

Review Article

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Algal-bacterial intervention as a management tool for next-generation aquaculture sustainability

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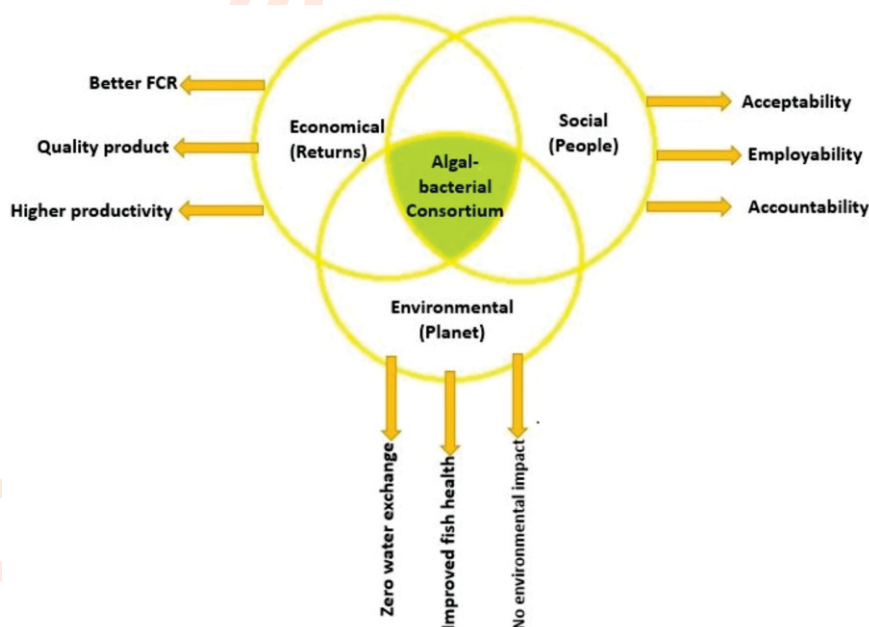
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Abstract

During the last few decades, aquaculture as a useful animal protein providing sector intensifies to meet the growing world population demands. Although fish culture technological advancement has resulted in increased production, intensive technology has negatively affected the environment—consequently, aquaculture research efforts have been diverted towards developing sustainable culture technology. Introducing algae and bacteria singly or in combination in aquaculture was advantageous both by ex-vivo and in-vivo culture techniques.

Utilization of microbial consortium in aquaculture can help to construct three pillars (social, economical, and ecological) of sustainability by improving water quality, reducing dependency on a wild fish stock as a feed ingredient, improving the health status of animals, and increasing economic returns along with protection of the environment. Numerous fruitful research outcomes on using algal-bacterial systems are available for its application in aquaculture. In this context, the present article highlights an updated review of current research trends on various aspects such as application of algal-bacterial consortia for aquaculture, available technologies based on their interaction, and recommendations for further improvement. This review will also provide some critical clues for the standardization of novel fish culture techniques based on microbial interaction.

**Key words:** Algal-bacterial association, Feed source, Immunity, Sustainable aquaculture, Water quality

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Introduction

Aquaculture is the fastest-growing food production sector in agriculture. During the last few decades, aquaculture has shown tremendous growth through intensive aquatic organism culture technology. World aquaculture production of farmed aquatic animals has grown on average at 5.3 percent per year from 2001 to the level of 82.1 million tonnes in 2018 (FAO, 2020). Along with increased production, this development phase has caused some negative impacts on the environment, such as habitat destruction, utilization of fish meal and fish oil in feeds, wastewater discharge, wild seed for stocking, genetic contamination, disease outbreak, and problems associated with overuse of antibiotics. Accordingly, researchers have surveyed prerequisites of standardized sustainable aquaculture technology with respect to social, economic and environmental benefits (Martinez-Porchas and Martinez-Cordova, 2012). Introducing algae-bacteria consortia in the aquaculture can be partially replaced sole with feed-based system to take advantage of feed optimisation by reducing the quantity of external feed, improvement of water quality, and health of cultured organisms (Azim *et al.*, 2001; Pandey *et al.*, 2014).

Even though microalgae and bacteria are the micro-players, they play macro-roles in nutrient cycling and energy flow in an aquatic ecosystem (Tandon *et al.*, 2017). Microalgae are the primary producers in the aquatic ecosystem and constitute the main natural food components for its residents. A close association exists between bacteria and algae for stabilizing ecosystems (Ramanan *et al.*, 2016). Microalgae can support the aquaculture system by supplying oxygen to all biological activities while bacteria detoxify the environment apart from collectively acting as a direct food source to the cultured animal (Avnimelech, 2014; Taziki *et al.*, 2016). Thus, the intervention of microalgae and bacteria can provide a path for sustainable aquaculture technologies for handling environmental concerns of aquaculture activities. The relationship between algae and bacteria has been widely studied for its applicability in aquaculture. Bacteria and algae interact by performing different associations like mutualism, commensalism, and parasitism (Ramanan *et al.*, 2016). Often, microbes and algae do a collective work that cannot perform the same singly (Yao *et al.*, 2019). All nitrogen applied in feed or fertilizer and not harvested in biomass is a potential ammonia source. Ammonia in the aquaculture environment is produced by the decomposition of meal and faecal matter.

In nitrification, Nitrosomonas bacteria oxidize ammonia to nitrite and Nitrobacter bacteria oxidize nitrite to nitrate. Simultaneously, microalgae have a great capacity to remove combined nitrogen compounds, ammonia, nitrate, and nitrite from the aquatic environment. Microalgae absorb ammonium and convert it into organic nitrogen in the form of a protein. It is well known that microalgae and bacterial biomass serve as a natural food source for cultured animals. The natural biota in the form of flocculated particles consisting mainly of microalgae and heterotrophic bacteria contribute substantially to the nutrition of aquatic organisms (Burford *et al.*, 2004). The nutrients present in the wastewater are converted into protein biomass due to the

association of photosynthetic microalgae and heterotrophic bacteria (Catarina and Xavier, 2012). It is also found that incorporation of algal bacterial system helps in improving the water quality by removal of harmful nitrogenous content from culture environment (Han *et al.*, 2019; He *et al.*, 2017; Pacheco-Vega *et al.*, 2018; Yadav *et al.*, 2021). The natural anti-microbial compounds or biomolecules in some microalgal species can serve as immunostimulants and improve the cultured organism's health (Charoonnart *et al.*, 2018).

