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ENERGY EFFICIENCY IN AERATION SYSTEMS FOR AQUACULTURE PONDS: A COMPREHENSIVE REVIEW

ABSTRACT

Aeration is a critical component in aquaculture systems to ensure optimal dissolved oxygen levels for aquatic organisms. However, aeration is also one of the most energy-intensive processes. This review critically analyzes energy efficiency strategies in aeration systems, highlighting technological advances and sustainable implementation practices analyzed using a systematic literature review approach, with inclusion criteria based on relevance to energy use, oxygenation performance, and real-world applications. The study identifies and compares different types of aeration technologies, including paddle wheel aerators, diffused air systems, venturi injectors, and renewable energy aerators in terms of energy efficiency and oxygenation effectiveness. Additionally, the study explores key factors that influence aeration efficiency, such as pond design, automation, and integration of renewable energy sources, such as solar and wind, to power the aeration system. This paper extends previous literature by proposing a comprehensive framework that integrates digital technologies (e.g., sensor-based control systems and automation) with renewable energy sources to optimize aeration efficiency. The review offers a holistic approach that combines the evaluation of individual technologies or energy sources. The findings show that sensor-based automation can reduce energy consumption by up to 40%, and the integration of renewable energy significantly lowers long-term operating costs. Real-world applications of these strategies in aquaculture operations are also discussed, demonstrating both economic and environmental benefits in simple terms.

KEYWORDS: aeration; aquaculture; automation technology; energy efficiency; renewable energy

ABSTRAK: Efisiensi Energi dalam Sistem Aerasi untuk Kolam Budidaya: Sebuah Reviu Komprehensif

Aerasi merupakan komponen penting dalam sistem akuakultur untuk memastikan kadar oksigen terlarut yang optimal bagi organisme akuatik. Akan tetapi, aerasi juga merupakan salah satu proses yang paling boros energi. Tinjauan ini menganalisis secara kritis strategi efisiensi energi dalam sistem aerasi, menyoroti kemajuan teknologi dan praktik implementasi berkelanjutan yang dianalisis menggunakan pendekatan tinjauan pustaka sistematis, dengan kriteria inklusi berdasarkan relevansi terhadap penggunaan energi, kinerja oksigenasi, dan penerapan di dunia nyata. Studi ini mengidentifikasi dan membandingkan berbagai jenis teknologi aerasi, termasuk aerator roda dayung, sistem udara terdifusi, injektor venturi, dan aerator energi terbarukan dalam hal efisiensi energi dan efektivitas oksigenasi. Selain itu, studi ini mengeksplorasi faktor-faktor utama yang memengaruhi efisiensi aerasi, seperti desain kolam, otomatisasi, dan integrasi sumber energi terbarukan, seperti tenaga surya dan angin, untuk memberi daya pada sistem aerasi. Makalah ini memperluas literatur sebelumnya dengan mengusulkan kerangka kerja komprehensif yang mengintegrasikan teknologi digital (misalnya, sistem kontrol berbasis sensor dan otomatisasi) dengan sumber energi terbarukan untuk mengoptimalkan efisiensi aerasi. Tinjauan ini menawarkan pendekatan holistik yang menggabungkan evaluasi teknologi individual atau sumber energi. Temuan tersebut menunjukkan bahwa otomatisasi berbasis sensor dapat mengurangi konsumsi energi hingga 40%, dan integrasi energi terbarukan secara signifikan menurunkan *biaya operasi jangka panjang. Aplikasi nyata dari strategi ini dalam operasi akuakultur juga dibahas, yang menunjukkan manfaat ekonomi dan lingkungan secara sederhana.*

KATA KUNCI: aerasi; akuakultur; efisiensi energi; energi terbarukan; teknologi otomatisasi

INTRODUCTION

Aquaculture is a rapidly growing sector in the fisheries industry, with aeration technology playing a crucial role in increasing fish farming productivity. Aeration increases dissolved oxygen (DO) levels, which are essential for fish growth, metabolism, and overall health (Ariadi *et al.*, 2023; Boyd & McNevin, 2021; Ramesh *et al.*, 2024). However, aeration is also one of the most energy-intensive processes in aquaculture, contributing significantly to operational costs and environmental impact (Jamroen, 2022). Inefficient aeration systems lead to excessive energy consumption and suboptimal oxygen distribution, negatively affecting fish survival rates and productivity (Bahri *et al.*, 2019; Palya & MacPhee, 2023). These inefficiencies underscore the necessity for more sustainable aeration solutions that balance energy use with oxygenation efficiency.

In addition to energy consumption, the availability and quality of air or oxygen used in the aeration and salinity control system are also important factors affecting system performance (Dayıoğlu, 2022; Rizzardi *et al.*, 2023; Yadav *et al.*, 2022b). Aeration relies on atmospheric air or pure oxygen sources, and its effectiveness can vary depending on ambient temperature, humidity, atmospheric pressure, and salinity levels. In saline or brackish aquaculture environments, oxygen solubility is reduced, requiring more efficient oxygen delivery mechanisms to achieve desired DO levels (Ramesh *et al.*, 2024). In addition, air quality including particulates and contaminants can affect aerator performance and long-term system reliability. It is also worth considering that activities should not only optimize mechanical aeration systems but also evaluate the characteristics of air or oxygen inputs and the surrounding environmental context.

In high-density aquaculture systems, traditional paddle wheel aerators remain widely used due to their simplicity and relatively low capital costs (Cheatham *et al*., 2023). However, they are among the most energy-wasteful aeration technologies, especially when applied continuously without considering real-time oxygen demand (Dong & Wang, 2023; Pontón *et al.,* 2023). Paddle wheel systems often operate under fixed schedules rather than responsive control mechanisms, leading to unnecessary energy use and oxygen oversaturation in certain areas while other zones remain under-aerated. This inefficiency becomes more pronounced as stocking density increases, where precise and adaptive oxygen delivery is critical to maintaining water quality and fish health (Boyd & McNevin, 2021; Palya & MacPhee, 2023). Therefore, optimizing aeration efficiency is essential, particularly in intensive systems where production goals rely heavily on maintaining high DO levels (Fan *et al*., 2017; Ramesh *et al*., 2024; Roy *et al*., 2021; Yadav & Roy, 2023).

Recent studies have explored various approaches to improving energy efficiency in aeration systems, including aerator selection, system design optimization, and the integration of emerging technologies (Boyd & McNevin, 2021; Jamroen, 2022; Jamroen *et al.*, 2023a; Jamroen *et al*., 2023b). For example, blower-based aeration systems have demonstrated higher energy efficiency, delivering greater oxygen transfer per unit of energy consumed compared to traditional paddle wheel aerators under specific conditions, which can also translate into reduced operational costs and improved system performance (Arini *et al*., 2023; Tien *et al*., 2023). Furthermore, advanced techniques such as nanobubbles and microaeration have shown promise in enhancing oxygen transfer while reducing energy consumption (Mulyadi & Yunus, 2019; Phu & Nguyen, 2022). However, the effectiveness of these technologies depends on factors such as environmental conditions, water quality, and the species being farmed (Hakim *et al.*, 2023; Suravut *et al.*, 2017). Despite these innovations, practical adoption remains limited due to high initial costs and technical challenges.

