UMT PRESS

Planetary Sustainability
Journal Homepage: https://journal.umt.edu.my/index.php/planetsust/
eISSN: 3009-0105
DOI: http://doi.org/10.46754/ps.2024.07.004

AQUACULTURE WASTE AS A RESOURCE: AN OVERVIEW

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HIGHLIGHTS

- The usefulness of aquaculture waste as resources for agriculture, energy generation and bioremediation are briefly discussed.
- Methods for converting waste into biofertiliser and biogas are introduced.
- Practical case studies of waste-to-resource strategies are presented.
- Policy implications for sustainable aquaculture development are discussed.

GRAPHICAL ABSTRACT

ARTICLE INFO

Article History:
Received: 2 June 2024
Accepted: 26 June 2024
Published: 31 July 2024

Keywords:
Aquaculture waste, circular economy, biofertilisers, bioremediation, sustainable development.

ABSTRACT

Aquaculture, a rapidly growing sector, produces substantial amounts of organic and inorganic waste, which, if not managed properly, can lead to environmental degradation. This review explores the potential of aquaculture wastes as valuable resources within a circular economy framework. The study focuses on various types of waste, including fish faeces, uneaten feed and mortalities, and their potential applications in agriculture, energy production and bioremediation. The current methods of waste management and their limitations are also analysed, besides highlighting innovative approaches for converting these wastes into biofertilisers, biogas and other bio-based products. Emphasis is placed on the role of microbial processes and biotechnological advancements in enhancing waste valorisation. Case studies demonstrating successful implementation of waste-to-resource strategies in different aquaculture systems are reviewed, providing practical insights and best practices. The paper also discusses policy implications and the need for integrated waste management strategies that align with sustainable development goals. By transforming aquaculture waste into valuable resources, the industry can mitigate its environmental footprint while contributing to global food security and sustainable development. This review aims to offer an overview of the current state of research and to identify future directions for maximising the potential of waste within a sustainable and resilient aquaculture system.

Introduction

Aquaculture, the farming of aquatic organisms such as fish, crustaceans, molluscs, and aquatic plants has emerged as one of the fastest-growing food production sectors globally (Troell *et al*., 2014; FAO, 2022). Driven by the increasing demand for seafood and the decline in wild fish stocks, aquaculture provides a promising solution to meet the protein needs of a growing global population (Troell *et al*., 2014; Tacon & Metian, 2015). However, its rapid expansion has brought significant environmental challenges, particularly relating to waste management. The industry generates substantial amounts of organic and inorganic waste, including uneaten feed, faeces and dead fish which, if not managed properly, can lead to water pollution, eutrophication and other ecological problems (Avnimelech, 2009; D'Abramo *et al*., 2021).

Traditional waste management practices in aquaculture such as direct discharge into water bodies or landfilling are increasingly recognised as unsustainable (D'Abramo *et al*., 2021). These methods not only contribute to environmental degradation, but also represent a loss of potentially valuable resources. In recent years, there has been growing interest in rethinking aquaculture waste management within the framework of a circular economy (Troell *et al*., 2014; Tacon & Metian, 2015). This approach emphasises the recovery and recycling of waste, transforming them into valuable products, thereby reducing their environmental impact and enhancing resource efficiency (Avnimelech, 2009; Wan Mahari *et al*., 2022).

The concept of utilising aquaculture waste as resources is grounded in the principles of waste valorisation, which involves converting waste materials into useful products (Troell *et al*., 2014; Wan Mahari *et al*., 2022) can be processed and repurposed in multiple ways. For instance, organic wastes can be composted to produce biofertiliser, while anaerobic digestion can convert them into biogas, a renewable energy source (Avnimelech, 2009; Ndiaye *et al*., 2020). Additionally, aquaculture waste can be used in bioremediation to remove contaminants from water and soil, a process that helps to restore the environment (Troell *et al*., 2014).

