tilapia. Based on extensive research conducted by Rawski et al. (2020) and Kierończyk et al. (2018), it has been observed that cultured fish exhibit a favorable response towards an insect-based diet. This could be attributed to the presence of aromatic compounds in the insects, which served as the potent natural attractants, stimulating the fish to actively consume them. In summary, it is evident that the utilization of BSFL meal holds great potential as a viable protein substitute in the realm of commercial aquaculture food production. These alternative exhibits commendable quality and can be readily generated in substantial quantities, surpassing the reliance on conventional fish meal or soybean meal. Moreover, a significant advantage lies in the reduced production costs attributed to the lower price of the principal ingredient and the streamlined mass production process.

Conclusion

Aquaculture has been confronted with a multitude of challenges in recent times, including disease outbreaks, the need for enhanced broodstock, concerns regarding water quality degradation, and limited land availability. Consequently, the imperative for the advancement of aquaculture technology has become increasingly apparent and obligatory. To effectively enhance aquaculture production and align with the Sustainable Development Goals (SDGs) pertaining to eradicating hunger and poverty, it is imperative for the aquaculture sector to employ a technologically advanced and highly productive approach. Currently, researchers and scientists in the field of aquaculture are diligently working on the advancement of new technologies. These innovations aimed to assist aquaculture societies in achieving enhanced production levels and promoting environmentally friendly practices within aquaculture operations. The ultimate goal is to establish a sustainable framework for aquaculture production in the foreseeable future.

References

Aflalo E.D., Hoang T.T.T., Nguyen V.H., Lam Q., Nguyen D.M., Trinh Q.S., Raviv S., Sagi A. (2006). A novel two-step procedure for mass production of all-male populations of the giant freshwater prawn *Macrobrachium rosenbergii. Aquaculture, 256,* 468–478. https://doi.org/10.1016/j.aquaculture.2006.01.035

Alexander K.A., Hughes A.D. (2017). A problem shared: technology transfer and development in European integrated multitrophic aquaculture (IMTA). *Aquaculture, 473,* 13–19. https://doi.org/10.1016/j.aquaculture.2017.01.029

Al-Qazzaz, M.F., Ismail, D., Akit, H., Idris L.H. (2016). Effect of using insect larvae meal as a complete protein source on quality. *Rev. Bras. de Zootec., 45,* 518–523. https://doi.org/10.1590/S1806-92902016000900003

Assefa, A., & Abunna, F. (2018). Maintenance of Fish Health in Aquaculture: Review of Epidemiological Approaches for Prevention and Control of Infectious Disease of Fish. *Veterinary medicine international*, *2018*, 5432497. https://doi.org/10.1155/2018/5432497

Avnimelech Y. (2007). Feeding with microbial flocs by tilapia in minimal discharge bio-flocs technology ponds. Aquaculture, 264, 140–147. https://doi.org/10.1016/j.aquaculture.2006.11.025

Barragan-Fonseca K.B., Dicke M., Van Loon J.J. (2017). Nutritional value of the BSF (*Hermetia illucens* L.) and its suitability as ani- mal feed – a review. *Journal of Insects as Food and Feed, 3*, 105–120. https://doi.org/10.3920/JIFF2016.0055

Barrington, K., Chopi, T., & Robinson, S. (2009). Integrated multi-trophic aquaculture (IMTA) in marine temperate waters. In Soto. D (Ed.) *Integrated Mariculture: A Global review.* (pp.7-46). FAO.

Barroso F., De Haro C., Sanchez-Muros M., Venegas E., Martinez- Sanchez A., Perez-Banon C. (2014). The potential of various insect species for use as food for fish. *Aquaculture, 422–423*, 193–201. https://doi.org/10.1016/j.aquaculture.2013.12.024

Bartley, D., Rana, K. & Immink, (2000). A. The use of inter-specific hybrids in aquaculture and fisheries. *Reviews in Fish Biology and Fisheries*, 10, 325–337. https://doi.org/10.1023/A:1016691725361

Belghi I., Liland N.S., Gjesdal P., Biancarosa I., Menchetti E., Li Y., Waagbo R., Krogdahl A., & Lock E.J. (2019). Black soldier fly lar- vae meal can replace fish meal in diets of seawater phase Atlantic salmon (*Salmo salar*). *Aquaculture, 503*, 609–619. https://doi.org/10.1016/j.aquaculture.2018.12.032

Bergqvist, J., & Gunnarsson, S. (2011). Finfish aquaculture: animal wel- fare, the environment, and ethical implications. *Journal of Agricultural and Environmental Ethics,* *26*(1), 75-99. https://doi.org/10.1007/s10806-011-9346-y

Che Hashim N.F.C., Manan H.., Okomoda V.T., Ikhwanuddin M., Khor W., Abdullah S.R.S.A., & Kasan N.A. (2021). Inoculation of bioflocculant-producing bacteria for enhanced biofloc formation and pond preparation: Effect on water quality and bacterial community. *Aquaculture Research, 53,* 1602–1607. https://doi.org/10.1111/are.15678

Clarke, J. L., Waheed, M. T., Lössl, A. G., Martinussen, I., & Daniell, H. (2013). How can plant genetic engineering contribute to cost-effective fish vaccine development for promoting sustainable aquaculture?. *Plant molecular biology, 83*(1-2), 33–40. https://doi.org/10.1007/s11103-013-0081-9

Deepak, A.P., Vasava, R.J., Elchelwar, V.R., Tandel, D.H., Vadher, K.H.,Shrivastava, V., & Prabhakar P. (2020). Aquamimicry: New and innovative approach for sustainable development of aquaculture. *Journal of entomology and zoology studies, 8*, 1029-1031.

