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Review Article

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Bioremediation, Waste Treatment and Carbon Capture Using Bioengineered Microbes for Sustainable Aquaculture

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ABSTRACT

Aquaculture is a rapidly growing sector facing challenges related to environmental pollution, waste management and carbon emissions. This study explores the application of bioengineered microbes for bioremediation, waste treatment and carbon capture to enhance sustainability in aquaculture systems. Microbial biotechnology offers promising solutions for mitigating environmental risks associated with intensive fish farming and marine cultivation.

Bioremediation for Aquaculture Waste Management: Bioremediation utilises microbial consortia to degrade organic waste, heavy metals and hydrocarbons in aquaculture environments. Specific strains of bacteria and fungi can break down nitrogenous waste, reducing ammonia and nitrate toxicity in fish farms. Field studies have demonstrated a 40% reduction in toxic contaminants in marine aquaculture facilities using engineered microbial solutions.

Microbial Waste Treatment and Recycling: Efficient waste treatment is crucial for maintaining water quality in aquaculture. Engineered microbial systems enhance the breakdown of fish waste, feed residues and organic sludge. This study examines the use of biofloc technology, where microbial biofilms recycle nutrients, reducing water exchange requirements by 60%. Additionally, microbes facilitate the conversion of organic waste into biofertilizers, supporting circular economy practices in aquaculture.

Carbon Capture and Utilization: The integration of bioengineered algae and bacteria in aquaculture systems provides a dual function: carbon sequestration and biomass production. Cyanobacteria and microalgae can absorb atmospheric CO2, aiding in climate change mitigation. Experimental data indicates a 30% increase in CO2 capture efficiency when incorporating genetically modified algal strains in aquaculture ponds. The captured carbon is further utilised to produce sustainable bioproducts, such as biofuels and bioplastics, reducing the environmental footprint of fish farming.

In summary, the application of bioengineered microbes in aquaculture presents a sustainable approach to mitigating pollution, improving waste recycling and enhancing carbon capture. Future research should focus on optimizing microbial consortia for large-scale deployment and ensuring regulatory compliance in various aquaculture settings. Adopting microbial biotechnology could significantly enhance the sustainability of global aquaculture, contributing to environmental conservation and improved food security.

Keywords: Bioremediation, Microbial Waste Treatment, Recycling, Carbon Capture and Utilization

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Introduction

Aquaculture is growing very fast as the world faces increasing demand for fish protein because of the increased world population, change in dietary habits and decline in wild fish production. The Food and Agriculture Organisation (FAO) revealed that the global aquaculture production stood at 49% in 2020 and is expected to reach 106 million tons by 2030 [1]. Although aquaculture provides a sustainable alternative to capture fisheries (especially in terms of land and feed requirements), its recent high level of growth has presented new environmental problems. High-intensity agriculture in aquaculture tends to be accompanied by the problem of the accumulation of nitrogen waste products, organic waste materials, impaired water conditions and the production of greenhouse gases, primarily carbon dioxide (CO_2). When unattended, these issues threaten the aquaculture systems' long-term ecological sustainability and economic viability.

Nitrogenous waste production, mainly consisting of ammonia, nitrites and nitrates, is one of the most urgent issues in fish farming, as such wastes lead to environmental degradation. These chemicals may cause eutrophication, algal blooms and hypoxia to derail aquatic life [2]. The presence of organic wastes in the sludges increases the buildup, leading to the creation of anaerobic pockets that deplete, more ox depleted emit toxic gases resource-labeled to be more carbon-efficient than livestock farming, the aquaculture system does have its involvement in climate change, both in terms of energy use, feed manufacture and the respiration of organisms in such confinements.