The "green water" technique has beneficial effects on health, survival rates and resistance of different organisms (Falaise *et al.*, 2016). Therefore, microalgae are regarded as a promising alternative to replace fishmeal and fish oil, considering nutritional and health benefits (Shah *et al.*, 2018). Earlier research attempts have been made to explore the beneficial effect of either algae or bacterial in aquaculture systems with rare attempts to explore combined benefits. It is necessary to have a detailed and updated review of algal-bacterial associations-based culture technologies for further progress towards sustainability. Therefore, the present article attempted a state-of-the-art review on the application of algae in combination with bacteria as a microbial management tool with possibilities of existing aquaculture system modification to increase the system's performance in regards to sustainability (Fig. 1).

Formation of Algal-Bacterial Film and Floc: The algal-bacterial mass is naturally found in biofilm attached to the submerged surface or in the form of a settled floc. Biofilm formation is a complex cyclic process involving initial, maturation, and dispersal phase (Khatoon *et al.*, 2018). During the initial phase, free-floating microorganisms attach to a surface by the surface tension components and hydrophobic effects (Briandet *et al.*, 2001; Takahashi *et al.*, 2010). Extracellular polymeric substance (EPS), a sticky matrix, plays a vital role in biofilm formation. EPS consist of water passages to distribute nutrients and oxygen to involved microorganisms. This microbial association protects itself from adverse environmental conditions. Once established, subsequent growth of biofilm occurs by cell division and recruitment from the outside environment until they become fully mature. After maturation, biofilm dispersion is caused by enzymatic degradation of EPS enabling biofilms to spread and colonize on new surfaces (Fig. 2).

Biofloc is a loosely clumped mass of aggregates of bacteria, algae, or protozoa, held together in a mucus matrix of extracellular polymeric substance (EPS) along with particulate organic matter. Mainly filamentous microorganisms are involved in the formation of biofloc, where cilia of these microorganisms entrap the suspended solids and other substances (Harun *et al.*, 2019). Feces, uneaten feed, and sludge particles held together by filamentous and other microbes cause floc formation in an aquaculture medium (Crab *et al.*, 2010). The biofloc is distributed in the water column due to intense aeration or loosely attached to the tank wall surface (Fig. 2). Biofloc formation is affected by carbon source, nitrogen types, and aeration intensity (Harun *et al.*, 2019). Different types of carbon sources such as acetate, cassava meal, cellulose, corn flour, dextrose, glycerol,

glucose, molasses, sorghum meal, tapioca, wheat flour, and starch have been successfully used separately or in combination for biofloc formation in the aquaculture system for maintaining appropriate carbon to nitrogen (C:N) ratio (Martínez-Córdova *et al.*, 2014). The dynamics of the removal of heterotrophic nitrogen are based on the type of organic carbon applied. For example, the faster reduction of ammonia was observed when simple sugars glucose or molasses were applied, while the same process of removal of ammonia slowed down with the addition of complex carbohydrates as these substances degrade slowly (Ekasari *et al.*, 2019).

Substrate addition for formation algal-microbial consortium in the aquaculture: The biofilm colonization was also found to be affected by substrate type present in the waterbody. Some fish species use biofilm biomass deposited on the substrate as their natural food. Many natural and artificial substrates have been used to study the deposition of biofilm biomass in the aquaculture environment. Natural substrates, mainly bamboo poles or sticks, was found more efficient for biofilm formation than other natural or artificial substrates (Table 1). Nevertheless, Rai *et al.* (2008) found higher weight gain of carps in bamboo sticks than rice straw treated ponds, but comparative economic analysis showed better performance in rice straw than bamboo sticks treated ponds. Few reports are available on the type of periphytic species developed on the substrate provided for attachment. Szlauer-Lukaszewska

(2007) reported that biofilm (periphyton) developed on a synthetic substrate immersed in a wastewater reservoir was characterized by the domination of euglenophytes during the initial phase; *Carchesium polypinum* during the intermediate stage and diatoms and chrysophyceans dominated the mature stage with a contribution of detritus more than 50%. However, some other studies reported diverse microalgal species composition comprising green algae or diatom as a dominant one on the substrate provided for attachment (Thompson *et al.*, 2002; Khatoon *et al.*, 2007; Kumar *et al.*, 2015; Gogoi *et al.*, 2018).

Improvement of water quality in the aquaculture: The self-purification process achieved via algal-bacterial symbiosis system is a widely known environment mitigation strategy. Several investigations were attempted to analyze the bioremediation of hazardous pollutants and heavy metals through algal-bacterial consortium (Pham, 2018; Subash chandra bose *et al.*, 2013). The algal-bacterial association detoxifies and assimilates metals through various physico-chemical processes, including physical adsorption, covalent bonding, ion exchange and chemisorption, surface precipitation, redox reactions, or crystallization (Ramanan *et al.*, 2016). Nutrients like organic carbon, dissolved organic nitrogen, dissolved organic phosphorus, sulfur, Vitamin B, and siderophores are exchanged in symbiotic algal-bacterial interaction for mutual benefits (Yao *et al.*, 2019).