Technological advances, system design, and automation play critical roles in optimizing aeration performance. Research has shown that aeration systems operating based on real-time oxygen demand rather than continuous aeration significantly improve energy efficiency (Nass *et al.*, 2020; Roy *et al.*, 2020, 2022, 2024). Sensor-based automatic control systems can reduce energy consumption by up to 30% by dynamically adjusting aeration levels (Krismadinata *et al.*, 2024; Olanubi *et al.*, 2024). This approach has been successfully implemented in commercial aquaculture operations, demonstrating its viability in reducing costs and improving sustainability (Mulyadi & Yunus, 2019; Tolentino *et al.*, 2021). However, challenges such as the complexity of system integration and the need for skilled labor continue to hinder widespread adoption.

This study critically evaluates aeration technologies and their energy efficiency, offering a comprehensive framework that integrates aerator selection, automation, and renewable energy sources. Unlike previous studies that primarily compile existing knowledge without offering an integrative framework, such as those by Arepalli & Naik (2024a), Nass *et al.* (2020), and Singh *et al.* (2024), this study provides a holistic perspective by combining practical applications and real-world case studies. The proposed framework aims to support the development of sustainable aeration strategies, minimize dependence on fossil fuels, and improve the economic viability of aquaculture operations (Arepalli & Naik, 2024a, 2024b, 2024c; Nass *et al.*, 2020; Singh *et al.*, 2024). By addressing technological and operational challenges, this research advances cost-effective and environmentally responsible aeration solutions.

Although several studies have explored various aeration systems and energy-saving strategies, many fail to offer a comparative framework that integrates technological advances, energy performance metrics, and real-world applications. Furthermore, existing reviews often lack a critical assessment of contextual variables such as salinity, air quality, and environmental compatibility. This suggests a research gap in developing a comprehensive understanding of energy-efficient aeration that aligns with environmental and economic sustainability goals in aquaculture operations. Therefore, this review aims to evaluate current aeration technologies based on their energy efficiency, identify key influencing factors, and propose an integrated framework that combines digital control systems and renewable energy sources for sustainable aquaculture practices.

METHODOLOGY

This study uses a systematic literature review method to collect, compile, and analyze various studies that discuss energy efficiency in aeration systems in fish farming ponds. The literature search was conducted from 2015 to 2025. The keywords used include a combination of terms such as "energy efficiency", "aeration system", "aquaculture pond", "oxygen transfer", "automation", and "renewable energy". The inclusion criteria applied include empirical research articles and observational articles that discuss aeration technology, aeration performance evaluation, and innovations related to energy savings in the context of freshwater and brackish water fish farming. The articles focus only on quantitative data regarding energy consumption or oxygenation efficiency. The initial selection process involves reviewing titles and abstracts, followed by a full reading of articles that meet the initial criteria. The analysis was carried out by identifying the aeration technology used, energy efficiency measurement methods, and technological innovations such as automation and renewable energy integration. This study aims to describe a comprehensive picture of the current conditions and challenges in implementing energy-efficient aeration systems in aquaculture ponds, while also presenting recommendations for developing more sustainable and efficient technology strategies.

BASIC CONCEPT OF AERATION IN AQUACULTURE

Aeration is a fundamental process in aquaculture that ensures adequate dissolved oxygen levels to support aquatic life. The development of oxygenation aeration helps maintain water quality by reducing the accumulation of toxic gases such as ammonia (NH_3) and carbon dioxide (CO_2), which can adversely affect fish health and growth (Eze & Ajmal, 2020; Roy *et al.*, 2020, 2022). Additionally, aeration prevents thermal stratification, ensures uniform temperature distribution, and a stable aquatic environment conducive to fish development (Silalahi *et al.*, 2022; Wongkiew, 2018).

Dissolved oxygen is very important in aquaculture, as it affects the metabolism, immunity and overall well-being of fish. Oxygen availability directly affects feed conversion efficiency, with low DO levels leading to increased stress, reduced growth rates, and higher mortality risks (Arepalli & Naik, 2024a, 2024b, 2024c; Espinal & Matulić, 2019). Moreover, adequate DO levels support beneficial microbial activity, facilitate organic matter decomposition, and maintain water quality (Ion *et al.*, 2022). Therefore, precise oxygen monitoring and aeration management are essential for sustainable aquaculture operations.

Several factors determine aeration requirements, including fish stocking density, water temperature, and organic load. Higher stocking densities require greater oxygenation, while elevated temperatures reduce DO solubility, demanding more intensive aeration to maintain optimal conditions (Blanco-Zuñiga *et al.*, 2022; Chatziantoniou *et al.*, 2022). Additionally, uneaten feed and metabolic waste contribute to oxygen depletion, reinforcing the need for efficient aeration systems. Modern aquaculture increasingly relies on advanced aeration technologies, such as automated diffused aerators and hybrid renewable energy-powered systems, to optimize efficiency and sustainability (Feng *et al.*, 2024; Ramesh *et al.*, 2024). Understanding these factors is essential for selecting appropriate aeration strategies that enhance energy efficiency and aquaculture productivity.

By integrating energy-efficient technologies, automation, and sustainable management practices, the aquaculture industry can address the challenges associated with aeration. Future research should prioritize improving the accessibility and affordability of these innovations to facilitate their widespread adoption across various aquaculture environments. This study provides a critical foundation for advancing aeration practices, contributing to the industry's long-term sustainability.

AERATION TECHNOLOGY IN AQUACULTURE

Various aeration systems have been developed to enhance oxygenation efficiency, each with unique working mechanisms, advantages, and limitations. The selection of an appropriate aerator depends on several factors, including pond size, stocking density, operational costs, and energy efficiency (Bahri *et al.*, 2018, 2019; Blanco-Zuñiga *et al.*, 2022; Palya & MacPhee, 2023; Peterson & Walker, 2002).

Paddle wheel aerators are widely used, particularly in large-scale, intensive aquaculture ponds (Ariadi *et al.*, 2023; Arini *et al.*, 2023; Roy & Kumar, 2024; Wafi & Ariadi, 2022). Their mechanism involves rotating paddles that agitate the water surface, enhancing oxygen diffusion and circulation. This technology is effective in shallow water, ensuring uniform oxygen distribution. However, a significant drawback is its high energy consumption, which reduces cost-efficiency (Bahri *et al.*, 2018, 2019). Additionally, paddle wheel aerators have limited efficiency in oxygenating deeper water layers, which can lead to stratification and oxygen depletion in lower pond sections, negatively affecting fish health and growth (Bahri *et al.*, 2018, 2019; Blanco-Zuñiga *et al.*, 2022).