Canadian Science Advisory Secretariat. (2013). Review of the organic extractive component of integrated multi-trophic aquaculture (IMTA) in Southwest New Brunswick with emphasis on the blue mussel. Retrieved from https://waves-vagues.dfo-mpo.gc.ca/library-bibliotheque/349878.pdf

Dietz C., & Liebert F. (2018). Does graded substitution of soy protein concentrate by an insect meal respond on growth and N-utilization in Nile tilapia (*Oreochromis niloticus*). *Aquaculture Reports, 12,* 43–48. https://doi.org/10.1016/j.aqrep.2018.09.001

Dimitroglou, A., Merrifield, D. L., Carnevali, O., Picchietti, S., Avella, M., Daniels, C., Güroy, D., & Davies, S. J. (2011). Microbial manipulations to improve fish health and production--a Mediterranean perspective. *Fish & shellfish immunology*, *30*(1), 1–16. https://doi.org/10.1016/j.fsi.2010.08.009

Duan, J., Cui, R., Huang, Y., Ai, X., Hao, Y., Shi, H., Huang, A., & Xie Z. (2022). Identification and characterization of four microalgae strains with potential application in the treatment of tail-water for shrimp cultivation. *Algal Research, 66,* 102790. https://doi.org/10.1016/j.algal.2022.102790

Duff, D.C. (1942). The Oral Immunization of Trout Against Bacterium Salmonicida. *The Journal of Immunology*, 44, 87–94.

Dupont, C., Cousin, P., & Dupont, S. (2018). *IoT for aquaculture 4.0 Smart and easy-to-deploy real-time water monitoring with IoT.* Proceeding from 2018

Global Internet of Things Summit (GIoTS), 1–5.

El-Gayar, O.F. (2008). The use of information technology in aquaculture management. *Aquaculture Economics & Managgement, 1*(1-2), 109–128. https://doi.org/10.1080/13657309709380207

El-Sayed, A.F.M. (2021). Use of biofloc technology in shrimp aqua-culture: a comprehensive review, with emphasis on the last decade. *Reviews in Aquaculture, 13,* 676–705. https://doi.org/10.1111/raq.12494

FAO (2001). Health and Nutritional Properties of Probiotics in Food Including Powder Milk with Live Lactic Acid Bacteria. Retrieved from https://www.iqb.es/digestivo/pdfs/probioticos.pdf

FAO. (2020). The State of World Fisheries and Aquaculture 2020. Sustainability in action. Food and Agriculture Organization of The United Nations. Retrieved from https://www.fao.org/3/ca9229en/online/ca9229en.html

FAO/WHO. (2001). Expert Consultation Report on Evaluation of Health and Nutritional Properties of Probiotics in Food Including Powder Milk with Live Lactic Acid Bacteria. Report of a Joint FAO/WHO Expert Consultation, Córdoba, Argentina. http://www.who.int/foodsafety/publications/fs_management/en/probiotics.pdf?ua=1

Felix, E., Avwemoya, F.E., & Abah, A. (2019). Some methods of monosextilapia production: A review. *International Journal of Fisheries and Aquatic Research, 4,* 42–49.

Fraser, T.W., Fjelldal, P.G., Hansen, T., & Mayer, I. (2012). Welfare Considerations of Triploid Fish. *Reviews in Fisheries Science, 20*, 192 - 211. https://doi.org/10.1080/10641262.2012.704598

Fuller R. (1989). Probiotics in man and animals. *The Journal of applied bacteriology*, *66*(5), 365–378.

Gao, Z., Wang, W., Lu, X., Zhu, F., Liu, W., Wang, X., & Lei, C. (2019). Bio- conversion performance and life table of black soldier fly (*Her- metia illucens*) on fermented maize straw. *Journal of Cleaner Production, 230,* 974–980. https://doi.org/10.1016/j.jclepro.2019.05.074

Ge, H. L., Tan, K., Shi, L. L., Sun, R., Wang, W. M., & Li, Y. H. (2020). Comparison of effects of dsRNA and siRNA RNA interference on insulin-like androgenic gland gene (IAG) in red swamp crayfish Procambarus clarkii. *Gene*, *752*, 144783. https://doi.org/10.1016/j.gene.2020.144783

Gismondo, M. R., Drago, L., & Lombardi, A. (1999). Review of probiotics available to modify gastrointestinal flora. *International journal of antimicrobial agents*, *12*(4), 287–292. https://doi.org/10.1016/s0924-8579(99)00050-3

Goh, J. X. H., Tan, L. T. H., Law, J. W. F., Ser, H. L., Khaw, K. Y., Letchumanan, V., Lee, L. H., & Goh, B. H. (2022). Harnessing the potentialities of probiotics, prebiotics, synbiotics, paraprobiotics, and postbiotics for shrimp farming. *Reviews in Aquaculture*, *14*(2), 1478-1557. https://doi.org/10.1111/raq.12659

Gudding R., Goodrich T. (2014). The history of fish vaccination. In: *Fish Vaccination*, Gudding R., Lillehaug A., Evensen O. (eds). 1st ed. John Wiley & Sons, Inc., New York, pp. 1–11.

Gupta, S., Gupta, A., & Hasija, Y. (2022). Chapter 30 – Transforming IoT in Aquaculture: A cloud solution. AI, Edge and IoT-based Smart Agriculture. *Intelligent Data-Centric Systems, 2022,* 517–531.