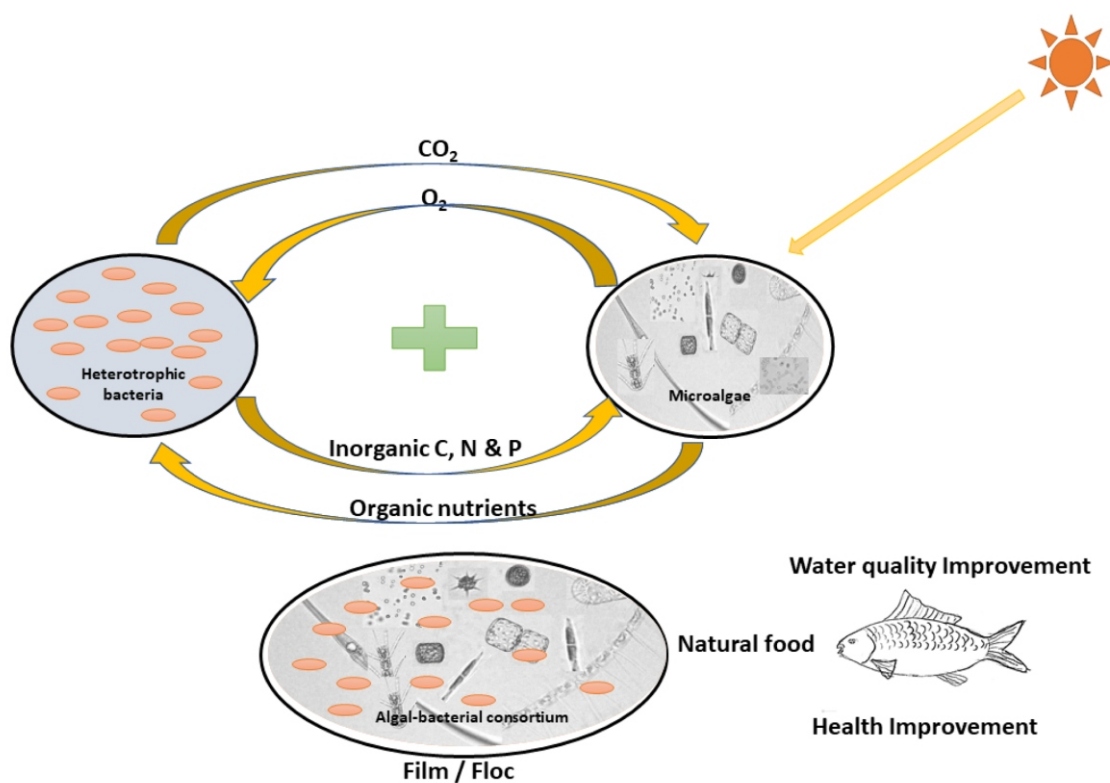


Fig. 1: Benefits of micro-algae and bacteria consortia through nutrient exchange in the aquaculture unit.

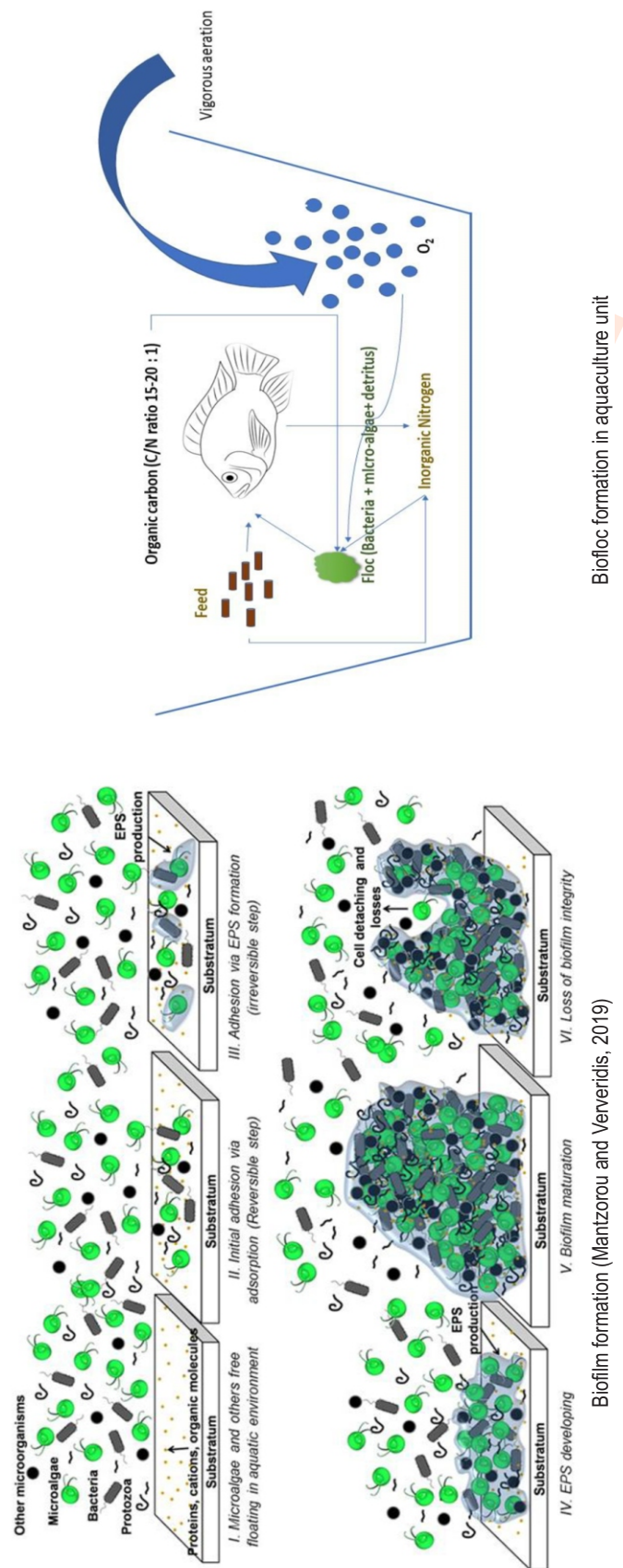


Fig. 2: Microalgal-bacterial biofilm and biofloc formation.