The potential benefits of transforming aquaculture waste into resources are manifold. First, it can significantly reduce the industry's environmental footprint by minimising discharge and mitigating pollution (Avnimelech, 2009; Tacon & Metian, 2015). Second, it offers economic advantages by creating additional revenue streams from waste-derived products (D'Abramo, 2021). Third, it supports the sustainability and resilience of aquaculture systems by promoting resource efficiency and reducing dependence on external inputs (Troell *et al*., 2014).

Despite the promising prospects, the implementation of waste-to-resource strategies in aquaculture faces several challenges. They include technical barriers relating to waste collection, processing and conversion, as well as economic and regulatory hurdles (Avnimelech, 2009; Tacon & Metian, 2015). There is also a need for greater awareness and acceptance among industry players and stakeholders about the potential of waste valorisation (Wan Mahari *et al*., 2022).

This review aims to provide an overview of the current state of research and practice in the valorisation of aquaculture waste. It will examine the types and characteristics of waste generated in aquaculture systems, the methods available for their conversion into valuable products, and the challenges and opportunities associated with these processes. By highlighting successful case studies and innovative approaches, this review seeks to offer practical insights for enhancing the sustainability of aquaculture through effective waste management. Through this overview, we aim to underscore the importance of integrating waste management into the broader context of sustainable aquaculture development and to inspire further innovation in this field.

Types and Sources of Aquaculture Wastes

Aquaculture systems generate a variety of waste products that can be broadly categorised into solid and liquid wastes. These wastes originate from several sources, including uneaten feed, fish faeces, metabolic excretions, and mortalities. Understanding the types and sources of these wastes is essential for developing effective waste management and valorisation strategies (D'Abramo, 2021).

Solid Wastes

Uneaten Feed

Uneaten feed is a major component of solid waste in aquaculture systems. It results from overfeeding or inefficient feeding practices, leading to excess feed particles settling at the bottom of the ponds. This waste not only represents a financial loss, but also contributes to water pollution as it decomposes, releasing its rich nutrients and organic matter into the environment (Avnimelech, 2009; Tacon & Metian, 2015).

Fish Faeces

Fish faeces constitute another significant portion of solid waste in aquaculture. They are rich in nitrogen and phosphorus, which may cause eutrophication if released into surrounding water bodies. The rate of faeces production depends on the type of fish stocks being cultured, their diet, and the efficiency of feed conversion (Troell *et al*., 2014; D'Abramo, 2021).

Mortalities

Dead fish, often referred to as mortalities, are an inevitable part of aquaculture operations. Mortalities can result from outbreaks, poor water quality or the fishes' inability to tolerate stress. If not properly managed, the remains of dead fish can become a source of secondary pollution and pose health risks to remaining stocks (Avnimelech, 2009; Troell *et al*., 2014).

Liquid Wastes

Metabolic Excretions

Fish excrete metabolic waste from their body, primarily ammonia, directly into the water through their gills and urine. Ammonia is toxic to aquatic organisms at high concentrations and must be effectively removed from the ecosystem to maintain water quality and fish health. In recirculating aquaculture systems (RAS), biofilters are commonly used to convert ammonia into less harmful substances through nitrification (Tacon & Metian, 2015).

Water Discharges

Aquaculture systems not only consume huge amounts of water resources, but the water they use will eventually become heavily contaminated with various wastes, including dissolved nutrients, chemicals, and suspended solids. Furthermore, periodic water changes in ponds and culture tanks are often required to maintain water quality and ensure survival of fish stocks, leading to the frequent discharge of nutrient-rich effluents into the environment in large quantities. These discharges can contribute to eutrophication and negatively impact surrounding ecosystems (Avnimelech, 2009; Troell *et al*., 2014).

Sources of Waste in Different Aquaculture Systems

Pond Systems

In traditional pond systems, waste accumulates at the bottom of the ponds, where it can decompose and release nutrients into the water column. Management practices such as pond draining and sediment removal are employed to control waste build-up (Troell *et al*., 2014).

Cage Systems

Cage systems, commonly used in marine and freshwater environments, allow for free exchange of water between the culture area and its surrounding environment. Wastes such as uneaten feed and faeces are directly released into the environment, necessitating the use of good farming practices to minimise environmental impacts (Avnimelech, 2009; Drizo & Shaikh, 2023).