Hamid N.A.A, Zakaria N.F., Ali N. (2021). Study on utilization of black soldier fly larvae (*Hermetia illucens*) as protein substitute in the pellet diet of *Clarias gariepenus* fingerling. *Advanced Agriculture of Food Research Journal, 3,* 1–6.

Hargreaves J.A. (2006). Photosynthetic suspended-growth system in aquaculture. Aquacultural Engineering, 34, 344–363. https://doi.org/10.1016/j.aquaeng.2005.08.009

Herath, S.S., & Satoh, S. (2015). *Environmental impact of phosphorus and nitrogen from aquaculture. Feed and Feeding Practices in Aquaculture.* Woodhead Publishing, pp. 369–386.

Huan, J., Li, H., Wu, F., & Cao, W. (2020). Design of water quality monitor-ing system for aquaculture ponds based on NB-IoT. *Aquacultural Engineering, 90*, 1–10. https://doi.org/10.1016/j.aquaeng.2020.102088

Hüssy, K., Coad, J. O., Farrell, E. D., Clausen, L. W., & Clarke, M. W. (2012). Sexual dimorphism in size, age, maturation, and growth characteristics of boarfish (*Capros aper*) in the Northeast Atlantic. *ICES Journal of Marine Science, 69*, 1729–1735. https://doi.org/10.1093/icesjms/fss156

Irianto, A., & Austin, B. (2003). Use of dead probiotic cells to control furunculosis in rainbow trout, Oncorhynchus mykiss (Walbaum). *Journal of fish diseases*, *26*(1), 59–62. https://doi.org/10.1046/j.1365-2761.2003.00414.x

Jakobsen, T., & Ajiad, A. (1999). Management implications of sexual dif-ferences in maturation and spawning mortality of Northeast Arctic cod. *Journal of. Northwest Atlantic Fishery Science, 25,* 125–132. https://doi.org/10.2960/J.v25.a11

Jiménez, M., Sobrino, I. & Ramos, F. (1998). Distribution pattern, reproductive biology, and fishery of the wedge sole *Dicologlossa cuneata* in the Gulf of Cadiz, south-west Spain. *Marine Biology, 131,* 173–187 (1998). https://doi.org/10.1007/s002270050308

Karimanzira, D. and Rauschenbach, T. (2019) Enhancing Aquaponics Management with IoT-Based Predictive Analytics for Efficient Information Utilization. *Information Processing in Agriculture, 6,* 375-385. https://doi.org/10.1016/j.inpa.2018.12.003

Kazun B., & Kazun K. (2014). Probiotics in aquaculture. *Medycyna Weterynaryjna, 70,* 25–29.

Kelly, C.J., Connolly, P.L., & Bracken, J.J. (1999). Age estimation, growth, maturity, and distribution of the bluemouth rockfish *Helicolenusd. dactylopterus* (Delaroche 1809) from the Rockall Trough. *ICES Journal of Marine Science, 56,* 61–74. https://doi.org/10.1006/jmsc.1998.0426

Jamaludin, M. A., Wan Khairuzzaman, M., & Abdullah Sani, M. S. (2021). Black Soldier Fly Larvae as Animal Feed: Implications on The Halal Status of Meat Products. *Halalpshere*, *1*(1), 32–42. https://doi.org/10.31436/hs.v1i1.27

Khanjani, M., Mozanzadeh, M. & Fóes, G. (2022a). Aquamimicry system: a sutiable strategy for shrimp aquaculture – a review. *Annals of Animal Science, 22*(4) 1201-1210. https://doi.org/10.2478/aoas-2022-0044

Khanjani, M. H., Zahedi, S., & Mohammadi, A. (2022b). Integrated multitrophic aquaculture (IMTA) as an environmentally friendly system for sustainable aquaculture: functionality, species, and application of biofloc technology (BFT). *Environmental science and pollution research international*, *29*(45), 67513–67531. https://doi.org/10.1007/s11356-022-22371-8

Khanjani, M.H., Mohammadi, A., & Emerenciano, M.G.C. (2022 c). Microorganisms in biofloc aquaculture system. *Aquaculture Reports, 26,* 1–17. https://doi.org/10.1016/j.aqrep.2022.101300

Kierończyk, B., Rawski, M., Pawełczyk, P., Różyńska, J., Golusik, J., Mikołajczak, Z. & Józefiak, D. (2018). Do insects smell attractive to dogs? A comparison of dog reactions to insects and commercial feed aromas – a preliminary study. *Annals of Animal Science, 18*(3), 795-800. https://doi.org/10.2478/aoas-2018-0012

Kim, C.H., Ryu, J., Lee, J., Ko, K., Lee, J., Park, K.Y., & Chung, H. (2021). Use of black soldier fly larvae for food waste treatment and energy production in Asian countries: a review. *Processes, 9,* 161. https://doi.org/10.3390/pr9010161

Korkea-aho, T. L., Papadopoulou, A., Heikkinen, J., von Wright, A., Adams, A., Austin, B., & Thompson, K. D. (2012). Pseudomonas M162 confers protection against rainbow trout fry syndrome by stimulating immunity. *Journal of applied microbiology*, *113*(1), 24–35. https://doi.org/10.1111/j.1365-2672.2012.05325.x

Lakra, W.S., & Ayyappan, S. (2003). Recent advances in biotechnology applications to aquaculture. *Asian-Australasian Journal of Animal*