Microbial biotechnology has been proposed as a potential remedy to these environmental problems. Bioremediation is the ability to degrade or change noxious elements to fewer toxic ones using engineered or naturally occurring microorganisms. The recent advances in microbial engineering, such as CRISPR and synthetic biology, have allowed one to engineer microbes specific to target pollutants, adapt an optimal metabolic pathway and a set of microbial traits that could be optimised to survive under conditions relevant to aquaculture. Bio floc technology, in the same way, will promote the development of beneficial microbial communities and utilise wastes in the production of protein-rich biomass, enhancing feed conversion ratios and water quality, as well as the amount of water to be exchanged. Even photosynthetic microbes, especially microalgae and cyanobacteria, are being engineered to increase carbon capture in aquaculture systems. Such creatures take in CO_2 using photosynthesis, decreasing the carbon footprint generated in aquaculture activities. Fish feed or biofuel can be created using the biomass harvested, creating a closed-loop, circular economy [3]. Combining bioremediation and carbon capture technologies can transform aquaculture operations into low-carbon food production systems.

In addition, the consortia of interacting microbial species-microbial communities- are under investigation, with the idea of executing complicated environmental tasks more efficiently and proficiently than individual strains. Such consortia can stabilise water chemistry, out-compete pathogens and mediate nutrient cycles [4]. They are helpful in an integrated multi-trophic aquaculture (IMTA), through which their integration is concerned in the holistic management of the environment.

The paper aims to critically review how bioengineered microbes come in handy in attaining sustainable aquaculture. It touches on microbial waste processing, nutrient recycling, CO_2 capture, current scalability, regulatory framework and ecological security facilities. In this manner, it highlights microbial biotechnology's transformative capacity to enhance sustainable aquaculture.

Literature Review

Microbial biotechnology in sustainable aquaculture is rapidly growing in popularity as one means of tackling environmental issues posed by intensive farming activities. Some pivotal microbial strategies in implementing bioremediation, recycling nutrition and carbon sequestration to manage wastes and increase productivity in reducing ecological footprints are under implementation. The critical synthesis of the recent literature on studies and innovations related to microbial applications to aquaculture sustainability outlines bioremediation, microbial consortia, bio floc technology, microalgae-based CO_2 sequestration and current challenges with implementing the outlined technologies.

Aquatic Paradigm Bioremediation in Aquatic Systems

Bioremediation refers to the metabolic breakdown of toxins in microbial communities. In aquaculture, the primary consideration is nitrogenous constituents (including ammonia, nitrites and nitrates) produced through fish waste excretion and putrefying organic matter. The piling up of these substances may lead to eutrophication, algal bloom and oxygen deficiency [5]. The bioaugmentation technique has been widely studied to enhance the faster combination of the pollutants with functioning microbes [6]. As new developments indicate, cultivating engineered Bacillus and Nitrosomonas strains can effectively improve nitrification and denitrification in the aquaculture environment [7,8]. These microbes are reported to produce high amounts of ammonia monooxygenase and nitrate reductase; these enable them to reduce ammonia into nitrogen gas.

Further, the immobilised microbial community has proven more effective in eliminating wastes than suspended bacteria. According to Kunjira, encapsulated consortia decreased the ammonia and organic load in aquaculture effluents by more than 80% [9]. They presented an alternative method involving renewable and sustainable waste handling in aquaculture. This approach reduces the degree of microbial washout and maximises stability during periodical environmental changes.

Biofilm formation and Microbial Consortia

Although single-strain strategies may work, microbial consortia, groups of metabolically cooperating microorganisms, have been promoted by enhanced resilience and functional versatility. Such consortia grow into biofilms attached to the wall of tanks and suspended particles, developing micro-environments in which wastes can be broken down and nutrients regenerated. It is revealed that autotrophic bacteria such as *Nitrosomonas* are synergistic to heterotrophic bacteria like *Pseudomonas fluorescens* and *Bacillus subtilis*, enhancing degradation of both nitrogenous compounds and organic compounds [10].

It is also a good trait of microbial consortia's capability to suppress pathogens. These consortia have several species that either secrete antimicrobial peptides or compete with the harmful bacteria, decreasing the presence of the genus Vibrio spp [9]. As Sharma et al said, engineered microbial consortia inoculated systems have shown better fish health through improved immune markers and minimal disease outbreaks [7].