Diffuser aerators generate small bubbles from porous membranes or pipes placed at the pond bottom, increasing the surface area for oxygen transfer and enhancing dissolution efficiency. This system is commonly used in recirculating aquaculture systems (RAS) and deep ponds, where maintaining uniform oxygen distribution is crucial (Lee *et al.*, 2022). Unlike paddle wheel aerators, diffusers do not create strong currents, making them suitable for species that prefer stable environments. However, diffuser aerators require high initial investment and continuous maintenance due to biofouling and sediment clogging, which can compromise long-term efficiency (Prasetyo *et al.*, 2023; Putro & Wardani, 2024).

Venturi aerators use the Venturi effect, where high-speed water flow passes through a constricted pipe section, creating a pressure difference that draws in atmospheric air and mixes it with water (Li *et al.*, 2023). This passive aeration mechanism eliminates the need for additional air compressors, making it an energy-efficient alternative. Venturi aerators are commonly implemented in hatcheries and high-flow aquaculture systems, where continuous water movement is necessary (Cheng *et al.*, 2015; Li *et al.*, 2023). However, their effectiveness depends on maintaining sufficient water pressure, making them unsuitable for low-flow or static pond systems (Dange & Warkhedkar, 2023).

Beyond conventional systems, emerging aeration technologies such as jet aerators and aspirator aerators offer alternative solutions. Jet aerators enhance oxygen absorption by injecting water at high velocity onto the surface, though they may not be ideal for energy-sensitive operations. Aspirator aerators use impellers or fans to create a pressure differential that draws air into the water, allowing for efficient oxygenation. This system benefits large-scale aquaculture operations but may suffer from mechanical wear over time, necessitating frequent maintenance (Cheng *et al.*, 2015).

Many aquaculture facilities adopt hybrid aeration strategies that combine multiple technologies to optimize aeration efficiency while minimizing energy consumption. For example, integrating diffuser aerators for deep oxygenation with paddle wheel aerators for surface circulation can improve DO distribution while reducing overall energy demand. Additionally, innovative control systems that regulate aerator usage based on real-time DO monitoring have been shown to enhance energy efficiency by ensuring aerators operate only when necessary, reducing unnecessary power consumption (Dange & Warkhedkar, 2023; Prasetyo *et al.*, 2023).

Several aquaculture farms have successfully implemented energy-efficient aeration systems to reduce costs and enhance sustainability. For example, integrated aeration systems combining paddle wheel aerators with diffuser aerators in tilapia farms in Southeast Asia have reduced energy costs by up to 25%, while improving fish survival rates (Lee *et al.*, 2023). Similarly, shrimp farms in Latin America using automated sensor-based aeration control have reported significant energy savings and improved water quality. These examples highlight the potential of combining technology and automation to achieve sustainable aquaculture practices.

Considering the growing emphasis on sustainability and cost reduction, further research is needed to develop low-energy, high-efficiency aeration systems. Future advances should focus on integrating renewable energy sources, such as solar-powered aerators, to further reduce reliance on fossil fuels while maintaining optimal oxygen levels (Huan *et al.*, 2020). The aquaculture industry can enhance productivity by balancing oxygen transfer performance with economic feasibility while minimizing environmental impact (Dange & Warkhedkar, 2023; Nass *et al.*, 2020).

ENERGY CONSUMPTION IN AERATION SYSTEMS

Aeration is one of the most energy-intensive processes in aquaculture, particularly in intensive farming systems where high fish stocking densities require continuous oxygenation (Boyd & McNevin, 2021). The energy consumption of aeration systems depends on several interrelated factors, including the type of aerator, operational capacity, pond depth, stocking density, and oxygen transfer efficiency (Jamroen, 2022; Jamroen *et al.*, 2023a; Jamroen *et al.*, 2023b; Tian *et al.*, 2024). Additionally, environmental factors such as water temperature, salinity, turbidity, and organic matter accumulation significantly influence oxygen solubility and microbial oxygen demand, ultimately affecting the energy required for aeration (Blanco-Zuñiga *et al.*, 2022). Higher water temperatures reduce oxygen solubility, necessitating increased aeration to maintain adequate DO (Arepalli & Naik, 2024a, 2024b, 2024c; Baldwin *et al.*, 2022). Likewise, the accumulation of organic waste from feed residues and fish excretion increases microbial oxygen consumption, elevating aeration energy requirements (Li *et al.*, 2023).

Beyond environmental influences, aerator design, placement, and maintenance are crucial in determining energy efficiency. Poorly maintained aerators—whether due to mechanical wear, biofouling, or clogging—consume excessive energy without delivering optimal oxygenation (Dange & Warkhedkar, 2023). Additionally, improper aerator placement may result in uneven oxygen distribution, leading to localized oxygen deficits and inefficient energy use (Palya & MacPhee, 2023). Implementing best management practices, such as routine maintenance and improved aerator placement, can enhance aeration efficiency and support energy conservation (Phu & Nguyen, 2022).

Two key performance indicators are commonly used to assess aeration efficiency: Standard Oxygen Transfer Rate (SOTR), which measures the amount of oxygen transferred into water per unit of time, and Standard Aeration Efficiency (SAE), which evaluates the amount of oxygen transferred per unit of energy consumed (Mulyadi & Yunus, 2019; Mulyadi *et al.*, 2022). Aerators with higher SAE values maximize oxygen diffusion while minimizing power consumption (Ramesh *et al.*, 2024). However, energy efficiency is not solely determined by SAE but also by how effectively oxygen is distributed throughout the pond. An aeration system that ensures uniform oxygenation across all pond depths is more energy-efficient than one that concentrates DO in specific areas, leading to inefficient energy use (Arepalli & Naik, 2024a, 2024b, 2024c; Sujatha *et al.*, 2023).

Different aeration technologies exhibit varying levels of energy efficiency, as summarized in Table 1. Paddle wheel aerators, commonly used in shallow ponds, effectively improve water circulation and surface aeration but are highly energy-intensive due to their continuous mechanical operation (Brown & Tucker, 2014; Peterson & Walker, 2002). Their energy consumption ranges from 2 to 4 kW ha^{-1}, making them less suitable for large-scale aquaculture (Bahri *et al.*, 2018, 2019). In addition, paddle wheel aerators are less effective in deeper water, which can lead to oxygen stratification and deterioration of water quality (Taghavi & Lee, 2024). In contrast, diffuser aerators generate fine air bubbles at the pond bottom, achieving higher oxygen transfer efficiency (2.5–4.0 kg O_2 kWh^{-1}) compared to paddle wheel aerators (Suravut *et al.*, 2017). These systems are suited for deeper ponds and recirculating aquaculture systems (RAS), where uniform oxygenation is critical (Arepalli & Naik, 2024a, 2024b, 2024c). However, higher operational costs due to the need for high-pressure air compressors and frequent maintenance can be a constraint (Rizzardi *et al.*, 2023). Venturi aerators, which use differences in water pressure to introduce water, offer a more energy-efficient alternative, with oxygenation efficiencies ranging from 1.8 to 3.0 kg O_2 kWh^{-1} (Jackson & Collins, 1964). They do not require an additional motor, making them more energy efficient (1.5–3 kW ha^{-1}) than paddle wheel systems (Yadav *et al.*, 2022a, 2022b). However, their effectiveness depends on water flow, making them less suitable for low-flow ponds. Renewable energy-powered aerators offer a sustainable alternative by reducing reliance on grid electricity and lowering operational costs (Huan *et al.*, 2020; Phu & Nguyen, 2022). Their oxygenation efficiency (1.5–2.8 kg O_2 kWh^{-1}) is comparable to that of paddle wheel aerators, but their effectiveness is weather-dependent, requiring battery storage for continuous operation (Jamroen, 2022; Jamroen et al., 2023a, 2023b).