Recirculating Aquaculture Systems (RAS)

RAS are designed to treat and reuse the water within an enclosed system, significantly reducing consumption and waste discharge. Solid wastes are removed through mechanical filtration, while biological filtration processes manage dissolved waste products. Despite these advanced waste management practices, RAS still produces solid waste that requires proper handling and disposal (Troell *et al*., 2014; Tacon & Metian, 2015).

Waste Valorisation Methods

The transformation of aquaculture waste into valuable products, known as waste valorisation, offers a sustainable solution to the environmental challenges posed by traditional waste management practices. This section explores various methods for waste valorisation, including composting, anaerobic digestion, and bioremediation—highlighting their processes, benefits, and potential applications.

Composting

Process Overview

Composting is a biological process that turns organic waste into a stable, humus-like product known as compost. This process involves using bacteria and fungi to break down organic matter in the presence of oxygen. Composting can be conducted in open windrows, enclosed vessels or static piles, depending on the scale and requirements of the operation (Wang *et al*., 2021).

Benefits

Compost produced from aquaculture wastes, such as fish faeces and uneaten feed, is rich in nutrients and organic matter, making it an excellent soil conditioner for agriculture (Illera-Vives *et al*., 2015). This compost provides essential nutrients that improve soil fertility, structure and water retention, benefiting crop growth and yield. The organic matter in the compost also promotes beneficial microbial activity in the soil, which further supports plant growth and resilience against pests and diseases.

Composting reduces the volume of organic waste, decreasing the environmental footprint of aquaculture operations (Lopes *et al*., 2021). By diverting fish waste and uneaten feed away from landfills and water bodies, composting minimises pollution and helps in maintaining cleaner and healthier aquatic ecosystems. This waste management strategy not only addresses the environmental challenges associated with aquaculture, but also aligns with sustainable development goals. Reducing organic waste through composting thus plays a crucial role in promoting environmentally responsible practices within the aquaculture industry.

The sale of compost as a biofertiliser can generate additional revenue streams for aquaculture farmers (Chiquito-Contreras *et al*., 2022). By transforming waste into a valuable product, aquaculture operations can create new economic opportunities. This additional income can help offset operational costs and provide financial stability for farmers. Furthermore, the market demand for organic and sustainable agricultural inputs is growing, providing a lucrative market for compost produced from aquaculture waste (Mahish *et al*., 2024). This not only supports the economic viability of aquaculture farms, but also promotes the adoption of sustainable agricultural practices.

Applications

Compost can be used to improve soil fertility and structure, which enhances crop yield and sustainability. By adding compost to their land, farmers can enrich the soil with essential nutrients and organic matter, leading to better crop growth and increased productivity (Mahish *et al*., 2024). This practice not only boosts crop yield, but also contributes to sustainable farming by improving soil health and reducing the need for chemical fertilisers that pollute the environment.

Compost is also suitable for use in gardens and landscapes as a natural fertiliser and soil conditioner. It enhances the soil's ability to retain moisture and provides a steady release of nutrients, promoting healthy plant growth (Illera-Vives *et al*., 2015). Gardeners and landscapers often use compost to enrich garden beds, improve soil texture and support robust plant development, all while fostering environmentally friendly gardening practices.

Anaerobic Digestion

Process Overview

Anaerobic digestion is a biological process that breaks down organic waste materials in the absence of oxygen, producing biogas (a mixture of methane and carbon dioxide) and digestate (a nutrient-rich residue). This process occurs in a sealed reactor, where microorganisms convert the organic matter through a series of biochemical reactions (Angelidaki & Sanders, 2004; Mata-Alvarez *et al*., 2014).

Benefits

Biogas produced from aquaculture waste can serve as a renewable energy source for heating, electricity generation and vehicle fuel, reducing the reliance on fossil fuels (Bücker *et al*., 2020). This sustainable energy option helps meet energy demands while lowering greenhouse gas emissions.

The digestate by-product contains essential nutrients that can support plant growth and improve soil health. Using digestate as a biofertiliser reduces the need for synthetic fertilisers, which enhances the sustainability of agricultural practices and fostering a closed-loop nutrient management system.