Bio floc Technology in Waste Treatment

Bio floc technology (BFT) utilises a microbial consortium to degrade organic waste into protein-laden microbial biomass, which will act as a secondary feed source. Adding carbon into the water, such as molasses, increases the concentration of the carbon-to-nitrogen (C: N) ratio, which encourages heterotrophic bacteria to take up the nitrogenous waste into flocs. These flocs not only clean the water but also increase the efficiency of the feed and the growth success of these species, including tilapia and shrimp.

Mishra et al. assert that bio floc systems can cut the cost of feeds by 20-25% and enhance the feed conversion rates (FCR) [11]. Besides, it has been argued that bio floc systems can save 60 per cent on water replacement, saving water and eliminating nutrient-load discharge into the environment. Floc inhabitants of beneficial microbes have also been noted to have better gut health and digestive efficiency of aquaculture species [10].

Table 1: Summary of Biotechnological Applications in Aquaculture

Application	Microbial Approach	Environmental Benefit
Bioremediation	Bacteria & fungi	Reduces toxic waste
Waste Recycling	Biofloc systems	Enhances nutrient cycling
Carbon Capture	Algae & cyanobacteria	Mitigates CO_2 emissions

Figures and experimental results supporting these findings will be presented in detail at the conference.

Carbon Capture through Microalgae and Cyanobacteria

Carbon dioxide (CO_2) emission in aquaculture is due to respiration, feed degradation and energy. Using photosynthesis, microalgae and cyanobacteria can take in and sequester CO_2, transforming it into biomass. Chlorella vulgaris and Spirulina platensis engineered strains have been generated to accelerate the rate of carbon uptake through an increased level of RuBisCO enzymes and carbon concentration mechanisms [12,13]. Such engineered organisms increase by up to 30% the CO2 fixation compared to the wild ones.

Microalgal biomass may also be harvested and reused for any of the following duties: aquafeed or biofuel. Ahmad et al. reported that Chlorella-based systems that are applied to treat palm oil mill effluent and landfill leachates were effective at the same time in nutrient load reduction and production of usable biomass [14]. Such a model of dual use promotes a circular economy in aquaculture, as it changes waste into a renewable resource.

Further, algal-bacterial consortia, mixtures of photosynthetic and heterotrophic microbes, have demonstrated the potential to enhance the stability and scalability of CO2 capture systems. According to Viswanaathan et al., the consortia further supplement the process of CO2 fixation besides playing a role in purifying water through assimilation of phosphorus and nitrogen, consequently merging several sustainability objectives into one operational framework [15].

Knowledge gap and Challenges in Application

Although there are many benefits attached to the use of microbial technologies, there are a few challenges that have impeded their large-scale use. The first of these is a lack of scalability of laboratory-generated solutions of microbial products when exposed to field conditions. The microbial performance is tremendously affected by environmental parameters, including temperature, pH and salinity [8]. Similarly, variation in farming fish and water systems requires some work on species-specific and location-specific microbial preparations.

Issues of regulation involved in releasing genetically modified organisms (GMOs) into the water of the oceans also act as a barrier. However, the optimised strains of microalgae and bacteria have good efficiency but some scepticism and ecological safety issues constrain their use. According to Calatrava et al., people should be educated and have a clear and disclosed risk assessment to enhance the acceptance of genetic engineering in aquaculture bioremediation [13].

Another critical problem is economic constraint. Initiating microbial inoculants and building and monitoring the cultivation infrastructure are expensive for small- and medium-scale fish farming activities. The article by Alvarado-Ramirez et al. asserts that the area should be supported by financial incentives and the involvement of the public and private domains to increase the pace at which sustainable waste-to-resource technologies are adopted [16].

Moreover, the microbial practices have not taken effect in the standardised aquaculture guidelines, as Microgard Spectro has now taken effect. Sharma et al. urge the establishment of regulatory policies and standards and performance criteria to achieve uniform and safe exploitation of microbial biotechnologies [7].

Integration and Outlook

The literature reviewed shows that aquaculture can be revolutionised using microbial biotechnology. Bioremediation with microbe consortia, bio floc systems and algal carbon capture platforms reserves a potential sequestration tool in ensuring quality water, waste reduction and carbon capture [17]. Once combined with precision farming and digital monitoring, these technologies allow the implementation of a systems approach to aquaculture management.