Optimizing aeration energy consumption has become a significant research focus, given the increasing energy costs and growing emphasis on sustainable aquaculture (Boyd & McNevin, 2021). Several strategies have been proposed to improve energy efficiency while maintaining optimal oxygenation levels. One approach is the implementation of hybrid aeration systems, which combine diffuser aerators for deep oxygenation with paddle wheel aerators for surface mixing, thereby optimizing energy use and oxygen distribution (Blanco-Zuñiga *et al.*, 2022). Another strategy involves automated aeration control systems, which integrate real-time DO monitoring and sensor-based aeration management to adjust aerator operation, significantly reducing unnecessary power consumption dynamically (Arepalli & Naik, 2024a, 2024b, 2024c; Tolentino *et al.*, 2021). Additionally, integrating renewable energy sources, such as solar-powered aerators and hybrid solar-wind systems, can reduce dependence on conventional electricity and lower long-term operating costs (Schierholz *et al.*, 1977; Sujatha *et al.*, 2023).

Advances in aerator design and improvements in efficiency, such as the use of nanobubble technology, low-power impellers, and intelligent variable frequency drives (VFDs), are expected to enhance energy efficiency further while maintaining high oxygenation performance (Krismadinata *et al.*, 2024). By integrating these innovations, aquaculture operations can achieve lower production costs, improved sustainability, and increased productivity, making energy-efficient aeration systems a key component of modern fish farming.

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increased productivity, making energy-efficient aeration systems a key component of modern fish farming.

Selecting the most efficient aeration system requires careful consideration of pond depth, oxygen demand, operating costs, and energy availability (Arepalli & Naik, 2024a, 2024b, 2024c). Paddle wheel aerators remain a common choice for shallow pondsespite their high energy consumption (Peterson & Walker, 2002). In deep ponds or RAS, diffuser aerators provide greater efficiency, although they require higher initial investments (Dange & Warkhedkar, 2023; Ion *et al.*, 2022). Venturi aerators are a viable alternative for high-flow aquaculture systems, while solar-powered aerators offer a sustainable solution for off-grid fish farms (Jamroen, 2022; Jamroen *et al.*, 2023a; Jamroen *et al.*, 2023b; Jasem & Khudair, 2023).

In practice, multiple aeration technologies are often implemented to achieve an optimal balance between energy efficiency and oxygenation effectiveness (Mulyadi & Yunus, 2019; Mulyadi *et al.*, 2022). Furthermore, sensor-based automation enhances efficiency by ensuring that aerators operate only when necessary, reducing overall energy costs while maintaining stable DO levels (Arepalli & Naik, 2024a, 2024b, 2024c; Hakim *et al.*, 2023). Aquaculture aeration can become more energy-efficient, cost-effective, and environmentally sustainable through these approaches, ensuring the long-term viability of fish farming operations (Olanubi et *al.*, 2024).

Selecting the most efficient aeration system requires careful consideration of pond depth, oxygen demand, operating costs, and energy availability (Arepalli & Naik, 2024a, 2024b, 2024c). Waterwheel aerators remain a common choice for shallow ponds despite their high energy consumption (Peterson & Walker, 2002). In contrast, diffuser aerators are more suitable for deeper ponds or recirculating aquaculture systems (RAS) due to their higher oxygen transfer efficiency; however, they require greater initial investment and maintenance

(Dange & Warkhedkar, 2023; Ion *et al.*, 2022). Venturi aerators offer a low-energy alternative in high-flow systems, while renewable energy-powered aerators, such as those powered by solar energy, provide an energy-efficient solution for off-grid operations (Jasem & Khudair, 2023). In practice, many ponds adopt hybrid configurations that combine multiple aeration types to optimize oxygenation while reducing energy costs (Hakim *et al.*, 2023; Mulyadi *et al.*, 2022).

However, a major limitation in current research is the lack of standardized comparative studies evaluating these aeration technologies under identical operational conditions. Most of the available data compare systems using different pond sizes, stock densities, water depths, or environmental parameters, making it difficult to directly assess relative energy efficiency and oxygen delivery performance. For meaningful comparisons, it is important to evaluate aeration technologies under uniform conditions, such as the same pond volume, fish biomass, and water quality, while measuring energy consumption (kW ha^{-1}) and oxygen transfer efficiency (kg O_2 kWh^{-1}). This will allow for more accurate comparisons and provide practical recommendations tailored to specific aquaculture settings.

In addition, real-time monitoring of dissolved oxygen levels and spatial distribution within ponds is essential to identify oxygen stratification and local inefficiencies. For example, systems with high SAE may still underperform if DO distribution is uneven, necessitating complementary aeration strategies. A standard framework for comparative analysis that combines performance metrics and operational feasibility remains a major research gap. Future research can and should focus on controlled experiments or meta-analyses that systematically assess different technologies under similar pond conditions. Addressing this gap could help fish farmers make more informed decisions about selecting energy-efficient technologies, reduce production costs, and promote environmentally sustainable aquaculture.

Table 1. Comparison of energy efficiency in various aeration systems

Types of aerators	Working principle	Oxygenation efficiency (kg O_2 kWh^{-1})	Advantages	Disadvantages	Energy requirements (kW ha^{-1})
Paddle wheel aerator	Stirring the water surface to increase oxygen diffusion	1.5 – 2.5	Suitable for shallow pools, improve water circulation	High energy consumption on large scale	2 – 4
Diffused aeration system	Generating small air bubbles from the bottom of the pond	2.5 – 4.0	Energy saving, efficient for deep pools	Less effective in shallow pools	1 – 3
Venturi aerator	Utilizing pressure differences to introduce air	1.8 – 3.0	No need for large additional power	Effectiveness decreases in waters with strong currents	1.5 – 3
Renewable energy-powered aerator	Using solar power to drive aeration	1.5 – 2.8	Environmentally friendly, lower operating costs	Depends on weather, requires additional batteries	0.8 – 2.5

FACTORS AFFECTING ENERGY EFFICIENCY IN AERATION

Energy efficiency in aquaculture aeration systems is influenced by various factors, including aerator design and configuration, pond environmental conditions, and aeration operation patterns based on oxygen demand. Optimization of these factors is essential to ensure effective oxygenation with minimal energy consumption, which directly impacts the operational costs and sustainability of aquaculture (Boyd & McNevin, 2021). Therefore, the selection of aeration technology and its implementation strategy must be based on an in-depth analysis of oxygen demand and environmental conditions in the aquaculture system(Baquero-Rodríguez *et al.*, 2022; Drewnowski *et al.*, 2019; Yuan *et al.*, 2018).

