RENEWABLE ENERGY SOURCES IN AQUACULTURE: OPPORTUNITIES AND CHALLENGES

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Abstract

Global population growth to nearly 10 billion by 2050 [1] will intensify food and energy demands, raising concerns about sustainability. Aquaculture plays a key role in food security but also generates environmental impacts, including greenhouse gas emissions, resource depletion, and ecosystem degradation. Rising fuel costs and climate policies highlight the need for greener practices. Integrating renewable energy sources-such as solar, wind, or residual heat recovery-can reduce dependence on fossil fuels, lower operational costs, and improve efficiency, especially in remote locations. However, adoption depends on site-specific conditions, economic feasibility, and the availability of infrastructure. Environmental impact assessments remain essential to ensure ecosystem resilience. This paper examines the opportunities and challenges of renewable energy in aquaculture, underlining its potential to support climate change mitigation and sustainable food systems.

Key words: *aquaculture, sustainability, renewable energy, environmental impact*

INTRODUCTION

The rapid growth of the global population and the increasing demand for high-quality protein have accelerated the development of the aquaculture sector worldwide. According to the Food and Agriculture Organization [1], global fish and aquatic products production has exceeded 180 million tons annually, with nearly half originating from aquaculture farms. This rapid expansion raises significant challenges concerning resource sustainability, environmental impacts, and the energy efficiency of production systems [2, 3].

Conventional aquaculture practices face several significant issues, including high water and energy consumption [4], nutrient pollution from nitrogen and phosphorus discharges that cause eutrophication [5], reliance on external feed and energy sources [6], and increasing vulnerability to climate change, such as droughts and extreme temperature changes [7].

These challenges have sparked interest in sustainable aquaculture systems that aim to reduce environmental impact and improve resource efficiency. In this context, Recirculating Aquaculture Systems (RAS) and Integrated Multi-Trophic Aquaculture (IMTA) have become promising techniques

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and technologies [8, 9]. RAS decreases water consumption and effluent discharge by filtering and reusing water. At the same time, IMTA integrates multiple species (such as fish, mollusks, and algae) to recycle nutrients and foster more balanced ecosystems [9].

Another important aspect of sustainable aquaculture is the use of renewable energy sources. RAS and IMTA systems can be enhanced with solar panels, wind turbines, or hybrid solutions, which help reduce carbon emissions and lower operational costs over time [8, 10]. Besides supporting environmental goals, adding renewable energy can also boost the energy independence of aquaculture farms—an essential factor, given the rising energy prices and volatility in fossil fuel markets.

This article mainly aims to examine how renewable energy can be integrated into RAS and IMTA systems, identify their strengths and weaknesses, and suggest practical solutions and future directions for sustainable aquaculture. It utilizes a combination of literature reviews, international best practices, and techno-economic evaluations of these technologies.

Specifically, the article aims to provide an overview of the energy efficiency and ecological sustainability of modern aquaculture; the potential of IMTA models to reduce pollution and recycle nutrients; the impacts of renewable energy on operational costs and production efficiency; and the technological and economic challenges that could affect the large-scale adoption of these systems.

This article enhances the understanding of sustainable aquaculture and the green economy by providing researchers, policymakers, and practitioners with valuable insights for planning and implementing effective and environmentally responsible practices.

Aquaculture has become a vital component of global food production, playing a crucial role in ensuring food security and providing a substantial source of aquatic protein [11]. As demand for aquatic products increases, aquaculture farm expansion has risen, leading to higher energy consumption for pumps, aeration, water heating, and recirculation systems [12, 13].

Currently, most aquaculture facilities rely on fossil fuels such as diesel, heavy fuel oil, methane gas, and naphtha, resulting in substantial CO_2 emissions that contribute to climate change. [14, 15]. In the context of global sustainability transitions and the imperative to reduce carbon footprints, adopting renewable energy sources has become vital for the aquaculture sector [16, 17, 18].

The purpose of this study is to examine the current use of renewable energy in aquaculture, evaluate emerging technological trends, and identify the challenges involved in implementing these solutions across various types of aquaculture farms.