Sciences, 16, 455–462. https://doi.org/10.5713/ajas.2003.455

Lalander, C.H., Fidjeland, J., Diener, S. *(2015).* High waste-to-biomass conversion and efficient *Salmonella* spp. reduction using black soldier fly for waste recycling. *Agron. Sustain. Dev., 35*, 261–271 (2015). https://doi.org/10.1007/s13593-014-0235-4

Laporte, M., Berrebi, P., Claude, J., Vinyoles, D., Pou-Rovira, Q., Raymond, J. C., Magnan, P., & Handling editor: Zhi-Yun Jia (2018). The ecology of sexual dimorphism in size and shape of the freshwater blenny *Salaria fluviatilis*. *Current zoology*, *64*(2), 183–191. https://doi.org/10.1093/cz/zox043

Lawrence, C.S., Cheng, Y.W., Morriss, N.M., & Williams, I.H. (2000). A comparison of mixed-sex vs. monosex grow out and different diets on the growth rate of freshwater crayfish *Cherax albidus*. *Aquaculture, 185,* 281–289. https://doi.org/10.1016/S0044-8486(99)00358-0

Lazado, C. C., Caipang, C. M., Brinchmann, M. F., & Kiron, V. (2011). In vitro adherence of two candidate probiotics from Atlantic cod and their interference with the adhesion of two pathogenic bacteria. *Veterinary microbiology*, *148*(2-4), 252–259. https://doi.org/10.1016/j.vetmic.2010.08.024

Li, H., Chen, S., Liao, K., Lu, Q., & Zhou, W. (2021). Microalgae biotechnology as a promising pathway to ecofriendly aquaculture: a state-of-the-art review. *Journal of Chemical Technology & Biotechnology*, *96*(4), 837–852. https://doi.org/10.1002/jctb.6624

Lim, J. H., & A Majid, H. (2021). IoT Monitoring System for Aquaculture Farming. *Progress in Engineering Application and Technology*, *2*(1), 567–577.

Lock, E., Arsiwalla, T., & Waagbø, R. (2016). Insect larvae meal as an alternative source of nutrients in the diet of Atlantic salmon (Salmo salar) postsmolt. *Aquaculture Nutrition, 22*, 1202-1213. https://doi.org/10.1111/anu.12343

Luis-Villasenor, I.E., Macias-Rodriguez, M.E., Gomez-Gil, B., Ascencio-Valle, F., & Campa-Cordova A.I. (2011). Beneficial effects of four *Bacillus* strains on the larval cultivation of *Litopenaeus vannamei*. *Aquaculture, 321,* 136–144. https://doi.org/10.1016/j.aquaculture.2011.08.036

Ma, J., Bruce, T. J., Jones, E. M., & Cain, K. D. (2019). A Review of Fish Vaccine Development Strategies: Conventional Methods and Modern Biotechnological Approaches. *Microorganisms*, *7*(11), 569. https://doi.org/10.3390/microorganisms7110569

Ma, K., Bao, Q., Wu, Y., Chen, S., Zhao, S., Wu, H., & Fan, J. (2020). Evaluation of Microalgae as Immunostimulants and Recombinant Vaccines for Diseases Prevention and Control in Aquaculture. *Frontiers in bioengineering and biotechnology*, *8*, 590431. https://doi.org/10.3389/fbioe.2020.590431

Mahdhi, A., Kamoun, F., Messina, C.M., Santulli, A., & Bakhrouf, A. (2012). Probiotic properties of Brevibacillus brevis and its influence on sea bass (Dicentrarchus labrax) larval rearing. *African Journal of Microbiology Research,* 6, 6487-6495. https://doi.org/10.5897/AJMR12.1201

Makkar, H., Tran, G., Heuzé, V., & Ankers, P. (2014). State-of-the-art on use of insects as animal feed. *Animal Feed Science and Technology, 197*, 1-33. https://doi.org/10.1016/j.anifeedsci.2014.07.008

Manan, H., Moh, J.H.Z., Kasan, N.A., Suratman, S., & Ikhwanuddin, M. (2017). Identification of biofloc microscopic composition as the natural bioremediation in zero water exchange of Pacific white shrimp, *Penaeus vannamei*, culture in closed hatchery system. *Applied Water Science, 7,* 2437–2446. https://doi.org/10.1007/s13201-016-0421-4

Manan, H., Rosland, N.A., Deris, Z.M., Hashim, N.F.C., Kasan, N.A., Ikhwanuddin, M., Suloma, A., & Fauzan, F. (2022). 16S rRNA se- quences of *Exiguobacterium* spp. bacteria dominant in a biofloc pond cultured with Whiteleg shrimp, Penaeus vannamei. *Aquacultural Research, 53,* 2029–2041. https://doi.org/10.1111/are.15731

Manor, R., Aflalo, E., Segall, C., Weil, S., Azulay, D., & Ventura, T. (2004) Androgenic Gland Implantation Promotes Growth and Inhibits Vitellogenesis in Cherax quadricarinatus Females Held in Individual Compartments. *Invertebrate Reproduction & Development, 45,* 151-159. https://doi.org/10.1080/07924259.2004.9652584

Meril, D., Piliyan, R., Perumal, S., Sundarraj, D.K., & Binesh, A. (2022). Efficacy of alginate immobilized microalgae in the bioremedia- tion of shrimp aquaculture wastewater. *Process Biochemistry, 122.* 196–202. https://doi.org/10.1016/j.procbio.2022.08.030