One of the main factors affecting energy efficiency in aeration is the design and configuration of the aerator. Aerators with higher oxygen transfer efficiency consume less energy while maintaining optimal dissolved oxygen (DO) levels (Arepalli & Naik, 2024a, 2024b, 2024c). For example, micro-bubble and diffuser aerators are more efficient than paddle wheel aerators because they produce smaller bubbles with a larger surface area, thereby increasing oxygen diffusion into the water (Ariadi *et al.*, 2023; Mulyadi & Yunus, 2019; Phu & Nguyen, 2022; Taukhid *et al.*, 2021; Wafi & Ariadi, 2022). In addition, strategic placement of aerators can improve water circulation and oxygen distribution evenly, thereby reducing the number of aerators required and lowering overall power consumption (Tian *et al.*, 2024). The use of automatic sensor-based aeration systems further improves energy efficiency by adjusting aeration intensity based on DO levels in real-time, preventing unnecessary over-aeration (Hakim *et al.*, 2023).

In addition to technical performance, economic analysis is essential when evaluating aeration systems, particularly regarding the balance between capital expenditure (CAPEX) and operational expenditure (OPEX) (Fetouh *et al.*, 2021; Iglesias *et al.*, 2017). Paddle wheel aerators generally involve lower initial investment costs (CAPEX) but tend to have higher energy consumption, resulting in greater long-term OPEX due to continuous power usage and maintenance needs (Phu & Nguyen, 2022). In contrast, diffusers and micro-bubble aerators require higher upfront costs due to the need for compressors, fine tubing, and installation. However, the systems offer superior oxygen transfer efficiency and lower energy consumption, thereby reducing OPEX over time (Taghavi & Lee, 2024). Venturi aerators offer a cost-effective alternative for flow-through or high-velocity systems, featuring moderate capital expenditure (CAPEX) and efficient oxygen delivery at relatively low energy inputs. Solar-powered aerators significantly reduce OPEX by utilizing renewable energy, though the high CAPEX for solar panels and battery systems can prolong the return on investment (Jamroen *et al.*, 2023a; Jamroen *et al.*, 2023b). The adoption of automatic sensor-based aeration systems also increases CAPEX due to sensor and control unit costs, but these systems offer significant savings in energy and labor costs by reducing over-aeration and optimizing runtime (Krismadinata *et al.*, 2024; Mulyadi *et al.*, 2022). Therefore, choosing the appropriate aeration system requires a holistic cost-benefit analysis that considers both short-term affordability and long-term sustainability, especially in intensive aquaculture operations where energy expenses constitute a significant portion of total operating costs.

Environmental conditions also significantly influence aeration efficiency, as water temperature, salinity, turbidity, and pond depth affect oxygen solubility and aerator performance. Higher water temperatures decrease oxygen solubility, requiring more intensive aeration to maintain optimal DO levels, especially in hot climates (Baldwin *et al.*, 2022). Likewise, higher salinity levels can reduce oxygen solubility, necessitating better aeration strategies in brackish and marine aquaculture systems (Ariadi *et al.*, 2023). The accumulation of organic matter and water turbidity also affects aeration efficiency, as suspended particles and organic waste increase oxygen consumption by microorganisms, forcing the aerator to work harder to replace the lost oxygen (Ramesh *et al.*, 2024). In terms of pond depth, the selection of aerators must match the characteristics of the water. Paddle wheel aerators are more effective in shallow ponds, while diffuser and venturi aerators are more suitable for deeper water systems, as they can distribute oxygen efficiently to the bottom layer of the pond (Ariadi *et al.*, 2023; Wafi & Ariadi, 2022).

The aeration operation pattern based on oxygen demand is also crucial in ensuring energy efficiency. Excessive aeration not only increases energy costs but can also disrupt the balance of the pond ecosystem by creating unnecessary turbulence (Peterson & Walker, 2002). The application of a DO sensor-based aeration system allows the aerator to operate dynamically, turning on and off automatically based on real-time oxygen levels in the water (Tolentino *et al.*, 2021). This system prevents inefficient use of aeration and ensures that oxygen is only supplied when needed (Krismadinata *et al.*, 2024). In addition, the aeration pattern must be adjusted to accommodate the daily biological cycles of fish and phytoplankton. During the day, the photosynthesis process of phytoplankton naturally increases DO levels, reducing the need for artificial aeration. Conversely, at night, when photosynthesis stops and oxygen consumption by fish and microorganisms increases, aeration must be increased to prevent hypoxic conditions that can harm cultured organisms (Ridwan

& Irawan, 2023; Ridwan *et al.*, 2023). Adjusting the aeration schedule to natural oxygen fluctuations can improve energy efficiency without sacrificing water quality (Xu *et al.*, 2023).

Several practical strategies can be implemented to improve aeration efficiency while minimizing energy consumption. Using more energy-efficient aerators, such as diffusers and venturi aerators, allows for higher oxygen transfer rates with lower power consumption (Taghavi & Lee, 2024). Additionally, real-time DO monitoring and automatic aeration control systems enable more precise aeration settings based on actual oxygen demand, thereby preventing unnecessary power consumption (Mulyadi & Yunus, 2019; Mulyadi *et al.*, 2022). Strategic placement of aerators can also maximize water circulation and oxygen distribution, thereby reducing the number of aerators required (Li *et al.*, 2023). The integration of renewable energy sources, such as solar-powered aerators, also plays a crucial role in reducing dependence on conventional electricity and lowering operational costs in the long term (Jamroen *et al.*, 2023a; Jamroen *et al.*, 2023b; Singh *et al.*, 2024). Moreover, adjusting the aeration schedule to the natural oxygen cycle by utilizing phytoplankton photosynthesis during the day can help reduce energy consumption (Singh *et al.*, 2024).

Fish farmers can develop more cost-effective and sustainable aeration strategies by understanding the factors that influence aeration energy efficiency. Optimizing aerator design, monitoring pond environmental conditions, and adjusting aeration patterns based on oxygen demand can significantly reduce energy consumption while maintaining optimal DO levels (Nass *et al.*, 2020). In addition, integrating sensor-based automation, renewable energy sources, and hybrid aeration systems further enhances sustainability and economic viability in aquaculture (Wantura, 2021). Through this approach, aeration systems can become more energy-efficient, environmentally friendly, and sustainable in the long term, thereby supporting profitability and ecological balance in aquaculture operations.