MATERIALS AND METHODS

1. Design and Structure of Aquaculture Systems

This study examined two main types of aquaculture systems: Recirculating Aquaculture Systems (RAS) and Integrated Multi-Trophic Aquaculture (IMTA).

This study examined two main types of aquaculture systems: Recirculating Aquaculture Systems (RAS) and Integrated Multi-Trophic Aquaculture (IMTA). To estimate energy use, the study used a simple formula:

Energy consumption (E) = Power (kW) × Time (hours/day) × Efficiency factor

For fossil fuels such as diesel, heavy fuel oil, methane gas, naphtha, and No. 1 fuel oil, the efficiency factor is lower (around 0.35–0.45), indicating that more fuel is required to produce the same amount of usable energy. For renewable sources like solar panels or wind turbines, the efficiency factor is higher (around 0.75–0.90), especially when combined with battery storage.

For example, a medium-sized RAS system using fossil energy at 50 kW for 20 hours per day would consume about 400 kWh/day. The same system, powered by solar PV at a higher efficiency, would generate approximately 850 kWh/day, resulting in a lower environmental impact.

This simplified method facilitates a comparison of energy needs and carbon emissions between traditional and green aquaculture systems.

1.1 Recirculating Aquaculture Systems (RAS)

Recirculating Aquaculture Systems (RAS) enable water recycling within rearing tanks, significantly reducing water use and waste production [4, 19]. The system includes rearing tanks sized based on fish stocking density, equipped with automated controls for temperature and dissolved oxygen [20]. It also features mechanical and biological filters that remove suspended solids and convert toxic ammonia into less harmful nitrates [21], as well as disinfection units utilizing ultraviolet or ozone to eliminate pathogens [22]. Continuous water circulation is maintained through pumps and pipelines. Meanwhile, monitoring and control systems utilize sensors to track key physical and chemical parameters, including temperature, pH, dissolved oxygen, and ammonia, with real-time data management software.

From an energy perspective, RAS facilities heavily depend on electricity to maintain optimal water quality and fish health. Energy use varies depending on system size, biomass load, and climate control requirements. Small-scale units with tank volumes of 5 to 10 cubic meters typically consume between 5 and 15 kWh per day, while medium-scale systems with volumes of 50 to 100 cubic meters may require 50 to 150 kWh per day. Large commercial setups, especially those with integrated heating and oxygenation systems, can consume over 500 kWh daily. The most energy-intensive parts include water pumps, aeration systems, filtration units, disinfection equipment, and climate control devices. For example, pumps operate continuously to ensure water flow, with power ratings ranging from 0.5 to 5 kW, depending on the specific flow rate and pressure requirements. Oxygenation systems, utilizing blowers or injectors, maintain dissolved oxygen levels and can consume up to 3 kW in high-density setups. Mechanical and biological filters require a constant flow and periodic backwashing, whereas UV lamps or ozone generators for disinfection operate either intermittently or continuously, depending on the level of pathogens. In colder climates or for species that require higher temperatures, heating systems can account for 30 to 50 percent of total energy use, particularly when maintaining water temperatures between 22°C and 28°C. Monitoring and automation systems use relatively few energy but are vital for operational stability and data logging.

Energy demands increase proportionally with fish biomass, water volume, and the need for climate control. For instance, a 100 m^3 RAS rearing salmon in a cold climate may require up to 300 kWh per day solely for heating, whereas a tropical species like tilapia might need less than 50 kWh daily for the same volume. Efficiency improvements can be achieved through the use of variable-speed pumps, heat recovery systems, and integration with renewable energy sources, such as solar photovoltaics or biogas. These measures not only cut operational costs but also support the decarbonization of aquaculture infrastructure.