Mondal, H., & Thomas, J. (2022). A review on the recent advances and application of vaccines against fish pathogens in aquaculture. *Aquaculture international : journal of the European Aquaculture Society*, *30*(4), 1971–2000. https://doi.org/10.1007/s10499-022-00884-w

Muller-Feuga, A. (2000). The role of microalgae in aquaculture: situation and trends. *Journal of Applied Phycology, 12*(3-5), 527-534. https://doi.org/10.1023/A:1008106304417

Nagamine, C., Knight, A. W., Maggenti, A., & Paxman, G. (1980). Masculinization of female Macrobrachium rosenbergii (de Man) (Decapoda, Palaemonidae) by androgenic gland implantation. *General and comparative endocrinology*, *41*(4), 442–457. https://doi.org/10.1016/0016-6480(80)90049-0

Nagappan, S., Das, P., AbdulQuadir, M., Thaher, M., Khan, S., Mahata, C., Al-Jabri, H., Vatland, A. K., & Kumar, G. (2021). Potential of microalgae as a sustainable feed ingredient for aquaculture. *Journal of biotechnology*, *341*, 1–20. https://doi.org/10.1016/j.jbiotec.2021.09.003

Nair, C.M., Salin, K.R., Raju, M.S., & Sebastian, M. (2006). Economic analysis of monosex culture of giant freshwater prawn (Macrobrachium rosenbergii De Man): a case study. *Aquaculture Research, 37*, 949-954. https://doi.org/10.1111/j.1365-2109.2006.01521.x

Nayak S. K. (2010). Probiotics and immunity: a fish perspective. *Fish & shellfish immunology*, *29*(1), 2–14. https://doi.org/10.1016/j.fsi.2010.02.017

Neori, A., Chopin, T., Troell, M., Buschmann, A.H., Kraemer, G.P., Halling, C., Shpigel, M. & Yarish C. (2004). Integrated aquaculture: rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. *Aquaculture, 231,* 361–391. https://doi.org/10.1016/j.aquaculture.2003.11.015

Panigrahi, A., Otta, S.K., Kumaraguru Vasagam, K.P., Shyne Anand, P.S., Biju, I.F., & Aravind, R., (2019). Training manual on Biofloc technology for nursery and grow-out aquaculture. *CIBA TM Series, 15,* 172.

Park, S., Chang, B.S., & Yoe, S.M. (2014). Detection of antimicrobial substances from larvae of the black soldier fly, Hermetia illucens (Diptera: Stratiomyidae). *Entomological Research, 44*. https://doi.org/10.1111/1748-5967.12050

Parker, R.B. (1974) Probiotics, the Other Half of Antibiotic Story. *Animal Nutrition & Health, 29*, 4-8.

Penman D.J., McAndrew B.J. (2000). Genetics for the management and improvement of cultured tilapias. In: T*ilapias: Biology and exploitation.* Springer, Dordrecht, pp. 227–266.

Perdikaris, C., Chrysafi, A., & Ganias, K. (2016). Environmentally friendly practices and perceptions in aquaculture: a sectoral case-study from a Mediterranean-based industry. *Rev. Fish. Sci., 24*, 113– 125.

Piferrer, F., Beaumont, A., Falguière, J.C., Flajšhans, M., Haffray, P., Colombo, L. (2009). Polyploid fish and shellfish: production, biology and applications to aquaculture for performance improvement and genetic containment. *Aquaculture, 293,* 125–156. https://doi.org/10.1016/j.aquaculture.2009.04.036

Prabu, E., Rajagopalsamy, C.B.T., Ahilan, B., Jeevagan, I.J.M.A., & Renuhadevi, M. (2019). Tilapia – an excellent candidate species for world aquaculture: a review. *Annual research & review in* *biology,* 1-14. https://doi.org/10.9734/ARRB/2019/V31I330052

Prapti, D.R., Shariff, A.R.M., Che Man, H., Ramli, N.M.., Perumal, T., & Shariff, M. (2021). Internet of Things (IoT)-based aquaculture: An overview of IoT application on water quality monitoring. *Reviews of Aquaculture, 14,* 979–992.

Qin, Y., Zhang, Y., Mo, R., Zhang, Y., Li, J., Zhou, Y., Ma, H., Xiao, S., & Yu, Z. (2019). Influence of ploidy and environment on grow-out traits of diploid and triploid Hong Kong oysters *Crassostrea hongkongensis* in southern China. *Aquaculture, 507*, 108–118. https://doi.org/10.1016/j.aquaculture.2019.04.017

Rahman M.A., Lee S.G., Yusoff F.M., Rafiquzzaman S.M. (2018). Hy-bridization and its application in aquaculture. In: *Sex control in aquaculture,* Wang H.P., Piferrer F., Chen S.L., Shen Z.G. (eds). John Wiley & Sons, pp. 163–178.

Raju, K.R.S.R., & Varma, G.H.K. (2017). *Knowledge Based Real Time monitoring system for aquaculture using IoT.* Proc. IEEE 7th International Advance computing conference (IACC), pp. 318–321.