Algal-bacterial consortium in the aquaculture system is also more beneficial than a single algal or bacterial system. Single bacterial techniques such as probiotics are found to improve the growth and health status of cultured organisms, while the single algal system acts as a direct food source (Martínez-Córdova *et al.*, 2014). The algal-bacterial system merges the advantages of both systems and improves the water quality, unlike conventional semi-intensive and intensive aquaculture systems where water quality deteriorates due to uneaten food and waste products generated by cultured organisms (Avnimelech, 2014). Microbial films have been reported to improve the water quality parameters and alleviate harmful effects of the overloaded population (Krishnani *et al.*, 2006a; Krishnani *et al.*, 2009, 2013; Krishnani and Kathiravan, 2010). Yadav *et al.* (2021) reported a significantly lower value of total ammonia concentration in the biofilm rearing system than sources of clear water fed fish seed rearing system.

The lower values of nitrogenous toxicants in the algal bacterial film system can be attributed to their oxidation by indigenous ammonia-oxidizing bacteria and nitrite-oxidizing bacteria onto the bagasse biofilm (Krishnani *et al.*, 2006a; Krishnani *et al.*, 2006b; Krishnani and Kathiravan, 2010). The conventional aquaculture systems are generally lower in C : N ratios than required for bacterial multiplication (Avnimelech, 1999). If the carbon and nitrogen (C: N) ratio of the culture medium is maintained by the external addition of organic carbon, then heterotrophic bacteria possess the capacity to convert nitrogenous waste generated into bacterial biomass (Schneider *et al.*, 2006). In complementary, algae can fix inorganic carbon using sunlight energy and combine the fixed carbon with nitrogen and phosphorus at relatively constant stoichiometric ratios (Klausmeier *et al.*, 2004).

Algae releases oxygen and dissolved organic carbon for bacterial activities (Muñoz and Guieysse, 2006). In return, the bacteria re-mineralize sulfur, nitrogen, and phosphorus with a direct supply of carbon dioxide and vitamin B to support microalgal growth (Yao *et al.*, 2019). In addition to this, microalgae have high efficiency in removing phosphorus, especially on immobilized layers (Shi *et al.*, 2007). Heterotrophic bacteria prefer high C: N conditions whereas autotrophic organisms favor low C: N ratios (Michaud *et al.*, 2006). Several bacteria exhibit an inverted curvilinear relationship with C/N and N/P ratio with optimum C/N ratio of 8-14:1 for soil, 28-29:1 for water and N/P ratio between 3-7:1 (Ghosh and Chattopadhyay, 2005). The optimum C: N ratio should be between 14:1 to 30:1 for microbial floc formation with heterotrophic bacterial dominance (Silva *et al.*, 2017). In a biofloc aquaculture system, a C: N ratio of 12–20:1 and 6:1 is required during the initial biofloc formation and maintenance phases, respectively, according to the total ammonia nitrogen values (Emerenciano *et al.*, 2017). Thus, the algal-bacterial consortium provides the potential to self-purify water quality in aquaculture by maintaining proper N:P ratio for autotrophs and C: N for heterotrophs by the heterotrophic pathway of nitrogen removal, which converts the ammonia nitrogen into bacterial biomass without accumulation of nitrite and nitrate (Ebeling *et al.*, 2006). Algal microbial floc produced by exposing culture system to natural light popularly known as “Green water biofloc” while

indoor system known as “Brown water biofloc” (Wasave *et al.*, 2020a). However, there is limited information available for producing optimum and selective microbial biomass by inputting the required level of nutrients and light intensity. In addition to the application of water quality improvement, algal-bacterial population dynamics study over a period enables timely prediction and controls the harmful algal bloom in an aquatic ecosystem (Srivastava *et al.*, 2015).

Sources of fish food: The main and costly ingredient of fish feed is fishmeal derived from wild fish harvests. It is estimated that approximately 1 kg of wild fish is required to produce 4.5 kg of farmed fish (IFFO, 2017). The use of wild fish stock to produce farm fish is not a sustainable technology. Therefore, recent research efforts are diverted to reduce the fish meal content to prepared fish feed. The conversion of algal and bacterial biomass into fish protein can be a good strategy towards aquaculture sustainability. In the aquaculture system, the major item of expenditure is feed which is about 50% of the total cost involved. Cultural animals assimilate only 20- 30% of the feed used in aquaculture and the remaining accumulate as waste (Wasave *et al.*, 2020a). Several research findings have revealed the importance of algae and bacteria as nutritional sources to the culture of aquatic organisms. An algal-bacterial complex's nutritional profile depends on the C: N ratio of culture medium, type of substrate used, and physico-chemical parameters of water (Martínez-Córdova *et al.*, 2014). Rice bran has been found as a better source of carbon for rearing of GIFT tilapia fry in microbial floc system in terms of growth and water requirement for rearing (Wasave *et al.*, 2020c, 2020b). Similarly, Shilta *et al.* (2016) reported algal microbial film produced on natural substrates, especially on bagasse, enhanced growth of *Etroplus suratensis* and reduced the necessity of water exchange during culture.

The level of crude protein in algal-bacterial floc/film was found in the range of 14 to 17 % by Azim *et al.* (2003), 35 to 41% by Garg *et al.* (2007), 28 to 33% by Ekasari *et al.* (2010) and 28.7 to 43.1% by Maicá *et al.* (2012). The photoautotrophic microorganisms-dominated film/floc is characterised by low protein and high lipid levels (Gangadhara and Keshavanath, 2008). On the contrary, high protein and low lipid concentrations are characteristic of heterotrophic bacteria-dominated film/floc (Emerenciano *et al.*, 2013). Although heterotrophic bacteria-dominated flocs have lower lipid levels, it is found to be a good source of n-3 and n-6 essential fatty acids (Martínez-Córdova *et al.*, 2014). Given the nutritional importance of algal-bacterial complex, numerous experimentation trials were carried out to incorporate microbial mass in aquafeed and replace a fish meal for lending hands to sustainable aquaculture (Fig. 3 and 4). These studies indicated that microbial supplementation could be successfully up to the level of 50 % in trout, 40 % in white leg shrimp, 25 % in common carp, and 10 % in tiger prawn. The bioactive microbial products or methane utilizing bacterial meal can replace fish meal in feed for tiger prawn totally, biofloc meal or a single-cell protein obtained from the bacteria *Corynebacterium ammoniagenes* up to 20 % in white leg shrimp feed and methane utilizing bacterial meal up to 55 % in salmon feed. Apart from the above *ex-situ* trials, some *in-situ* research efforts have revealed