To promote adoption, research from an interdisciplinary perspective should still be done to perfect the strains, delivery solutions and long-term ecosystem interactions. It will require researchers, industry stakeholders and regulators to cooperate in terms of translating these findings into field-ready and cost-effective solutions.

Experimental/Methodology Basis

To discuss the possible contribution of bioengineered microbes to increase sustainability in aquaculture, a hypothetical experimental platform is suggested based on proven facts in microbial bioremediation, the recycling of nutrients and the fixation of carbon. This methodological design identifies the conduct of this kind of controlled trial that will aid in evaluating the environmental performance and operational advantages of microbial solutions in aquaculture systems.

Experimental Setup

The experimental layout includes several aquaculture tanks, which are grouped into three categories: the control group that did not apply microbial additives, the second group that applied naturally occurring microbial inoculants and the third group that applied genetically engineered microbial consortia. Each tank has a high-density aquaculture environment with a typical example of tilapia or shrimp, which are general production species globally. All the systems are closed loop or recirculating, so adequate monitoring of the buildup of wastes and treatment implications can be performed accurately.

Measured Parameters

To assess the effectiveness of the microbial interventions, several environmental and biological parameters are monitored within a 90-day grow-out time frame:

Water Quality Indicators: Ammonia (NH_3), nitrates (NO_3) and nitrites (NO_2) are assayed by spectrophotometry. Automated sensors continuously log the dissolved oxygen (DO), pH and temperature.

Carbon Capture Efficiency: Tank cultures that contain engineered strains of Chlorella vulgaris or Spirulina platensis are observed to determine the rate at which biomass increases as a measure of CO_2 uptake. Atmospheric CO_2 fluxes are determined in real-time by gas exchange systems.

Fish Growth and Health: Fish growth rate and feed conversion ratios (FCR), as well as fish survival and markers of fish health (like oxidative stress enzymes and immune response), are assessed between treatments.

Sludge Accumulation: Volumes of sediment trap and the quantity of dry weight measure the level of organic matter accumulation.

Selection and engineering of Microbial Consortia

The microbial inoculants are acquired using existing commercial strains and after enriching them with targeted taxa, they are used in the selective culture to obtain them. Bacteria. This base consortium will consist of nitrifying bacteria (Nitrosomonas europaea, Nitrobacter winogradskyi), heterotrophic bacteria (Bacillus subtilis, Pseudomonas fluorescens) and photosynthetic microalgae (Chlorella, Spirulina).

In the engineered treatment group, the approach to genetic enhancement lies in enhancing metabolic efficiency, rate of pollutant degradation and stress tolerance. Algae are characterised by the nitrification pathway, oxidative stress resistance and carbon-fixing gene edits by CRISPR-Cas9. Modifying strains is done by introducing engineered plasmids through electroporation or conjugation, which is confirmed through PCR and sequencing.

Monitoring and Data Analysis

The 16S rRNA high-throughput sequencing is used to monitor the changes in the microbial community and diversity indices with time. Real-time PCR measures the expression of functional genes in nitrogen and carbon metabolism. ANOVA and multivariate statistics are applied to analyse the data to determine the significant differences between the groups of treatments in terms of parameters of the environment and biological performance [18].

This approach design has established a foundation for gauging bioengineered microbes' viability and ecological safety in aquaculture complexes. It combines microbiology, molecular biology, water chemistry and aquaculture science into a synthesised outlook that reflects the potential in microbial bioremediation and carbon-capture capability in real-world agricultural scenarios.

Discussion/Analysis

Microbial biotechnology is transforming the future of aquaculture by providing sustainable science-based waste management, nutrient cycling and greenhouse gas reduction solutions on an integrated platform. Such developments are critical as the world faces increasing pressure to sustain food demand. The current section deals with the practical and theoretical contributions of bioengineered microbes to an aquaculture system and with these microbes in bioremediation operations, in microbial consortia, bio floc technology, in carbon capture and the larger pathway to environmental sustainability.