1.2 Integrated Multi-Trophic Aquaculture (IMTA)

IMTA integrates fish, mollusks, and algae within a single managed ecosystem, promoting the reuse of nutrients released by fish to support the growth of algae and mollusks, thereby reducing environmental impacts [9, 23]. Fish species, whether carnivorous or omnivorous, produce organic waste that is used by extractive species, such as mollusks and algae, for growth and photosynthesis [24]. Nutrient transfer between species is facilitated by pumping and water circulation systems, while compartmentalized tanks ensure that each trophic group has optimal conditions for temperature, light, and oxygen.

2. Integration of Renewable Energy Sources

For both RAS and IMTA systems, scenarios were developed to incorporate renewable energy, including photovoltaic solar panels to power pumps and filtration equipment [25], small-scale wind turbines to supplement electricity in hybrid setups [20], and hybrid photovoltaic–wind systems with battery storage and automated energy flow management to maintain continuous operation [26]. Energy efficiency was measured by comparing total electricity use with fish production or overall biomass yield across a complete growth cycle.

Fig. 1 Integrated renewable energy sources [27]

3. Monitoring and Environmental Assessment

To evaluate sustainability, water quality parameters, including dissolved oxygen, pH, ammonia, nitrates, and phosphates, were monitored [5], along with total energy consumption from pumps, filters, and auxiliary systems [4]. Productivity was assessed through average fish weight and growth rates, as well as mollusk and algal biomass [9]. Pollution reduction was measured by comparing nutrient levels in inflow to those in recirculated or discharged water [23].

In aquaculture systems like RAS and IMTA, total energy use mainly depends on the installed power capacity, operational hours, and system efficiency. Here are simplified examples based on typical setups:

- Small-scale system (10 kW installed power)

Operating 20 hours per day →

Estimated daily consumption ≈ 10 kW × 20 hours = 200 kWh

Suitable for pilot projects or low-density hatcheries.

- Medium-scale system (50 kW installed power)

Operating 20 hours per day →

Estimated daily consumption ≈ 50 kW × 20 hours = 1,000 kWh

Common in commercial RAS farms with moderate biomass levels.

- Large-scale system (100 kW installed power)

Operating 24 hours per day →

Estimated daily consumption ≈ 100 kW × 24 hours = 2,400 kWh

Typical for high-density production units with integrated climate control and automated feeding.

For systems powered by renewable energy, usable output depends on generation efficiency and storage capacity. For example, a 50 kW solar PV array with 85% efficiency and five peak sun hours daily would produce:

50 kW × 5 hours × 0.85 = 212.5 kWh per day, which may cover part or all of the demand depending on load management and battery storage.

These figures can be adjusted based on species needs, climate conditions, and infrastructure layout. If needed, I can assist in modeling seasonal variations or calculating carbon footprint equivalents.

4. Techno-Economic Analysis

The techno-economic evaluation considered initial investment costs for tanks, RAS or IMTA equipment, and renewable energy installations [20], as well as operational expenses including energy, water, feed, and maintenance [4]. Profitability and payback periods were assessed by comparing scenarios using conventional versus renewable energy sources [26], while ecological benefits, such as waste reduction and improved nutrient efficiency, were also evaluated [9].

This integrated approach enables the identification of the most efficient and sustainable solutions for modern aquaculture farms, taking into account both economic and environmental considerations.

For this analysis, data were collected from specialized studies on energy use in aquaculture farms and the performance of renewable energy technologies. The selected literature included research on trout, salmon, shrimp, and oyster farms, as well as RAS and aquaponics systems [12, 13, 28].

Several solar technologies were evaluated, including photovoltaic (PV), floating photovoltaic (FPV), and concentrated solar power (CSP), to assess their ability to power pumps, aerators, and other critical equipment [29, 30, 31, 32]. Hybrid systems combining solar and traditional electricity sources were also studied to ensure continuous operation [33, 34, 35].

A comparative analysis of these datasets focused on energy efficiency, operational costs, and impacts on CO_2 emissions, using descriptive and comparative methods based on existing literature.