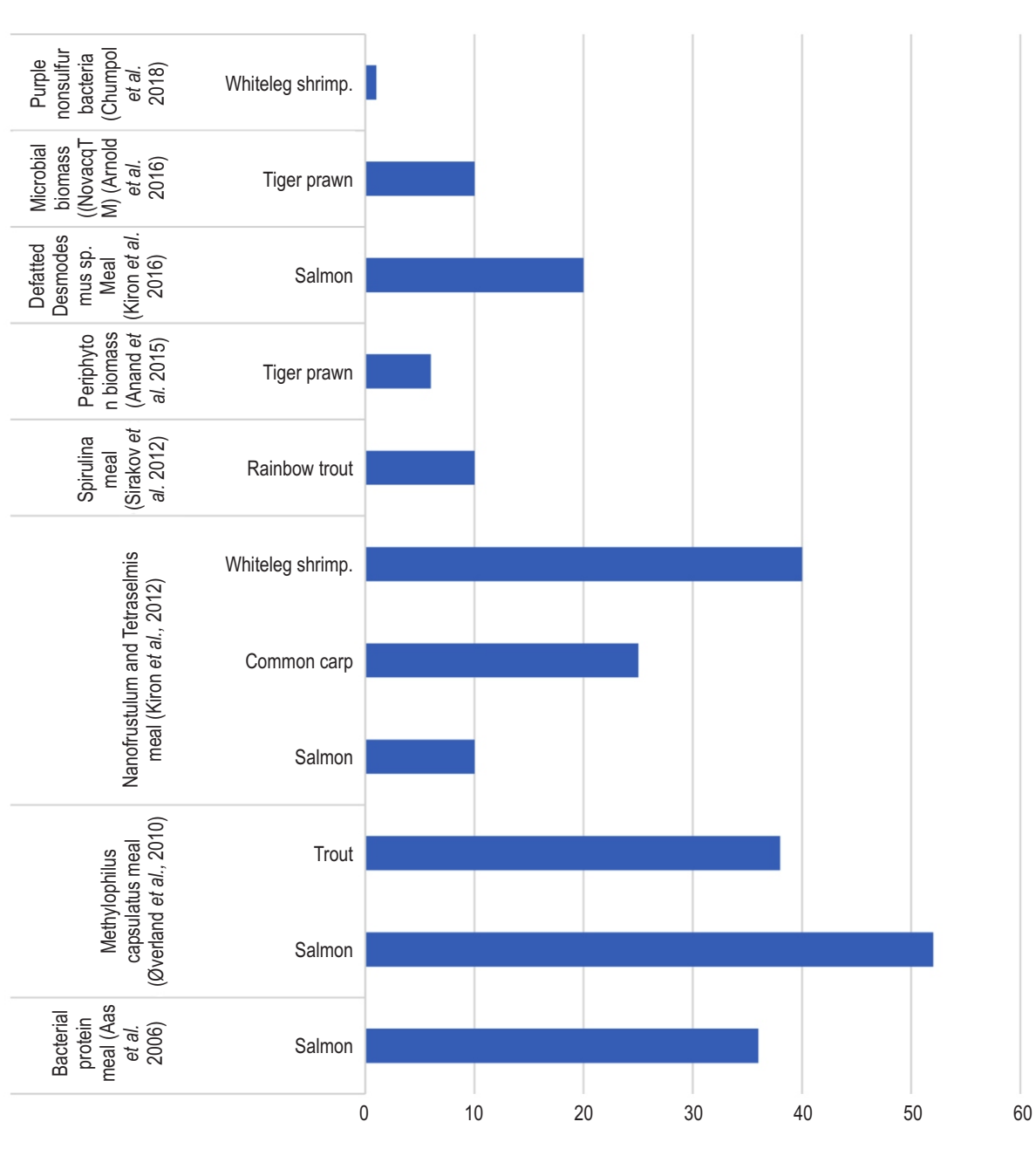


Fig. 3: Successful dietary inclusion of microbial supplementation (%) for improved performance of various aquaculture species.

the economic importance of algal-bacterial systems. The algal-bacterial film (Periphyton) based culture technique for tilapia was economical as it reduced 31 to 40 % feed cost (Garcia *et al.*, 2016; Ghosh *et al.*, 2019; Milstein *et al.*, 2008). Similarly, potential feed cost-cutting was observed in biofloc technology compared with conventional aquaculture systems in tilapia grow-out culture (De Schryver *et al.*, 2008; Pérez-Fuentes *et al.*, 2018). The comparative proximate composition study of fish reared in a

biofilm-based system showed an increase in protein level and decrease in lipid level compared with the traditional fed aquaculture system (Yadav *et al.*, 2021).