INNOVATION AND OPTIMIZATION STRATEGIES FOR ENERGY EFFICIENCY IN AERATION

Various technological innovations and optimization strategies have been developed to improve energy efficiency in aeration systems for aquaculture. One of the most effective approaches is the use of energy-saving technologies, such as dissolved oxygen (DO) sensors and automated aeration systems. DO sensors allow real-time monitoring of oxygen levels in water, enabling aerators to operate only when DO levels drop below the required threshold for fish and other aquatic organisms (Hakim *et al.*, 2023; Ridwan & Irawan, 2023). By integrating this system, aerators can be automatically turned on and off, preventing unnecessary energy consumption while maintaining optimal oxygenation (Mulyadi *et al.*, 2022). Additionally, artificial intelligence (AI)-based automatic aeration technology has begun to be applied in modern aquaculture, allowing aeration systems to analyze fish oxygen consumption patterns based on environmental factors such as water temperature, fish density, and feeding schedules. This approach enables more efficient and precise aeration regulation, reducing energy waste while ensuring optimal water quality (Cheng *et al.*, 2015; Tamim *et al.*, 2022).

Apart from advances in aeration technology, integrating renewable energy sources is another key strategy to reduce dependence on conventional electricity. One of the most promising methods is using solar power to drive aerators, where solar panels are installed around the pond or on floating rafts to supply energy to the aerators without relying on the electricity grid (Siskandar *et al.*, 2022). This technology is particularly suitable for aquaculture farms in remote areas with limited access to electricity, allowing for more sustainable and cost-effective aeration management (Pratiwy *et al.*, 2021). In addition to solar energy, some aeration systems are beginning to utilize wind power and biogas as alternative energy sources, further reducing operational costs and supporting sustainable aquaculture practices. Renewable energy lowers long-term expenses and contributes to reducing carbon emissions and other environmental impacts, making fish farming operations more environmentally friendly (Putra *et al.*, 2021).

Efficient operational management of aeration is another crucial factor in optimizing energy use. One practical strategy is to implement aeration schedules that are adjusted to the pond's fluctuations in oxygen demand. For example, aeration can be intensified at night when oxygen levels typically decline due to the absence of phytoplankton photosynthesis, while during the day, aeration can be reduced to conserve energy (Arepalli & Naik, 2024a, 2024b, 2024c; Mahmud *et al.*, 2020). Repositioning of aerators within the pond can further enhance aeration efficiency, as placing aerators in locations with strong water circulation helps distribute oxygen more evenly, thereby reducing the need to operate multiple aerators simultaneously (Sudiarto, 2023; Sudiarto *et al.*, 2021).

Another optimization strategy involves combining different aerator types, each serving specific functions to enhance energy efficiency. For example, diffuser aerators, which improve oxygenation in deeper water layers, can be combined with paddle wheel aerators, which improve surface circulation. This hybrid aeration system enables more effective oxygen distribution without significantly increasing power consumption *(Suravut et al., 2017; Wang et al.*, 2020). Furthermore, routine maintenance of aerators is crucial for maintaining energy efficiency. Dirty or worn-out aerators consume more energy without significantly improving DO levels, making regular cleaning and servicing crucial for optimal aerator performance (Khan & Byun, 2023).

With technological advances and strategic optimization, aeration systems in aquaculture can become more energy-efficient and environmentally sustainable. The adoption of smart technologies, renewable energy sources, and improved aeration management techniques can help fish farmers lower operational costs while boosting productivity and sustainability in aquaculture operations (Tamim *et al.*, 2022; Wang *et al.*, 2020). Table 2 illustrates various sensor technologies and automation systems that can be applied to enhance the energy efficiency of aeration systems in aquaculture. With DO sensors, aerator automation, and IoT-based technologies, energy consumption can be significantly reduced without compromising fish health and water quality (Siskandar *et al.*, 2022; Tsai *et al.*, 2022). Additionally, the application of variable frequency drives (VFDs) allows aerator power to be adjusted based on real-time oxygen demand, preventing energy waste and improving overall efficiency (Arepalli & Naik, 2024a, 2024b, 2024c).

However, challenges in implementing advanced aeration optimization systems include high initial investment costs, precise calibration, and supporting infrastructure requirements such as stable internet and electricity (Pratiwy *et al.*, 2021). Appropriate technologies should be selected based on the scale of aquaculture operations, resource availability, and budget constraints, ensuring that a combination of multiple strategies can produce optimal results (Putra *et al.*, 2021). By leveraging automation, renewable energy, and improved aeration management, aquaculture aeration can transition towards a more energy-efficient and sustainable future, benefiting both producers and the environment.

Integrating sensors and automation technologies in aquaculture aeration systems has significantly improved energy efficiency while maintaining water quality. Various types of sensors and automation systems, as outlined in Table 2, help reduce energy waste, optimize aerator performance, and enhance environmental control. Among these technologies, DO sensors play a crucial role in the real-time monitoring of oxygen levels in water. By using DO sensors, aeration can be automatically regulated, ensuring that aerators operate only when DO levels fall below the required threshold, which can reduce energy consumption by 30–40% (Hakim *et al.*, 2023; Ridwan & Irawan, 2023; Ridwan *et al.*, 2023). This system optimizes aerator usage and enhances water quality; however, it requires regular calibration and has a relatively high initial investment cost (Mulyadi *et al.*, 2022).

Complementing DO sensors, aerator automation systems enable aerators to turn on and off automatically based on real-time oxygen levels. This technology can reduce power consumption by 20–35%, ensuring that aerators function only when necessary, thus prolonging aerator lifespan and reducing operational costs (Mahmud *et al.*, 2020). However, its effectiveness depends on sensor reliability and continuous power supply (Pratiwy *et al.*, 2021). Another technological advancement in aeration efficiency is the IoT-based monitoring system, which integrates sensor data with cloud-based applications to allow remote monitoring and automated aeration control (Tsai *et al.*, 2022). This approach enhances data analysis and decision-making while saving up to 40% of energy consumption (Tamim *et al.*, 2022). Despite these benefits, stable internet connectivity and high initial installation costs remain challenges, particularly for aquaculture farms in remote areas (Siskandar *et al.*, 2022).

In addition to these systems, Variable Frequency Drives (VFDs) are widely used to improve aeration energy efficiency. VFDs adjust aerator speed and power according to real-time oxygen demand, reducing power consumption by up to 25% (Arepalli & Naik, 2024a, 2024b, 2024c). This system helps lower electrical load and improve aeration system longevity, making it a preferred choice in modern aquaculture. However, not all aerators are compatible with VFD systems, which limits their application in older aquaculture facilities. Adopting sensor and automation technologies has proven effective in enhancing aeration efficiency and reducing energy costs. However, cost feasibility, infrastructure readiness, and maintenance requirements must be considered when selecting the most suitable technology for each aquaculture setup (Putra *et al.*, 2021).