Rawski, M., Mazurkiewicz, J., Kierończyk, B., & Józefiak, D. (2020). Black Soldier Fly Full-Fat Larvae Meal as an Alternative to Fish Meal and Fish Oil in Siberian Sturgeon Nutrition: The Effects on Physical Properties of the Feed, Animal Growth Performance, and Feed Acceptance and Utilization. *Animals : an open access journal from MDPI*, *10*(11), 2119. https://doi.org/10.3390/ani10112119

Restrepo, L., Domínguez-Borbor, C., Bajaña, L., Betancourt, I., Rodríguez, J., Bayot, B., & Reyes, A. (2021). Microbial community characterization of shrimp survivors to AHPND challenge test treated with an effective shrimp probiotic (Vibrio diabolicus). *Microbiome*, *9*(1), 88. https://doi.org/10.1186/s40168-021-01043-8

Roderick E. (2004). Monosex tilapia production. Global aquaculture advocate. Retrieved from https://www.globalseafood.org/advocate/monosex-tilapia-production/

Romano N. (2017). Aquamimicry: a revolutionary concept for shrimp farming. The Global Aquaculture Advocate. Retrieved from https://www.globalseafood.org/advocate/aquamimicry-a-revolutionary-concept-for-shrimp-farming/

Rosa, J., Lemo, M.F.L., Crespo, D., Nunes, M., Freitas, A., Ramos, F., Miguel, Â.P., & Leston, S. (2020). Integrated multitrophic aquaculture systems – potential risks for food safety. *Trends in Food Science & Technology, 96,* 79–90. https://doi.org/10.1016/j.tifs.2019.12.008

Rosen, O., Manor, R., Weil, S., Gafni, O., Linial, A., Aflalo, E. D., Ventura, T., & Sagi, A. (2010). A sexual shift induced by silencing of a single insulin-like gene in crayfish: ovarian upregulation and testicular degeneration. *PloS one*, *5*(12), e15281. https://doi.org/10.1371/journal.pone.0015281

Sagi A. (2013). Monosex culture of prawns through androgenic gene silencing. Infofish International. Retrieved from globalseafood.org/advocate/monosex-culture-of-prawns-through-temporal-andro-genic-gene-silencing/

Sagi, A., & Aflalo, E.D. (2005). The androgenic gland and monosex culture of freshwater prawn Macrobrachium rosenbergii (De Man): a biotechnological perspective. *Aquaculture Research, 36*, 231-237. https://doi.org/10.1111/j.1365-2109.2005.01238.x

Sagi, A., Ra'anan, Z., Cohen, D., & Wax, Y. (1986). Production of *Macrobrachium rosenbergii* in monosex population: yield characteristics under intensive monoculture conditions in cages. *Aquaculture, 51,* 265–275. https://doi.org/10.1016/0044-8486(86)90318-2

Sagi, A., Cohen, D., & Milner, Y. (1990). Effect of androgenic gland ablation on morphotypic differentiation and sexual characteristics of male freshwater prawns, Macrobrachium rosenbergii. *General and comparative endocrinology*, *77*(1), 15–22. https://doi.org/10.1016/0016-6480(90)90201-v

Saha, S., Hasan, Rajib, R., & Kabir, S. (2018). *IoT based automated fish farm aquaculture monitoring system.* Proc. International Con- ference on Innovations in Science, Engineering and Technology (ICISET), pp. 201–206.

Saima, M.A., Khan, M.Z., Anjum, M.I., Ahmed, S., Rizwan, M., & Ijaz M. (2008). Investigation on the availability of amino acids from dif- ferent animal protein sources in golden cockerels. *The Journal of Animal and Plant Sciences, 18,* 3–56.

Sandhya, S., Sandeep, K.P., & Vijayan, K.K. (2020). In vivo evaluation of microbial cocktail of microalgae-associated bacteria in larval rearing from zoea I to mysis I of the Indian white shrimp, Penaeus indicus. *Journal of Applied Phycology, 32*, 3949 - 3954. https://doi.org/10.1007/s10811-020-02230-0

Sanz-Lazaro, C., & Sanchez-Jerez, P. (2020). Regional Integrated Multi-Trophic Aquaculture (RIMTA): Spatially separated, ecologically linked. *Journal of environmental management*, *271*, 110921. https://doi.org/10.1016/j.jenvman.2020.110921

Satoh, N., Takaya, Y., & Takeuchi, T. (2009). The effect of docosahexaenoic and eicosapentaenoic acids in live food on the development of abnormal morphology in hatchery-reared brown sole pseudopleuronectes herzensteini. Fisheries Science, 75(4), 1001-1006. https://doi.org/10.1007/s12562-009-0125-x

Sharifinia, M., Keshavarzifard, M., Hosseinkhezri, P., Khanjani, M. H., Yap, C. K., Smith, W. O., Jr, Daliri, M., & Haghshenas, A. (2022). The impact assessment of desalination plant discharges on heavy metal pollution in the coastal sediments of the Persian Gulf. *Marine pollution bulletin*, *178*, 113599. https://doi.org/10.1016/j.marpolbul.2022.113599

Shefat, S. (2018). Vaccines for use in finfish aquaculture. *Acta Scientific Pharmaceutical Sciences, 2,* 15–19.

Shreedharan K., Kulkarni A., Rajendran K.V. (2022). Prospects of vaccination in crustaceans with special reference to shrimp. In: *Fish immune system and vaccines,* Makesh M., Rajendran K.V. (eds). Springer, Singapore, pp. 181–216.

Sirakov, I., Velichkova, K., Stoyanova, S., & Staykov, Y. (2015). The importance of microalgae for aquaculture industry. *International Journal of Fisheries and Aquatic Studies, 2*, 31–37.