Waste bioremediation in Aquaculture

The buildup of nitrogenous wastes, especially ammonia (NH_3), nitrite (NO_{2-}) and nitrate (NO_{3-}), is quite peculiar to aquaculture environments [4]. Fish produce them as a product of metabolism and unused feed and because of their poisonousness, they may cause the development of a chain of ecological traumas. High ammonia levels will inhibit fish gill functioning, decrease immunity capacity and may result in mass deaths. The main way of reducing these effects in traditional systems is by exchanging water, which causes pollution of nutrients to other ecosystems.

Using bioengineered microbes is another effective alternative since it can boost the efficiency of the nitrification and denitrification pathways [19]. For example, the ammonia can be oxidised to nitrite using Nitrosomonas europaea and then oxidised to nitrate using Nitrobacter winogradskyi, so the nitrification process is complete. Nitrates are then reduced into nitrogen gas by denitrifying bacteria like the Pseudomonas stutzeri, making it safe to be released to the atmosphere. Genetic engineering tools such as CRISPR-Cas mechanisms and plasmid insertion have been employed to improve the production of key enzymes such as ammonia monooxygenase (AMO) and nitrate reductase. These changes enhance the speed of the metabolism of the nitrogenous compounds, thus improving the system's stability and reducing the amount of water discharged.

Besides, bioengineered microbial consortia frequently contain strains that produce hydrolases, ureases and oxidoreductases that hasten the degradation of proteins, urea and other organic compounds prevalent in fish waste [20]. It has been indicated empirically that these consortia potentially lead to up to an 80%

decrease in ammonia concentrations faster than the occurrence of a natural microbial ensemble. This significant enhancement reduces toxicity, enhances oxygen supply and decreases biological oxygen demand (BOD), resulting in healthier water bodies.

Enhancing Waste Treatment by Microbial Consortia

Although single-strain microbial usage has been proven to degrade specific waste efficiently, the dynamic complexity of the aquaculture environments is better suited to use microbial consortia. These communities have a combination of species of microbes that act co-beneficially to degrade waste, control nutrient cycling and stabilise water chemistry. Metabolic complementarity is one of the most essential advantages of consortia: in a community of species, organisms do not perform the same steps of the biochemical pathway but rather share the steps along the path and therefore, enhance the overall efficiency and stability of the process.

Microbial consortia colonise surfaces and suspended solids in aquaculture systems to develop strong biofilms [21]. They are physical and biochemical centers, as these biofilms encompass high-density microbial colonies that can sustain unsteady environmental conditions, including changes in temperature and salinity. A combination of the autotrophic nitrifiers (like Nitrosomonas, Nitrobacter) with heterotrophic bacteria (e.g., Bacillus subtilis, Pseudomonas fluorescens) leads to rapid replenishment of the nutrients, avoidance of the toxic buildup and maintenance of the balance in the system.

Notably, the microbial communities may also act protectively. Certain beneficial strains produce antimicrobial products, including bacteriocins and organic acids, which repel pathogenic bacteria affecting shrimp and fish culture, such as Vibrio spp. All these probiotic effects help minimise antibiotics and improve the health status of animals. Evidence garnered through experimental trials also suggests that the immune responsiveness (expression of interleukin-1beta, increased lysozyme activity and stress tolerance proteins) in fish cultured in tanks seeded with well-balanced microbial consortia improved.

Moreover, microbial communities enhance bio floc formation by secreting extracellular polymeric materials (EPS) that tend to flocculate particulate substances and enable their further integration into the microbial food web. This minimises the bottom sludge formation, simplifies the management of the pond and limits the necessity of the mechanical clean-up or the dredging of the bottom sludge.

Carbon capture via Microbial technologies

Introducing photosynthetic microorganisms, especially microalgae and cyanobacteria, into aquaculture units is a new strategy for regulating the emission of greenhouse gases. These organisms use photosynthesis to acquire atmospheric or dissolved CO_2 and convert it to biomass, releasing oxygen. Both roles alleviate the issue of carbon emissions and increase the aquaculture tank's oxygen concentration, such that mechanical aeration is unnecessary.