Improvement in aquatic animal health: During the last few decades, intensification of aquaculture has led to an outbreak of various kinds of diseases affecting the economics of the culture system. Eventually, farmers were compelled to use antibiotics

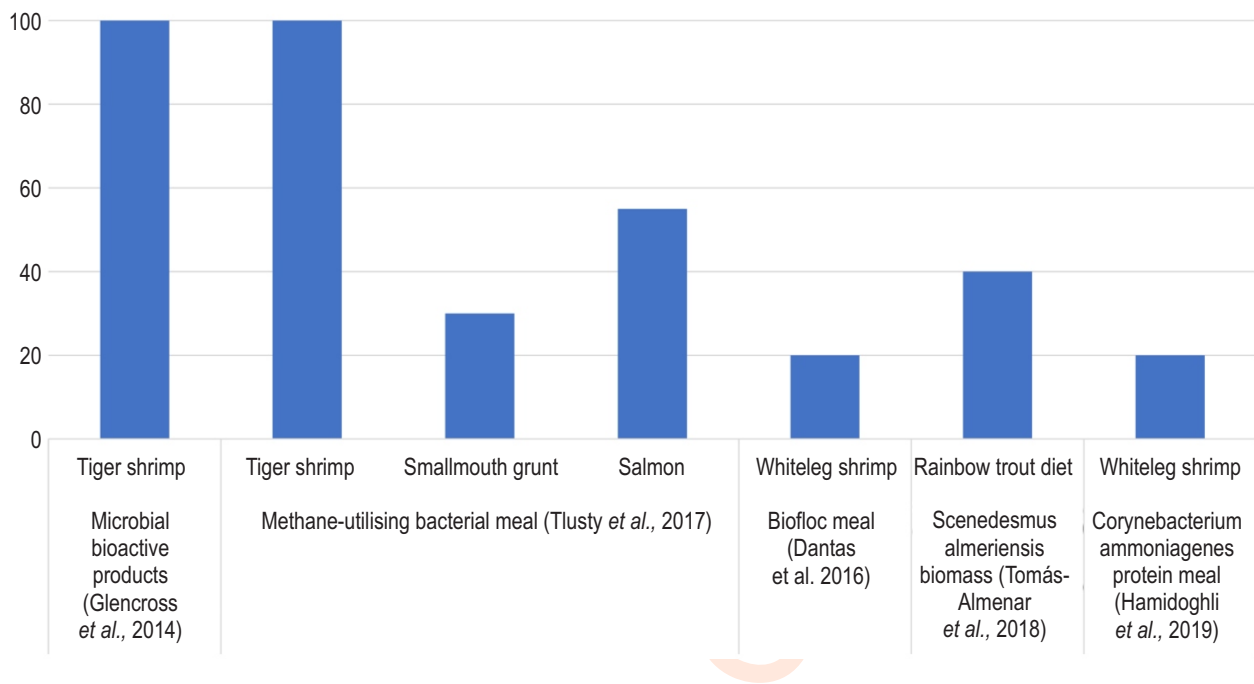


Fig. 4: Replacement of fish meal (%) through microbial supplementation in the feeds for different cultivable species.

and other therapeutics to tackle the infectious condition to manage disease prevalence (Henriksson et al., 2018). However, it is observed that such a management strategy comprises several drawbacks, including ineffective against viral diseases, detrimental effects to the environment, antibiotic contamination of the product, and advent drug resistance among pathogens (Miranda et al., 2018). Vaccination is an excellent tool to bring sustainability in global aquaculture but sometimes unable to deliver a correct immune response to fish (Ma et al., 2019). Moreover, it is quite difficult to develop vaccines for invertebrates like shrimp as they lack an adaptive immune system and rely entirely on innate immunity (Bachere, 2000). Therefore, research diverted to use other kinds of microbial-originated probiotics or immunostimulant substances to modulate the immunity of fish and shellfish. Various probiotics and their role in fish and shellfish immunity have been extensively studied and have higher utility in aquaculture (Nayak, 2010). Similarly, microalgal species such as *Chaetomorpha aerea*, *Schizochytrium* sp., *Chlorella vulgaris*, etc., are also found to have a positive immune-modulatory effect on different cultivable aquaculture species due to the presence of bioactive compounds (Charoonnart et al., 2018; Ju et al., 2008; Khani et al., 2017; Sattanathan et al., 2020; Sirakov et al., 2015; Souza et al., 2020). In some recent studies, it has been found that microalgae-bacterial based *in-situ* or *ex-situ* culture techniques such as biofloc or biofilm develops natural innate immunity of fish or crustaceans against different pathogens (Kim et al., 2014; Kumar et al., 2015; Pandey et al., 2014; Yu et al., 2020).

The improvement resistance against *Aeromonas hydrophila* in a biofilm-based rearing system was observed in

common carp fry (Joice et al., 2002) and in Rohu, *Labeo rohita* (Rajesh et al., 2008). Similarly, Vinay et al. (2019) observed an elevated level of immunity of Pacific white shrimp, *L. vannamei*, by oral administration of *Vibrio harvei* biofilm. Among some *ex-vivo* studies, Lee et al. (2017) demonstrated that dietary inclusion of freeze-dried biofloc powder at the level of 4.0% increases innate immunity in Pacific white shrimp. Similarly, Anand et al. (2015) found the improved immune response of tiger prawn by dietary addition of dried periphyton powder at the rate of 3 to 6% level. Microbial consortium, especially *Chaetoceros calcitrans*, *Nitzschia* sp., *Leptolyngbia* sp., *Skeletonema costatum* and the yeasts *Rhodotorula* sp., *Saccharomyces* sp. and *Candida* sp. as well as filamentous fungi *Penicillium* sp., *Mycelia sterilia* were found effective against *Luminous vibriosis* (Lio-Po et al., 2005). In another investigation, Crab et al. (2010) found that biofloc grown on glycerol protects brine shrimp *Artemia franciscana* larvae against vibriosis. Correspondingly, the disease resistance of Pacific white shrimp against *Vibrio harveyi* was improved by including freeze-dried biofloc powder in the diet (Lee et al., 2002). In other studies, biofloc added diet resulted in an upregulated expression of genes responsible for the enhanced immune system in Genetically Improved Farmed Tilapia (Menaga et al., 2019) and in Rohu (Kheti et al., 2017). Numerous *in-situ* studies on algal-bacterial-based aquaculture systems point out that an appropriate C: N ratio is required to improve the immunological status of cultured animals and improve water quality (Panigrahi et al., 2019; Xu and Pan, 2013). However, Menaga et al. (2019) found better animal performance in *in-situ* algal-bacterial systems than *ex-situ* with improved water quality. The non-pathogenic and pathogenic bacteria species were reported in the biofloc system

