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Bamboo Charcoal as a Sustainable Water Quality Management Tool in Aquaculture Systems: A Review

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Abstract: *The rapid intensification of aquaculture production has increased the need for sustainable water quality management strategies. Bamboo charcoal, a porous carbonaceous material produced through pyrolysis of bamboo biomass, has emerged as an eco-friendly alternative for improving aquaculture environments. Its high adsorption capacity, large surface area, and ability to support microbial colonization make it suitable for removal of nitrogenous wastes, organic pollutants, and residual chemicals from aquatic systems. This review synthesizes current knowledge on physicochemical properties, mechanisms of action, and applications of bamboo charcoal in pond aquaculture, recirculating aquaculture systems (RAS), and aquaculture wastewater treatment. The review highlights benefits, limitations, and future research prospects, emphasizing bamboo charcoal as a low-cost and sustainable component of green aquaculture technologies.*

Keywords: Bamboo charcoal; Biochar; Aquaculture water quality; Biofiltration; Nitrogen removal; Sustainable aquaculture

I. INTRODUCTION

Aquaculture is one of the fastest-growing food production sectors globally, contributing significantly to food security and economic development. However, intensified production systems generate high organic loads and nitrogenous wastes that degrade water quality and increase disease risks.Ammonia accumulation remains one of the primary constraints affecting fish growth and survival. Conventional management approaches rely on water exchange, chemical treatments, or synthetic filtration media, which may increase operational costs and environmental impacts.Biochar materials derived from agricultural biomass have gained attention as sustainable filtration agents.

Among these, bamboo charcoal is particularly promising due to rapid bamboo growth, renewability, and favorable physicochemical properties. The highly porous structure of bamboo charcoal enables adsorption of pollutants and provides substrate for beneficial microbial communities.Bamboo charcoal, a form of biochar derived from lignocellulosic biomass, has emerged as a promising and sustainable material for water quality management in aquaculture systems. Its effectiveness is primarily attributed to its high porosity, large surface area, and abundance of functional groups, which facilitate adsorption of a wide range of contaminants including ammonia, heavy metals, and organic pollutants (Ahmad et al., 2014; Tan et al., 2015; Mohan et al., 2014).One of the most critical challenges in aquaculture is the accumulation of nitrogenous wastes, particularly ammonia, which is toxic to fish and shrimp even at low concentrations (Boyd, 2015). Studies have demonstrated that chemically modified bamboo charcoal significantly enhances ammonia adsorption capacity, making it highly relevant for use in recirculating aquaculture systems (RAS) and intensive pond culture (Zhang et al., 2012; Liu et al., 2022). The presence of micropores and surface-active sites enables efficient trapping of ammonium ions, thereby improving overall water quality.In addition to nitrogen control, bamboo charcoal has shown strong potential in removing heavy metals such as copper, zinc, and cadmium, which may enter aquaculture systems through feed, fertilizers, or contaminated water sources. Surface modification techniques,

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including alkali treatment and metal impregnation, further improve adsorption efficiency by increasing surface charge and active binding sites (Ma et al., 2024; Yang et al., 2023; Wang et al., 2022; Zhang et al., 2013). This is particularly important for maintaining a safe culture environment and preventing bioaccumulation in aquatic organisms (Inyang et al., 2016).

Another emerging concern in aquaculture is the presence of antibiotics and pharmaceutical residues, which can contribute to antimicrobial resistance. Bamboo-derived biochar has been found effective in adsorbing antibiotics such as tetracycline and quinolones, thereby reducing their environmental impact (Li et al., 2025; Ouyang et al., 2024; Chen et al., 2024; Cheng et al., 2024). The adsorption mechanisms typically involve π–π interactions, hydrogen bonding, and electrostatic attraction, indicating its suitability for complex wastewater matrices.

From a system perspective, bamboo charcoal can be integrated into filtration units, biofilters, and sediment beds in aquaculture setups. In recirculating aquaculture systems, it can function as a supplementary adsorbent alongside mechanical and biological filtration, enhancing overall treatment efficiency (Timmons and Ebeling, 2010). Moreover, its compatibility with biofloc technology suggests that it can support microbial communities while simultaneously removing excess nutrients and toxins (Crab et al., 2012; Mukherjee and Zimmerman, 2013).

Despite its advantages, certain limitations need to be considered. The adsorption capacity of bamboo charcoal may decline over time, requiring regeneration or replacement, and its efficiency depends on factors such as pyrolysis temperature, particle size, and modification method (Lehmann and Joseph, 2015; Liu et al., 2022). Economic feasibility and large-scale applicability also require further investigation, particularly in commercial farming systems.Bamboo charcoal represents a sustainable and efficient water quality management tool for aquaculture systems due to its excellent adsorption properties and environmental compatibility (Ahmad et al., 2014; Tan et al., 2015). It is capable of removing a wide spectrum of pollutants, including ammonia, heavy metals, and antibiotics, thereby improving the health and productivity of cultured species (Li et al., 2025; Ma et al., 2024).