Smith, C. A., Roeszler, K. N., Ohnesorg, T., Cummins, D. M., Farlie, P. G., Doran, T. J., & Sinclair, A. H. (2009). The avian Z-linked gene DMRT1 is required for male sex determination in the chicken. *Nature*, *461*(7261), 267–271. https://doi.org/10.1038/nature08298

Snieszko, S.F., & Friddle, S.B. (1949). Prophylaxis of furunculosis in brook trout (*Salvelinus fontinalis*) by oral immunization and sulfamerazine. *Progressive Fish-Culturist, 11,* 161–168.

Snieszko, S., Piotrowska, W., Kocylowski, B., & Marek, K. (1938). *Badania bakteriologiczne i serologiczne nad bakteriami posocznicy karpi. Memoires de l'Institut d'Ichtyobiologie et Pisciculture de la Station de Pisciculture Experimentale a Mydlniki de l'Universite Jagiellonienne a Cracovie,* Nr 38.

Soto, D. (2009). *Integrated mariculture: a global review.* FAO fisheries and aquaculture technical paper no. 529. Food and Agriculture Organization of the United Nations (FAO).

Soto-Rodriguez, S.A., Magollon-Servin, P., Lopez-Vela, M., & Sot M.N. (2021). Inhibitory effect of marine microalgae used in shrimp hatcheries on *Vibrio parahaemolyticus* responsible for acute hepatopancreatic necrosis disease. *Aquacultural Research, 53,* 1337–1347. https://doi.org/10.1111/are.15668

Su, H., Yakovlev, I. A., van Eerde, A., Su, J., & Clarke, J. L. (2021). Plant-Produced Vaccines: Future Applications in Aquaculture. *Frontiers in plant science*, *12*, 718775. https://doi.org/10.3389/fpls.2021.718775

Sugita, H., Miyajim,a C., & Deguchi, H. (1991). The vitamin B_{12}-producing ability of the intestinal microflora of freshwater fish. *Aquaculture, 92,* 267–276. https://doi.org/10.1016/0044-8486(91)90028-6

Swinscoe, I., Oliver, D.M., Gilburn, A.S., Lunestad, B.T., Lock, E., Ørnsrud, R., & Quilliam, R.S. (2019). Seaweed-fed black soldier fly (Hermetia illucens) larvae as feed for salmon aquaculture: assessing the risks of pathogen transfer. *Journal of Insects as Food and Feed*, 5, 1–14. https://doi.org/10.3920/JIFF2017.0067

Taher, S., Romano, N., Arshad, A., Ebrahimi, M., The, J.C., Ng, W.K., & Kumar, V. (2017). Assessing the feasibility of dietary soybean meal replacement to the swimming crab, *Portunus pelagicus*, juveniles. *Aquaculture, 469,* 88–94. https://doi.org/10.1016/j.aquaculture.2016.11.036

Taketomi, Y., Murata, M., & Miyawaki, M. (1990). Androgenic Gland and Secondary Sexual Characters in the Crayfish Procambarus clarkii. *Journal of Crustacean Biology*, *10*(3), 492–497. https://doi.org/10.2307/1548339

Tan, K., Zhou, M., Jiang, H., Jiang, D., Li, Y., & Wang, W. (2020). siRNA-Mediated MrIAG Silencing Induces Sex Reversal in Macrobrachium rosenbergii. *Marine biotechnology (New York, N.Y.)*, *22*(3), 456–466. https://doi.org/10.1007/s10126-020-09965-4

Ta,n K., Jiang, H., Jiang, D., & Wang, W. (2020 b). Sex reversal and the androgenic gland (AG) in *Macrobrachium rosenbergii:* A review. Aquaculture & Fisheries, 5, 283–288. https://doi.org/10.1016/j.aaf.2019.11.004

Taranger, G. L., Carrillo, M., Schulz, R. W., Fontaine, P., Zanuy, S., Felip, A., Weltzien, F. A., Dufour, S., Karlsen, O., Norberg, B., Andersson, E., & Hansen, T. (2010). Control of puberty in farmed fish. *General and comparative endocrinology*, *165*(3), 483–515. https://doi.org/10.1016/j.ygcen.2009.05.004

Ten Doeschate, K.I., & Coyne, V.E. (2008). Improved growth rate in farmed *Haliotis midae* through probiotic treatment. *Aquaculture, 284,* 174–179. https://doi.org/10.1016/j.aquaculture.2008.07.018

Thomas, M., Pasquet, A., Aubin, J., Nahon, S., & Lecocq, T. (2021). When more is more: taking advantage of species diversity to move to- wards sustainable aquaculture. *Biological Reviews, 96*(2), 767-784. https://doi.org/10.1111/brv.12677

Tom, A.P., Jayakumar, J.S., Biju, M., Somaraja, J., & Ibrahim, M.A. (2021). Aquaculture wastewater treatment technologies and their sustain- ability: a review. *Energy Nexus., 4,* 1–9. https://doi.org/10.1016/j.nexus.2021.100022

Troell, M., Joyce, A., Chopin, T., Neori, A., Buschmann, A.H., & Fang, J.G. (2009). Ecological engineering in aquaculture – potential for inte- grated multi-trophic aquaculture (IMTA) in marine offshore systems. *Aquaculture, 297*, 1–9. https://doi.org/10.1016/j.aquaculture.2009.09.010

Ventura T. (2018). Monosex in Aquaculture. In: Marine organisms as model systems in biology and medicine. *Results and problems in cell differentiation,* Kloc M., Kubiak J. (eds). Springer, Cham, 65.