Anaerobic digestion of aquaculture waste significantly reduces the volume and environmental impact of organic waste (Mata-Alvarez *et al*., 2014). This process minimises the amount of waste sent to landfills besides decreasing pollution. By treating aquaculture waste with anaerobic digestion, the environmental footprint is reduced, aligning with waste minimisation and resource recovery goals, and contributing to a more sustainable waste management strategy.

Applications

Biogas generated from aquaculture wastes can be channelled to on-site energy needs or injected into the natural gas grid (Choudhury *et al*., 2022). This renewable energy source helps reduce dependence on fossil fuels and can be used for heating, electricity generation and vehicle fuel. By converting aquaculture waste into biogas, operations can achieve greater energy self-sufficiency and contribute to a more sustainable energy system.

The digestate, the byproduct of anaerobic digestion, can be applied directly to agricultural fields, providing a sustainable source of nutrients for crop production (Samoraj *et al*., 2022). Rich in essential nutrients, digestate enhances soil fertility, and promotes healthy plant growth.

Bioremediation

Process Overview

Bioremediation is the use of microorganisms or plants to remove or neutralise contaminants from polluted environments. In aquaculture, bioremediation techniques can be applied to treat waste effluents and improve water quality (Liu *et al*., 2014; Bharagava *et al*., 2020).

Benefits

Bioremediation helps to mitigate the impact of aquaculture waste on the environment by reducing nutrient loads and contaminants in effluents (Chávez-Crooker *et al*., 2010). By using natural processes to break down and remove harmful substances, bioremediation protects water quality and supports healthier aquatic ecosystems.

This method is often more cost-effective and sustainable than traditional chemical treatments. Bioremediation leverages natural biological processes, which typically require fewer resources and lower operational costs compared with chemical methods. This makes it an attractive option for managing aquaculture waste, offering economic benefits while maintaining environmental integrity.

It promotes the use of natural processes for waste treatment, aligning with sustainable aquaculture practices (Liu *et al*., 2014; Bharagava *et al*., 2020). This practice supports long-term environmental health and is in line with broader goals of sustainable development and responsible resource management.

Applications

Constructed wetlands use plants and microorganisms to treat wastewater from aquaculture operations, effectively removing nutrients and pollutants. These natural treatment systems mimic the functions of natural wetlands, where plants and microbial communities break down and absorb contaminants (Lin *et al*., 2002). Constructed wetlands offer an eco-friendly solution for managing aquaculture wastewater, improving water quality before it is discharged into the environment.

Biofilters, or biological filtration systems, can be integrated into aquaculture systems to continuously treat water, enhancing water quality and reducing waste discharge (Lukwambe *et al*., 2019). These systems utilise beneficial bacteria to break down organic matter and convert harmful substances into less toxic forms. By maintaining cleaner water, biofilters support healthier aquatic environments and more sustainable aquaculture practices, ensuring the longevity and productivity of aquaculture operations.

Each of these waste valorisation methods offers unique advantages and can be tailored to specific types of aquaculture waste and operational contexts. The following sections will present case studies that demonstrate successful implementation of these strategies in various aquaculture systems, providing practical insights and best practices for maximising the potential of aquaculture wastes.

Case Studies of Successful Waste Valorisation

In Canada, the Integrated Multi-Trophic Aquaculture (IMTA) has been successfully implemented to valorise waste from salmon farming by culturing different species from various trophic levels together. This approach utilises waste from fed species like salmon to support the growth of extractive species such as seaweeds and shellfish, which absorb dissolved nutrients and filter particulate matter, respectively (Troell *et al*., 2009; Chopin, 2010).

In Norway, the anaerobic digestion of fish waste, including heads, bones and entrails, has been adopted to produce renewable energy (Sarker, 2020). This process generates biogas, which is used for electricity and heat production, thereby reducing reliance on fossil fuels. The digestate produced is used as a biofertiliser, returning valuable nutrients to soil and contributing to a circular nutrient cycle (Batstone *et al*., 2009).