Its application in systems such as recirculating aquaculture systems (RAS), ponds, and biofloc technology highlights its versatility and practical relevance (Timmons and Ebeling, 2010; Crab et al., 2012). Furthermore, its low cost and renewable nature make it an attractive alternative to conventional chemical treatments and synthetic adsorbents.

However, to fully realize its potential, further research is needed to optimize modification techniques, regeneration methods, and system integration strategies (Lehmann and Joseph, 2015). Field-scale studies and economic analyses will be crucial for promoting its adoption in commercial aquaculture.

II. PRODUCTION AND PHYSICOCHEMICAL PROPERTIES OF BAMBOO CHARCOAL

2.1 Production Process

Bamboo charcoal is produced through pyrolysis of bamboo biomass at temperatures ranging from 400–900 °C under limited oxygen conditions. Pyrolysis temperature strongly influences pore structure, adsorption capacity, and surface chemistry.Higher temperatures generally increase:

Carbon purity
Surface area
Microporosity
Adsorption efficiency

Activation processes using steam or chemicals further enhance adsorption performance.

2.2 Structural Characteristics

Bamboo charcoal exhibits:

Surface area: 200–800 $m^2 g^{-1}$
High pore volume
Stable carbon framework
Mechanical durability in aquatic environments

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The hierarchical pore structure supports microbial biofilm development essential for biological filtration.

2.3 Chemical Properties
Important chemical features include:
Alkaline pH buffering capacity
Functional groups enabling ion exchange
High affinity toward ammonium and dissolved organic compounds
These properties contribute to improved water stability in aquaculture systems.

III. MECHANISMS OF BAMBOO CHARCOAL IN AQUACULTURE
3.1 Adsorption of Nitrogenous Compounds
Fish metabolism releases ammonia and organic nitrogen into culture water. Bamboo charcoal adsorbs ammonium ions through electrostatic attraction and surface functional groups.
Studies report significant reductions in:

- Total ammonia nitrogen (TAN)
  Nitrite concentrations
  Total phosphorus
  This adsorption reduces toxicity and improves fish health.

3.2 Microbial Immobilization and Biofilm Formation
The porous surface acts as a microbial carrier supporting nitrifying bacteria such as:

- Nitrosomonas
- Nitrobacter

These bacteria convert ammonia into less toxic nitrate, enhancing biological filtration efficiency.

3.3 Organic Matter Removal
Bamboo charcoal adsorbs dissolved organic carbon, reducing turbidity, odor formation, and microbial oxygen demand. This results in improved dissolved oxygen conditions and system stability.

3.4 Removal of Antibiotics and Heavy Metals
Recent studies indicate bamboo biochar can adsorb antibiotic residues and trace metals commonly found in aquaculture effluents, reducing environmental discharge risks.

IV. APPLICATIONS IN AQUACULTURE SYSTEMS
4.1 Pond Aquaculture
Applications include:
Bottom sediment amendment
Floating filtration units
Feed additive carrier materials
Benefits observed:
Reduced sludge accumulation
Improved survival rates
Stabilized pH conditions

4.2 Recirculating Aquaculture Systems (RAS)
In RAS, bamboo charcoal functions as a biological filter medium replacing synthetic plastic media.

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Advantages include:
Increased microbial colonization
Improved ammonia oxidation
Lower operational cost

4.3 Biofloc Technology

Bamboo charcoal enhances floc aggregation by providing nucleation surfaces for microbial communities, improving nutrient recycling efficiency.

4.4 Aquaculture Wastewater Treatment

Activated bamboo biochar effectively removes excess nutrients before discharge, enabling water reuse and reducing eutrophication risks.

V. ADVANTAGES OF BAMBOO CHARCOAL

Aspect	Benefit
Environmental	Renewable and biodegradable
Economic	Low-cost filtration medium
Biological	Supports beneficial microbes
Chemical	Adsorbs toxins and pollutants
Operational	Reduces water exchange requirement

VI. LIMITATIONS AND CHALLENGES

Despite promising outcomes, challenges remain:
Variability in charcoal quality depending on production conditions
Saturation of adsorption sites over time
Need for regeneration or replacement
Limited commercial-scale validation studies
Standardization protocols are required for aquaculture applications.

VII. FUTURE RESEARCH PERSPECTIVES

Future studies should focus on:
Long-term field trials in commercial aquaculture ponds
Optimization of particle size and dosage levels
Integration with probiotics and biofloc systems
Application in ornamental aquarium filtration systems
Carbon sequestration assessment in aquaculture ecosystems
Bamboo charcoal may play an important role in climate-resilient aquaculture practices.

VIII. CONCLUSION

In conclusion, bamboo charcoal can play a significant role in advancing sustainable and environmentally responsible aquaculture practices, contributing to improved water quality, reduced environmental impact, and enhanced production efficiency. Overall, bamboo charcoal offers a low-cost, eco-friendly, and locally available solution, especially in regions where bamboo resources are abundant, making it highly suitable for sustainable aquaculture development.

DECLARATION OF COMPETING INTEREST

The author declares no conflict of interest.

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