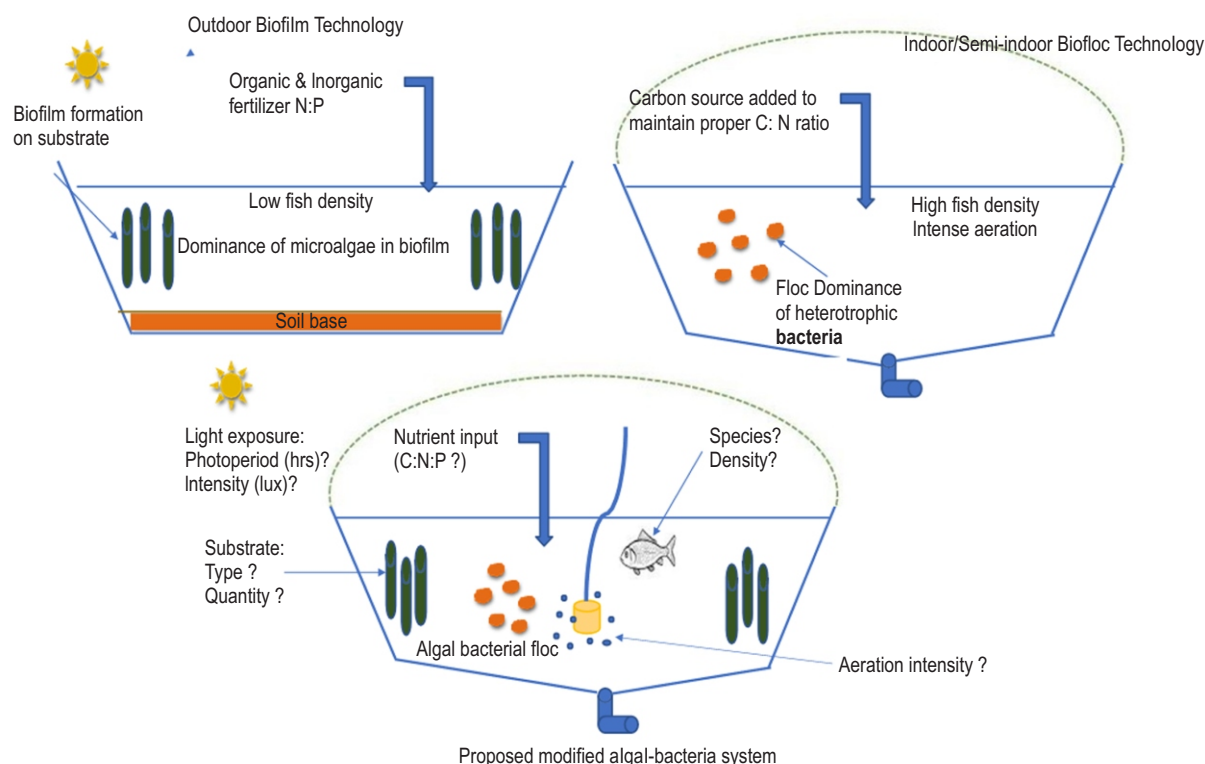


Fig. 5: Proposed modified algal-bacterial system through integration of existing biofilm and biofloc fish culture technique.

with *Enterobacter* sp., *Aeromonas salmonicida*, *Pseudomonas oryzae* and *Vibrio fluvialis* most common ones (Pérez-Fuentes et al., 2018). Therefore, research efforts are needed to study the effect of the presence of pathogenic bacteria in the system and adoption of proper inoculum strategy to minimize pathogenic microbial load from the culture system or by adding specific carbon sources at the required level to promote the growth of beneficial microbes and to inhibit the growth of harmful microbes.

Scope for modification of existing algal bacterial aquaculture system for sustainability: Conventional biofilm culture is performed by the addition of substrate, soil base at the bottom of the culture unit and fertilizers to supply nitrogen and phosphorus for developing algae (Yadav et al., 2021). Addition of substrate in biofilm culture and biofloc system have shown improved shrimp growth and health by trapping the suspended biofloc particles, better water quality parameters, enhanced biofilm growth, and quality of natural food (Kumar et al., 2019). Most biofilm type of culture is performed in outdoor conditions (Azim et al., 2003) and biofloc in greenhouses, where light intensity plays a significant role in biofilm/floc formation. Furthermore, higher shrimp production was found in biofloc systems exposed to light than without light (Baloi et al., 2013). The oxygen demand of the biofloc system may be reduced with the integration of algae through the utilization of freely available sunlight energy and nutrient inputs in the required ratio.

Interestingly, it was also found that the algal-bacterial system performs better at low aeration systems ($0.2 \text{ l air min}^{-1}$) to treat domestic wastewater in sequencing batch reactors (Tang et al., 2016). While de Moraes et al. (2020) found better nitrification efficiency with a median air flow rate (33.75 l min^{-1}) during the culture of white shrimp *Litopenaeus vannamei* in biofloc with a biofilm system. These studies revealed the possibility of reducing aeration intensity by employing a modified algal-bacterial system in aquaculture. However, there is limited information on optimum nutrient C:N:P ratio for better heterotrophic bacterial and algal growth. Further, research is needed to carry out standardization of the integrated system through species selection and its density, aeration intensity, photoperiod and intensity, the addition of substrate and its quantity, etc. (Fig. 5). If this kind of integration is found successful, it will open a new avenue toward sustainability. Three wings of sustainability in the sense of social – adoptable by society, environmental – improving productivity without hampering the environment and finally, economical—reducing feed and other input costs may be achieved through this integration.