Small-scale fish farms in Vietnam have adopted composting to manage their organic waste and produce biofertiliser (Hiu *et al*., 2021). By composting fish waste together with materials like rice husks and straw, the farms have managed to produce high-quality compost, which is then used to enhance soil fertility in local agricultural fields. This practice improves soil health and crop yield while reducing the environmental impact of fish waste.

In China, “wetland” areas have been constructed to treat wastewater from aquaculture ponds, leveraging the natural processes in the environment for waste management. These wetlands use plants and microorganisms to filter and degrade waste products from aquaculture effluents, effectively removing nutrients, suspended solids and contaminants. This sustainable treatment method had been shown to improve water quality, which allows for the safe discharge or even reuse of the "treated" water, besides reducing pollution and contributing to environmental conservation (Vymazal, 2011; Chen *et al*., 2014).

Economic and Environmental Impacts

The implementation of waste valorisation methods in aquaculture not only addresses environmental challenges but also yields significant economic benefits. This section examines the dual impacts of these strategies, highlighting their role in promoting sustainability and economic viability within the aquaculture industry.

Environmental Benefits

Nutrient Management

Waste valorisation techniques such as composting, anaerobic digestion, and bioremediation may effectively manage nutrients present in aquaculture waste. By converting organic matter into useful products like compost or biogas, they can reduce nutrient loading in aquatic ecosystems, mitigating the risk of eutrophication and algae blooms (Angelidaki & Sanders, 2004; Bharagava *et al*., 2020).

Water Quality Improvement

Processes like "constructed wetlands" in China and bioremediation can enhance water quality by filtering out pollutants and contaminants from aquaculture effluents. This results in cleaner water bodies and reduces the environmental impact of nutrient-rich discharges on surrounding ecosystems (Liu *et al*., 2014; Mata-Alvarez *et al*., 2014).

Climate Mitigation

Anaerobic digestion technology, in particular, contributes to climate change mitigation by capturing methane—a major greenhouse gas otherwise released into the atmosphere from organic waste decomposition. The utilisation of biogas as a renewable energy source further reduces greenhouse gas emissions associated with fossil fuel use in aquaculture operations (Mata-Alvarez *et al*., 2014).

Economic Benefits

Revenue Generation

Waste valorisation generates additional revenue streams for aquaculture farmers through the sale of compost, biofertilisers and renewable energy products like biogas. This diversification of income sources helps improve their economic resilience and increase profitability in the face of fluctuating market conditions (Lopes *et al*., 2021).

Cost Savings

By utilising waste materials for energy production or soil enhancement, aquaculture operations can reduce disposal costs and expenditure on external inputs like synthetic fertilisers. This cost-effective approach improves operational efficiency and has long-term financial sustainability (Chiquito-Contreras *et al*., 2022).

Regulatory Compliance

Adopting sustainable waste management practices helps aquaculture enterprises comply with environmental regulations and standards. Reduced nutrient discharge and improved water quality contribute to regulatory compliance and will enhance the industry's reputation for environmental stewardship (Liu *et al*., 2014).

Conclusions

Integrating waste valorisation into aquaculture practices represents a holistic approach to sustainability, balancing environmental stewardship with economic prosperity. By optimising resource use and minimising waste production, aquaculture operations can enhance productivity while safeguarding natural resources and the ecosystem. The continued advancement of waste-to-resource technologies and practices will be crucial in addressing the environmental challenges posed by the aquaculture industry. Encouraging the adoption of these methods through policy support, education, and collaboration among stakeholders can drive the transition towards more sustainable and resilient aquaculture systems. Future research should focus on refining waste valorisation processes, developing new applications for waste-derived products, and exploring innovative solutions to overcome existing barriers. By transforming aquaculture wastes into valuable resources, the industry can play a significant role in achieving global food security and sustainable development goals.

Acknowledgement

The author expresses gratitude to Universiti Malaysia Terengganu for supporting this work through Matching Grant 1+3 (UMT/MG1+3/2023/53550).

Conflict of Interest Statement

The author declares no conflict of interest.

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