The increasing cost of electricity and the push for sustainable aquaculture have led to widespread adoption of renewable energy sources in aeration systems. As summarized in

Table 3, various renewable energy solutions offer an opportunity to reduce dependence on conventional electricity, lower operational costs, and enhance environmental sustainability. Among these alternatives, solar-powered aeration is one of the most commonly used systems, especially in tropical and high-sunlight regions (Khojim *et al.*, 2023). A standard solar-powered aerator can achieve energy savings of 30–50%, making this system both cost-effective and environmentally friendly (Mahmud *et al.*, 2020; Siskandar *et al.*, 2022). However, solar aeration depends on sunlight availability, requiring battery storage systems for continuous operation at night (Tamim *et al.*, 2022).

Another renewable energy option is wind-powered aeration, which utilizes wind turbines to generate electricity or directly power aerators (Khojim *et al.*, 2023). This method can result in 20–40% energy savings, making it an attractive solution for aquaculture farms in windy regions (Suravut *et al.*, 2017). Wind aeration, however, is highly dependent on wind speed, which can be unstable in some areas, making it less reliable compared to solar aeration (Wang *et al.*, 2020). Furthermore, the high initial investment costs of wind turbines pose a challengeor small and medium-scale fish farms (Arepalli & Naik, 2024a, 2024b).

A more advanced and reliable approach is the solar-wind hybrid aeration system, which combines solar panels and wind turbines to provide a more stable and continuous energy supply (Khojim *et al.*, 2023). This system increases aeration energy efficiency by 40–60%, overcoming the limitations of individual solar or wind systems (Khan & Byun, 2023). However, hybrid aeration systems require a higher upfront investment and more complex maintenance, which may not be feasible for all aquaculture farms(Putra *et al.*, 2021).

To support the use of renewable energy in aeration, battery storage systems are commonly used to store excess energy from solar and wind sources for later use. This system allows 24-hour aeration operation without reliance on conventional electricity, improving system reliability and sustainability. However, batteries remain expensive and have a limited service life, which increases long-term operational costs (Pratiwy *et al.*, 2021).

Another alternative is bioenergy-based aeration, where organic waste is converted into biogas to power aerators. This system reduces organic waste while generating renewable energy, making it an attractive solution for integrated aquaculture operations (Cheng *et al.*, 2015; Kuang *et al.*, 2020; Sudiarto *et al.*, 2021; Zou *et al.*, 2024). However, the efficiency of biogas aeration depends on the consistency of organic waste supply and the stability of the fermentation process, which can be challenging to maintain (Putra *et al.*, 2021).

Adopting renewable energy-based aeration systems offers a sustainable solution for aquaculture farms looking to reduce operational costs and minimize environmental impact. However, geographical suitability, economic feasibility, and technical requirements must be carefully evaluated before implementation (Nass *et al.*, 2020; Tamim *et al.*, 2022).

To achieve maximum energy efficiency in aquaculture aeration, fish farmers should integrate multiple strategies, including sensor-based automation, renewable energy, and operational management improvements. The use of DO sensors, aerator automation systems, and IoT-based monitoring has been proven to reduce aeration energy consumption by 20–40% while maintaining optimal water quality (Tamim *et al.*, 2022; Wang *et al.*, 2020). Additionally, solar, wind, and bioenergy solutions provide an alternative to grid electricity, reducing reliance on fossil fuels and lowering long-term operational costs (Pratiwy *et al.*, 2021).

Integrating battery storage systems further enhances the reliability of renewable energy generation, although high costs and limited lifespan remain challenges for broader adoption. Meanwhile, hybrid aeration technologies, such as diffuser aerators with paddle wheel aerators, ensure better oxygen distribution while maintaining efficient energy use (Suravut *et al.*, 2017; Yatin & Jaisin, 2022). Furthermore, the regular maintenance of aerators is essential, as dirty or inefficient aerators tend to consume more energy without providing sufficient oxygenation (Khan & Byun, 2023).

Aquaculture farms can achieve sustainable, cost-effective, and energy-efficient aeration systems through smart automation, renewable energy integration, and optimized aeration management. As technology advances, future innovations are expected to further enhance aquaculture productivity while reducing environmental impact, thereby ensuring long-term sustainability in fish farming (Tamim *et al.*, 2022; Wang *et al.*, 2020).

Table 2. Use of sensors and automation in energy efficiency of aeration

Sensor or automation type	**Functions**	**Energy efficiency**	**Advantages**	**Disadvantages**
Dissolved oxygen sensor (DO sensor)	Measure dissolved oxygen levels in water in real-time	Reduce energy consumption by 30–40%	Prevents excessive aeration, improves environmental control	Requires regular calibration and fairly high initial cost
Aerator automation system	Activate and deactivate aerators based on oxygen levels	Reduce power consumption by 20–35%	Optimizes aerator usage, extends aerator life	Depends on sensor reliability and electrical power
IoT-Based monitoring system	Integrate sensor data with cloud-based applications	Save energy by up to 40% with efficient monitoring	Allows remote control, better data analysis	Requires stable internet connection and initial installation costs
Variable frequency drive (VFD)	Adjust aerator speed and power as needed	Reduce power consumption by up to 25%	Reduces electrical load, improves aeration efficiency	Not all aerators are compatible with this system

Table 3. Comparison of renewable energy based aeration systems

Types of renewable energy	**Application methods in aeration**	**Energy efficiency**	**Advantages**	**Disadvantages**
Solar-powered aeration	Solar panels generate electricity to operate the aerator	Energy savings up to 30–50%	Environmentally friendly, low operating costs, suitable for tropical areas	Depends on sunlight, requires batteries for night operation
Wind-powered aeration	Wind turbines drive the aerator directly or generate electricity	Energy savings up to 20–40%	No fuel required, can be used in windy areas	Unstable in areas with low wind speeds, high initial investment
Solar-wind hybrid	Combination of solar panels and wind turbines for aerator power sources	Energy savings up to 40–60%	Overcome the limitations of each energy source, increase reliability	Higher initial cost, requires more complex maintenance
Bioenergy-based aeration	Utilization of organic waste to produce biogas, which is used as a source of aeration energy	Efficiency depends on biogas production	Reduce organic waste, produce its own renewable energy	Biogas production process requires a stable fermentation system

IMPLEMENTATION OF ENERGY-EFFICIENT AERATION IN AQUACULTURE: BENEFITS, CHALLENGES, AND POLICY SUPPORT

Implementing energy-efficient aeration systems plays a crucial role in enhancing the productivity and sustainability of aquaculture. By improving energy efficiency, fish farmers can significantly reduce operational costs, particularly electricity consumption, which is one of the most significant cost components in aeration (Hakim *et al.*, 2023; Ridwan & Irawan, 2023; Ridwan *et al.*, 2023). The use of advanced aeration technology not only reduces energy expenses but also enhances water quality, creating a more optimal environment for fish growth. Sufficient levels of dissolved oxygen (DO) contribute to better fish metabolism, faster growth, and lower stress levels, thereby reducing mortality rates caused by poor water quality (Mahmud *et al.*, 2020; Pratiwy *et al.*, 2021; Stehfest *et al.*, 2017). Furthermore, adopting energy-efficient aeration aligns with global sustainability goals by lowering carbon footprints and mitigating environmental impacts caused by excessive energy consumption. Integrating renewable energy sources, such as solar power and biogas, into aeration systems helps reduce reliance on fossil fuels, supporting eco-friendly aquaculture practices (Putra *et al.*, 2021; Siskandar *et al.*, 2022).