The current review revealed that the algal-bacterial integration systems have social, environmental, and economic advantages for rearing aquatic animals. Presently, biofloc and periphyton-based aquaculture technologies are based on the algal-bacterial consortia. Biofloc technology mainly focuses on producing

Table 1: Deposition of microbial biomass on several types of substrate experimented in various aquaculture systems

Species	Culture system	Substrate type	Microbial biomass on substrate	Reference
Nile Tilapia <i>Oreochromis niloticus</i> (about 20 g) stocked @ 3 fish m ⁻²	Outdoor concrete tanks	Plastic baffles Bamboo poles	AFDM: 0.3 mg cm ⁻² AFDM: 0.4 mg cm ⁻²	(Shrestha and Knud-Hansen, 1994)
Common carp, <i>Cyprinus carpio</i> (2.1 g) and rohu, <i>Labeo rohita</i> (1.5 g) @ 1 m ⁻²	Cement cisterns	Sugarcane bagasse Paddy straw Eichhornea	Bacterial biomass: 0.02–30.33 × 10 ⁷ Phytoplankton biomass: 51–276 nos. cm ⁻² Zooplankton biomass: 40–206 nos. cm ⁻² Bacterial biomass: 0.03–21.00 × 10 ⁷ Phytoplankton biomass: 32–300 nos. cm ⁻² Zooplankton biomass: 34–165 nos. cm ⁻² Bacterial biomass: 0.10–13.33 × 10 ⁷ Phytoplankton biomass: 72–364 nos. cm ⁻² Zooplankton biomass: 34–244 nos. cm ⁻²	(Ramesh et al., 1999)
Common carp (<i>Cyprinus carpio</i>) and rohu (<i>Labeo rohita</i>) (1.5 g) stocked @ 1 m ⁻²	Outdoor cement cisterns	Sugarcane bagasse	Bacterial biomass: 6.74 × 10 ⁷ Phytoplankton biomass: 119 nos. cm ⁻² Zooplankton biomass: 104 nos. cm ⁻²	(Umesh et al., 1999)
<i>C. catla</i> , <i>L. rohita</i> and <i>C. carpio</i> (1 to 3.8 gm) stocked @ 0.2 numbers m ⁻²	Pond culture	Sugarcane bagasse	AFDM: 0.05 - 0.07 mg cm ⁻² with no feed AFDM: 0.08 to 0.17 mg cm ⁻² with feed	(Keshavanath et al., 2001)
Genetically improved farmed tilapia (GIFT) strain (<i>Oreochromis niloticus</i>) 27 gm @ 22 numbers per m ³	Cage culture	Halved Palstic bottles	AFDM: 1.12 mg cm ⁻² at the time of stocking suddenly dropped to 0.34 mg cm ⁻² within one week of stocking	(Huchette and Beveridge 2003)
Polyculture: Indian Major Carp + Chinese Carp (25 – 30 gm)	Pond (8 X 5 X 1.5 m)	Bamboo stick Rice straw	AFDM per pond: 382.8g AFDM per pond: 280.0g	(Rai et al., 2008)
Shrimp post larvae with postlarvae (PL 43) @ 30m ⁻²	Brackishwater ponds	Bamboo Pole PVC pipe Plastic sheet Fibrous scrubber Ceramic tile Bamboo poles	Chlorophyll a: 1137.2 to 398.9 µg m ⁻² Chlorophyll a: 929.6 to 138.1 µg m ⁻² Chlorophyll a: 684.2 to 217.9 µg m ⁻² Chlorophyll a: 179.1 to 35.9 µg m ⁻² Chlorophyll a: 657.0 to 154.2 µg m ⁻² AFDM: 1.18 – 2.49 0mg cm ⁻²	(Khatoon et al., 2007)
<i>M. rosenbergii</i> (5.0 g) @ 2 juveniles m ⁻²	Pond culture	Bamboo poles	AFDM: 1.18 – 2.49 0mg cm ⁻²	(Asaduzzaman et al., 2008)
Jaraqui (<i>Semaprochilodus insignis</i>) 1.46 g and length 4.15 cm stocked @ 1 m ⁻²	Masonry tanks	Floating macrophyte Plastic screen	DP: 1.36 - 1.48 mg cm ⁻² DP: 0.65 - 0.84 mg cm ⁻²	(Tortolero et al., 2016)
Jaraqui (<i>Semaprochilodus insignis</i>) length 6.5 cm and weight 5.83 g stocked @ 1 per m ²	Mud-bottomed outdoor tanks	Bamboo, (<i>Bambusa vulgaris</i>) Ambay (<i>Cecropia pachystachya</i>) Leucaena (<i>Leucaena leucocephala</i>)	DP: 1.12 – 1.43 mg cm ⁻² DP: 0.95 – 1.22 mg cm ⁻² DP: 0.87 – 0.98 mg cm ⁻²	(Keshavanath et al., 2017)

AFDM – Ash free dry matter; and DP – Dry periphyton

heterotrophic microorganisms by adding carbon sources to maintain the C: N ratio for augmenting intensive fish production. In comparison, periphyton-based extensive technology prefers algal production by adding fertilizers to support N: P ratios and substrate addition to increase the surface area for biofilm formation for moderate fish production intensity.

The benefits of biofloc and biofilm systems can be integrated into a combined approach. For this purpose, further research efforts should focus on selection of an appropriate cultivable species or their combination, light intensity and energy

budget, standardization optimum stocking level of each species, identification of microalgal and bacterial species that can fulfil required food properties for fishes, capacity to control water quality, doses of nutrient inputs in the form of fertilizers and carbon sources, aeration requirement, substrate addition for enhancement of productivity, and finally the economics of culture system. Modern aquaculturists are knowledgeable about the role of the heterotrophic group of microorganisms in nitrogen removal from the culture system. However, a detailed study needs to be carried out to understand photoautotrophic and chemoautotrophic pathways to remove harmful nitrogen. The

appropriate quantity of bacterial and algal biomass can be produced at a low cost in a combined aquaculture system to gain advantages in water quality improvement, health improvement, and food sources. In this way, it can be safely recommended that the algal-bacterial consortium can be a better solution for next-generation sustainable aquaculture.

Data availability statement: The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation, to any qualified researcher.

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