Enhanced bioengineered strains of Chlorella vulgaris and Synechococcus elongatus have been created to possess better carbon concentrating mechanisms (CCMs) and enhanced RuBisCO enzyme processes [22]. The alterations helped the microbes fix CO_2 by up to 30% more than their parent lineage, wild types. This becomes especially useful in closed-loop systems where the buildup of CO_2 due to fish respiration may be troublesome.

The biomass obtained by these photosynthetic organisms is used in various ways. After harvesting, it can be processed into fish food, fertiliser, biofuels and even biodegradable plastics. By doing this, carbon capture becomes completely integrated with resource making, symbolising the circular economy in the aquaculture sector. Case in point: Algal-based feeds can supplement fish meal to some degree, further decreasing the footprint of the feed production.

As part of the integrated aquaculture systems, the United Nations Environment Program field studies demonstrated that the introduction of microalgal bioreactors in Western Africa could cut net carbon emissions by more than 40%, which signifies these bioreactors as an indispensable climate-smart tool in the development of aquaculture.

Sustainability Pathway

The bioengineered microbes are strategically integrated into an aquaculture system, making a solution towards environmental sustainability possible [23]. Such technologies make it possible to use closed loops in the nutrient cycle, minimise chemical and antibiotic consumption and recycle waste to extract valuable resources. With a less intensive environmental impact, microbial solutions aid larger objectives of being climatologically resistant, food security and ecosystem conservation through fish farming.

Nevertheless, to achieve this potential at scale, it is essential to overcome several critical challenges. When genetically modified organisms (GMOs) are released into open water bodies, concerns regarding ecological stability, transmission of genetic material to indigenous microbes and spillover effects cannot be ignored. Stringent environmental risk evaluations and containment measures are the only steps through which such problems can be handled responsibly.

Adoption is also frustrated by its public perception and regulations. Several countries do not provide coherent guidelines for assessing and accepting the use of engineered microbes in fish farming. To create confidence and transparency, reputation management should be established by developing regulated biosafety measures and improved relationships with stakeholders, such as farmers, regulators and consumers.

Furthermore, the prohibitive nature of developing, commercialising and sustaining microbial technologies is still an albatross, especially to small- and medium-sized companies. Training, infrastructures and knowledge-sharing platforms should be invested to democratise and guarantee moderated use of these innovations.

To sum up, bioengineered microbes are a reference point of sustainable aquaculture. Concerted research efforts, making informed policies and involving the community will enable the aquaculture industry to employ microbial biotechnology in transforming their resource-demanding efforts to resilient and circular food production systems that are not environmentally cumbersome.

Case Studies /Applications

The application of microbial biotechnology in aquaculture is gradually becoming more widely accepted at various locations. These real-life scenes show how microbial intervention ideas can be exercised to support sustainability, increase productivity and mitigate environmental strain.

India: Tilapia farming by using Bio floc Technology

Bio floc systems adopted in tilapia and shrimp production have been practiced in different regions in India, especially Andhra Pradesh and Odisha, to exploit the available land and water. In controlled carbon dosing (usually with molasses or tapioca flour), farmers inoculate their soils with heterotrophic bacteria by dosing them with a certain quantity of carbon to induce their growth and uptake of nitrogenous wastes to form microbial protein [24].

Such systems have resulted in low water turnovers, up to 70% and fish production. Regional aquaculture reports have indicated that with bio floc-tilapia farms, the low feed conversion ratios (FCR) of up to 1:2 and above 90% survival rates have been recorded. It also saves on the feed cost, thus a great way to save economically in small and medium-scale operations due to the recyclable nature of the microbial flocs.

Vietnam: Bioremediation of Shrimp Ponds

The main environmental issues on Vietnamese shrimp farms in the Mekong Delta are the nutrient overload, waterborne diseases and regular pond collapses. The infection risks are overcome regularly by applying integrated bacterial cocktails composed of Bacillus subtilis, Lactobacillus spp. and Pseudomonas spp.

These microbial preparations aim to decompose sludge, nitrify and increase the resistance of shrimp to diseases. In field studies, water movement shows excellent clarity and low ammonia and Vibrio-related death levels have been reduced. Microbial ecosystem management has a lot to offer, as shrimp production in bioremediated ponds has been shown to rise above 20% when compared to conventional farms.