Ventura, T., & Sagi, A. (2012). The insulin-like androgenic gland hormone in crustaceans: From a single gene silencing to a wide array of sexual manipulation-based biotechnologies. *Biotechnology advances*, *30*(6), 1543–1550. https://doi.org/10.1016/j.biotechadv.2012.04.008

Ventura, T., Manor, R., Aflalo, E. D., Weil, S., Raviv, S., Glazer, L., & Sagi, A. (2009). Temporal silencing of an androgenic gland-specific insulin-like gene affecting phenotypical gender differences and spermatogenesis. *Endocrinology*, *150*(3), 1278–1286. https://doi.org/10.1210/en.2008-0906

Ventura, T., Rosen, O., & Sagi, A. (2011). From the discovery of the crustacean androgenic gland to the insulin-like hormone in six decades. *General and comparative endocrinology*, *173*(3), 381–388. https://doi.org/10.1016/j.ygcen.2011.05.018

Ventura, T., Manor, R., Aflalo, E. D., Weil, S., Rosen, O., & Sagi, A. (2012). Timing sexual differentiation: full functional sex reversal achieved through silencing of a single insulin-like gene in the prawn, Macrobrachium rosenbergii. *Biology of reproduction*, *86*(3), 90.

https://doi.org/10.1095/biolreprod.111.097261

Verschuere, L., Rombaut, G., Sorgeloos, P., & Verstraete, W. (2000). Probiotic bacteria as biological control agents in aquaculture. *Microbiology and molecular biology reviews : MMBR*, *64*(4), 655–671. https://doi.org/10.1128/MMBR.64.4.655-671.2000

Wang, Y. S., & Shelomi, M. (2017). Review of Black Soldier Fly (Hermetia illucens) as Animal Feed and Human Food. *Foods (Basel, Switzerland)*, *6*(10), 91. https://doi.org/10.3390/foods6100091

Xiao, J., Zou, T., Chen, Y., Chen, L., Liu, S., Tao, M., Zhang, C., Zhao, R., Zhou, Y., Long, Y., You, C., Yan, J., & Liu, Y. (2011). Coexistence of diploid, triploid and tetraploid crucian carp (Carassius auratus) in natural waters. *BMC genetics*, *12*, 20. https://doi.org/10.1186/1471-2156-12-20

Xu, H., Li, Q., Han, Z., Li, S., Yu, H., & Kong, L. (2019). Fertilization, survival and growth of reciprocal crosses between two oysters, *Crassostrea gigas* and *Crassostrea nippona.* Aquaculture, 507, 91–96. https://doi.org/10.1016/j.aquaculture.2019.04.012

Yoo G.Y., Lee T.H., Gil H.W., Lim S.G., Park I.S. (2018). Various Characteristics of Hybrid between River Puffer, *Takifugu obscurus* and Tiger Puffer, *T. rubripes*, and Their Hybrid Triploid. *Development & reproduction*, *21*(2), 181–191. https://doi.org/10.12717/DR.2017.21.2.181

Yue, K., & Shen, Y. (2022). An overview of disruptive technologies for aquaculture. *Aquaculture and Fisheries, 7,* 111–120. https://doi.org/10.1016/j.aaf.2021.04.009

Yuvarajan, P. (2020). Study on floc characteristics and bacterial count from biofloc-based genetically improved farmed tilapia culture system. Aquaculture Research, 52, 1743–1756. https://doi.org/10.1111/are.15030

Zeng, S., Khoruamkid, S., Kongpakdee, W., Wei, D., Yu, L., Wang, H., Deng, Z., Weng, S., Huang, Z., He, J., & Satapornvanit, K. (2020). Dissimilarity of microbial diversity of pond water, shrimp intestine and sediment in Aquamimicry system. *AMB Express*, *10*(1), 180. https://doi.org/10.1186/s13568-020-01119-y

Zhang, P., Peng, R., Jiang, X., Jiang, M., & Zeng, G. (2022 b). Effects of *Nannochloropsis oculata* and *Thalassiosira pseudonana* mono- cultures on growth performance and nutrient composition of *Lito- penaeus vannamei. Algal Research, 66.* https://doi.org/10.1016/j.algal.2022.102769

Zheng, L., Crippen, T. L., Singh, B., Tarone, A. M., Dowd, S., Yu, Z., Wood, T. K., & Tomberlin, J. K. (2013). A survey of bacterial diversity from successive life stages of black soldier fly (Diptera: Stratiomyidae) by using 16S rDNA pyrosequencing. *Journal of medical entomology*, *50*(3), 647–658. https://doi.org/10.1603/me12199

Zhou, Q.C., Buentello, J.A., & Gatlin III, D.M. (2010). Effects of dietary prebiotics on growth performance, immune response and intesti- nal morphology of red drum (*Sciaenops ocellatus*). *Aquaculture, 309,* 253–257. https://doi.org/10.1016/j.aquaculture.2010.09.003

Zokaeifar, H., Balcázar, J. L., Saad, C. R., Kamarudin, M. S., Sijam, K., Arshad, A., & Nejat, N. (2012). Effects of Bacillus subtilis on the growth performance, digestive enzymes, immune gene expression and disease resistance of white shrimp, Litopenaeus vannamei. *Fish & shellfish immunology*, *33*(4), 683–689. https://doi.org/10.1016/j.fsi.2012.05.027

Zozo, B., Wicht, M. M., Mshayisa, V. V., & van Wyk, J. (2022). The Nutritional Quality and Structural Analysis of Black Soldier Fly Larvae Flour before and after Defatting. *Insects*, *13*(2), 168. https://doi.org/10.3390/insects13020168