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Perspective

Biofilm-Mediated Nutrient Cycling in Sustainable Aquaculture Systems

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DESCRIPTION

Biofilms are complex microbial communities that develop on submerged surfaces in aquaculture environments. They consist of bacteria, archaea, fungi, algae, protozoa, extracellular polymeric substances, organic particles, and trapped minerals. In ponds, tanks, raceways, biofilters, cages, pipes, substrates, and other aquatic structures, biofilms can become important sites for the transformation and movement of nutrients. Their activities influence nitrogen, phosphorus, carbon, sulfur, and several trace elements within cultured aquatic environments. Understanding these processes is useful for improving water quality and reducing the accumulation of unwanted nutrients in intensive production systems.

Aquaculture animals continuously release metabolic wastes into their surroundings. Uneaten feed, fecal material, mucus, dead microorganisms, and other organic residues contribute additional carbon and nitrogen to the culture water. When these materials accumulate, microbial decomposition can increase concentrations of ammonia, nitrite, dissolved organic compounds, and other metabolites. Biofilms provide surfaces where diverse microorganisms can attach and process these compounds. Their activity can therefore alter the chemical composition of water and sediment while supporting nutrient recycling within the production unit.

Nitrogen cycling is one of the most important functions associated with aquaculture biofilms. Fish and crustaceans excrete nitrogen mainly in forms that can contribute to ammonia accumulation. Organic nitrogen from feed residues and feces can also be converted into ammonium through microbial decomposition. In oxygenated portions of a biofilm, ammonia-oxidizing microorganisms convert ammonium into nitrite, while nitrite-oxidizing microorganisms convert nitrite into nitrate. These processes are commonly described as nitrification. In deeper or oxygen-limited layers, other microorganisms may use nitrate as an electron acceptor and convert it into gaseous nitrogen through denitrification. This creates a sequence in which nitrogen can move between dissolved, particulate, microbial, and gaseous forms. Biofilm structure strongly influences these transformations. A mature biofilm may contain oxygen-rich layers near the water interface and oxygen-limited regions deeper within the microbial matrix. This spatial separation permits microorganisms with different metabolic requirements to operate within a relatively small area. Oxygen-consuming bacteria can occupy outer regions, while anaerobic microorganisms may become more active in deeper layers. Consequently, several nitrogen transformation reactions can occur simultaneously across different microsites. The thickness, density, porosity, organic content, and microbial composition of the biofilm influence the rates of these reactions.

Carbon cycling is also closely associated with microbial biofilms. Organic carbon enters aquaculture systems through feed, animal waste, dead biomass, and dissolved organic compounds. Heterotrophic microorganisms use many of these materials as energy and carbon sources. During microbial respiration, organic carbon is converted into carbon dioxide, while some carbon becomes incorporated into microbial biomass and extracellular polymeric substances. Part of this material may later be consumed by grazing organisms or released back into the water as dissolved compounds. Biofilms can therefore function as active zones where organic matter is captured, transformed, stored, and redistributed.

Phosphorus behavior in aquaculture systems is influenced by both microbial activity and chemical interactions within biofilms. Phosphorus can enter production systems through feed and animal waste. Microorganisms may assimilate dissolved phosphate into cellular material, while phosphate can also associate with minerals and particulate matter. When microbial cells die or release cellular compounds, phosphorus may return to the surrounding environment. Changes in oxygen conditions, pH, microbial metabolism, and mineral composition can influence whether phosphorus remains associated with particles or becomes available in dissolved form. These processes are especially relevant in systems where phosphorus accumulation contributes to excessive algal growth.

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CONCLUSION

Biofilm-mediated nutrient cycling represents an important biological process within aquaculture systems. Microbial communities attached to surfaces participate in the transformation of carbon, nitrogen, phosphorus, sulphur, and other materials introduced through feed, animal metabolism, and environmental inputs. Their activities are controlled by oxygen, organic matter, temperature, salinity, pH, flow conditions, substrate characteristics, and microbial composition. A better understanding of these processes can help aquaculture producers design biological treatment systems, manage nutrient loads, and maintain suitable culture conditions. Careful integration of microbial ecology with water-quality monitoring can make nutrient management more efficient while supporting stable aquatic production.