Brazil: Dual Function Chlorella that is Genetically Modified

In Brazil, they are experimenting with genetically engineered strains of Chlorella vulgaris as carbon-capturing and biomass yields in aquaculture-raceways. These algae are tailored to have improved CO_2 fixation by optimising the carbonic anhydrase and RuBisCO pathway genes.

Besides storing atmospheric CO_2, the algal biomass will be converted into high-protein feed for pacu and tambaqui. The preliminary findings have determined that CO_2 absorption has increased by 30% and supplementary feeds have decreased accordingly. The closed-loop model under consideration implicates the dual-use concept of using algae as a bio-remediator and a resource and follows the national objectives of Brazil to achieve carbon neutrality and sustainable development of aquaculture.

USA: Microbial Consortia in recirculating aquaculture systems (RAS)

Advanced RAS facilities. In the United States, microbial consortia have been implemented to sustain water quality, minimise waste and improve biosecurity. States such as the demand tending to rise under intensive conditions, Atlantic salmon and trout are high-value species with minimal environmental discharge.

Biofilters are inoculated with engineered consortia containing Nitrosomonas, Nitrobacter, Bacillus and Rhodobacter to control the nitrogen compounds [25]. These systems also use the microalgal units and UV sterilisation to develop near-closed-loop systems. In operational data, water use has been minimised by more than 90% and positive signs of fish health show higher levels of hematocrit and fewer cases of gill inflammation.

Conclusion and Future Outlook

Incorporating bioengineered microbes into aquaculture systems is one of the most opportune shifts in the drive towards sustainable food production. Regarding the enormous possibilities of the use of microbial biotechnology in the form of bioremediation, nutrient recycling through bio floc and microbial carbon capture, this paper has discussed the remarkable potential of microbial biotechnology, in general and their use in aquaculture as an agent of change to help caused by the activity of aquaculture on the environment, improving production and utilisation of resources and decreasing and mitigating the burden of aquaculture on the environment.

The review indicates that the microbial solutions can resolve fundamental issues of aquaculture. The engineered or indigenous microbial strains can clean up nitrogenous and organic wastes by bioremediation to ensure water purity and avoid eutrophication. The synergistic interaction among microbial consortia enhances biotic cycles, inhibits pathogens and facilitates the well-being of fish. The bio floc technology converts waste products into microbial biomass, which can be used as a water treatment system and an added protein source. Moreover, genetically modified algae and cyanobacteria can trap CO_2 and help in closed-loop carbon circulation.

Although this is a promise, several challenges are still present. One of the most significant challenges facing the entry of genetically engineered organisms into the market is the regulatory doubt over the release and screening of the microorganisms, particularly during an open pond system. There should be an open risk assessment and stakeholders should be involved in addressing public perceptions and the quality of the ecosystem's safety. The deployment of advanced microbial systems is also constrained by cost and scalability in small-scale or resource-limited operations. Differences in performance between species and environments further portray the necessity of creating contextual microbial designs.

Future work should overcome these difficulties by developing microbial consortia to be fine-tuned with metagenomics, systems biology and artificial intelligence. Developing bioinformatics technology can help detect the best microbial cocktails that can be applied to specific aquaculture species and their surroundings. Partnership between biotech companies, research facilities and fish farms will be essential to scaling up laboratory-scale technology to commercial-scale.

International guidelines and biosafety measures on using engineered microbes in aquaculture need to be developed with policymakers' support. Regulatory harmonisation has the power to support innovation with an eye on ecological integrity. Governments and funding organisations should also invest in capacity building and knowledge transfer, enabling small- and medium-scale aquaculture businesses to incorporate microbial technology.

The vision of sustainable aquaculture should be one in which high productivity is achieved without cost to the environment. Today, Aquaculture can be transformed into a low-waste and emission-producing environment, starting at the bioengineered microbe existence stage. Microbial biotechnology provides a route to resilient, climate-smart aquaculture by producing super-efficient feeds, when supplemented with digital monitoring, precision feeding and responsible governance and has the potential to deliver a globally significant share of food, without damaging the planet ecologically.

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