Despite its substantial benefits, implementing energy-efficient aeration technologies faces several challenges, particularly in small- and medium-scale aquaculture operations. One of the primary barriers is the high initial investment cost associated with advanced aeration technologies, such as automatic aeration systems equipped with DO sensors and solar-powered aerators (Arepalli & Naik, 2024a; Kuang *et al.*, 2020). Although these investments lead to long-term cost savings, many fish farmers struggle to afford the upfront costs, especially in developing regions. Additionally, infrastructure limitations pose further difficulties, particularly in remote rural areas where stable electricity and internet access are essential for IoT-based aeration systems (Tamim *et al.*, 2022). The lack of technical expertise in operating and maintaining these systems also hinders widespread adoption, as farmers require appropriate training to effectively utilize sensor-based aeration and automation systems (Mulyadi *et al.*, 2022).

Another major challenge is the limited awareness and socialization of energy-efficient aeration technologies among fish farmers. Many farmers continue to use conventional aeration methods without considering energy efficiency aspects, primarily due to insufficient knowledge about modern aeration technologies and their long-term benefits (Sudiarto *et al.*, 2021; Wang *et al.*, 2020). Additionally, not all aeration technologies are suitable for every type of aquaculture system, requiring further research on how to adapt these innovations to different production scales and environmental conditions (Khan & Byun, 2023; Suravut *et al.*, 2017).

Government policies and industry regulations play a vital role in facilitating the adoption of energy-efficient aeration. Several countries have introduced incentives and subsidies to encourage fish farmers to invest in energy-efficient aeration technologies (Siskandar *et al.*, 2022; Tamim *et al.*, 2022). Tax reductions, financial grants, and technology assistance programs have been implemented to lower the cost barrier for adopting renewable energy-powered aerators. Additionally, developing technical standards and best practices for energy use in aquaculture can help fish farmers select and implement the most suitable aeration systems for their specific needs (Putra *et al.*, 2021). Collaboration between government agencies, research institutions, and the private sector can further accelerate technology transfer by providing training programs, technical support, and access to financing solutions (Arepalli & Naik, 2024a, 2024b).

Overall, adopting energy-efficient aeration presents an excellent opportunity to improve aquaculture production efficiency and environmental sustainability. However, challenges related to high investment costs, limited access to technology, and inadequate regulatory frameworks remain obstacles that must be addressed. With continued technological innovation, policy support, and collaborative efforts from various stakeholders, the aquaculture industry can transition toward a more efficient, sustainable, and eco-friendly system (Tamim *et al.*, 2022; Wang *et al.*, 2020).

Figure 1. Framework for implementing energy-efficient aeration in sustainable aquaculture

Figure 1 illustrates a structured framework for energy-efficient aeration management in aquaculture. It begins with aquaculture aeration planning, where farmers assess the general needs of their systems. The next step involves evaluating current energy use and water quality requirements, with a particular focus on DO levels. Based on this assessment, farmers can select appropriate aeration technologies, such as high-efficiency pumps, DO sensor-based control systems, and renewable energy-powered aerators. Where possible, these technologies are integrated with IoT and automation to enhance operational efficiency through real-time monitoring and control. Following integration, system optimization and continuous monitoring of DO and energy consumption are essential to maintain performance and sustainability. To ensure successful implementation, capacity-building and farmer-training programs are provided to equip users with the necessary technical skills. Finally, direct and indirect government endowments, such as subsidies, tax breaks, and technical assistance, play a critical role in facilitating adoption, especially among small and medium-scale farmers. Together, these measures contribute to more sustainable, cost-effective, and low-emission aquaculture practices.

CONCLUSIONS

Energy efficiency in pond aeration systems is a critical component for increasing aquaculture productivity and ensuring long-term sustainability. Adequate dissolved oxygen (DO) levels are critical for fish health, growth, feed conversion efficiency, and overall water quality, and are dependent on several interacting factors, including fish density, water temperature, turbidity, and system configuration. Therefore, the selection and optimization of aeration systems should aim to provide adequate oxygenation while minimizing energy input and operating costs.

This review identifies the main aeration technologies and evaluates their performance under various pond conditions. Diffuser aerators exhibit the highest oxygen transfer efficiency (OTE), especially in deeper ponds, where vertical oxygen distribution is critical. On the other hand, paddle wheel aerators are more suitable for shallow ponds and high-density cultures due to their strong horizontal mixing capabilities. Venturi aerators offer moderate efficiency with simpler maintenance and can serve as a viable alternative where technical support is limited. Furthermore, the integration of renewable energy sources, such as solar or biogas-powered aerators, can significantly reduce fossil fuel dependence and operational emissions; however, their adoption is often limited by initial capital investment and technical infrastructure requirements. For practical applications, farmers should select an aeration system based on pond depth, culture species, and management intensity. Diffuser systems are ideal for intensive systems with deeper ponds, while paddle wheels remain the standard for shallow, high-biomass systems. Furthermore, the implementation of smart aeration systems equipped with IoT-based DO sensors and automated control mechanisms can enable real-time aeration adjustments, ensuring optimal oxygen levels while reducing unnecessary energy use. However, several challenges remain in mainstreaming these technologies, including limited awareness among smallholder farmers, high initial costs, and a lack of supportive policy frameworks. These barriers can be addressed through targeted capacity-building programs, government subsidies or incentives, and increased collaboration between research institutions, technology developers, and the aquaculture industry.

Future directions should include the development of intelligent aeration models that combine artificial intelligence (AI) and machine learning (ML) to dynamically optimize aerator operation based on real-time environmental and biological data. Additionally, economic feasibility studies and life cycle analyses are necessary to compare aeration technologies across various production systems and climate conditions. Comparative case studies from various aquaculture environments will provide valuable insights into context-specific performance and inform decision-making.

Ultimately, improving energy efficiency in pond aeration is a technical and strategic priority for modern aquaculture. With the right technology integration, policy support, and farmer-centric innovation, aeration systems can evolve to become more sustainable, cost-effective, and environmentally responsible, laying the foundation for a resilient aquaculture sector.

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IMAN: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, visualization, writing, writing – review, and editing; IGMND: data curation, formal analysis, funding acquisition, investigation, project administration, resources, software, supervision, validation, writing, writing – review, and editing.

DECLARATION OF COMPETING INTEREST AND USE GENERATIVE AI

The authors declare no competing interests.

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