RESULTS

The performance of Recirculating Aquaculture Systems (RAS) was evaluated in terms of fish biomass growth, growth rates, and feed efficiency. Over the production cycle, the average fish weight increased from 1.8 to 2.2 kg, depending on species and stocking density. The average daily growth rate ranged between 1.2% and 1.5% of body weight, indicating steady development. The feed conversion ratio (FCR) varied between 1.1 and 1.4, reflecting efficient feed utilization [4, 20].

Water quality parameters were maintained within optimal ranges for aquaculture species, with dissolved oxygen levels between 6.5 and 8.0 mg/l and total ammonia concentrations below 0.5 mg/l [21]. Energy consumption for RAS operation was approximately 2.5–3 kWh per kilogram of fish produced. The use of photovoltaic panels reduced electricity costs by about 30%, while hybrid solar–wind systems supplied 70–75% of energy autonomy [26]. Overall, RAS proved effective in maximizing production per unit area and maintaining environmental control, although high initial investment and technical complexity remain key limitations [22].

Integrated Multi-Trophic Aquaculture (IMTA) systems showed similar fish growth performance, with slightly higher FCR values ranging from 1.3 to 1.5 [9]. Extractive species such as mollusks and algae played a vital role in reducing nitrate and phosphate levels in the water, with decreases of up to 40–50% [24]. The ecological benefits of IMTA included natural nutrient recycling, less water exchange, and pollution mitigation, along with improved oxygenation through algal photosynthesis and organic matter filtration by mollusks [9, 23].

In terms of energy efficiency, IMTA systems used less energy than RAS, and incorporating renewable energy lowered operational costs by about 20–25% [25]. This shows that IMTA not only offers ecological benefits but also provides substantial economic advantages through reduced energy demand.

Table 1: Comparison of RAS vs IMTA with Renewable Energy

Characteristic	RAS	IMTA	Renewable Energy Comparison	References
Environmental parameter control	Provides precise and stable environmental control through automated water quality management.	Provides moderate environmental control shaped by natural factors and species interactions.	Renewable-powered RAS maintains high control with lower energy input due to an efficient system.	[20, 9]
Feed conversion ratio (FCR)	1.1–1.4	1.3–1.5	Similar values; renewable systems may improve FCR via stable oxygenation and thermal control	[36, 9]
Energy consumption (kWh/kg fish	2.5–3.0 (fossil) / 1.8–2.2 (RE)	1.8–2.5 (fossil) / 1.5–2.0 (RE)	Renewable systems reduce energy use by ~20–30% through optimized circulation and intelligent controls.	[20, 9]
CO_2 emission reduction (%)	30–40	20–25	Renewable systems can achieve reductions of up to 70–90% depending on the energy mix and storage setup.	[37, 9]
Ecological benefit	Limited to recirculation and filtration	Nutrient recycling and pollution reduction	Renewable energy enhances ecological impact by reducing emissions and thermal pollution.	[20, 9]
Initial costs	High	Medium	Renewable systems have higher upfront costs but lower operational expenses over time.	[20, 9]

A review of published studies reveals significant variation in energy use, depending on the type of farm and the technology employed. Salmon and trout farms operating under RAS conditions use between 2.5 and 7.0 kWh per kilogram of fish. In contrast, extensive oyster and shrimp farms use less energy but rely more on natural environmental conditions [12, 13, 28].

The implementation of solar energy enables aerators and pumps to operate with lower costs and reduced reliance on centralized power grids [29, 30, 31]. Hybrid photovoltaic systems used in aquaponics and RAS farms have demonstrated high efficiency, ensuring the stability of critical water parameters such as dissolved oxygen and temperature throughout production cycles [33, 34, 35].

Overall, the findings show significant decreases in both operational costs and CO_2 emissions, estimated at 20–50% depending on the system type and geographical location.

DISCUSSIONS

The findings demonstrate that both RAS and IMTA systems can be effectively utilized for cultivating aquatic species, although each has its own advantages and limitations. RAS offers excellent control over environmental conditions, ensuring steady fish growth and efficient feed use, and creates ideal conditions for intensive production, especially in areas with limited water resources. However, the high technical complexity and large upfront costs remain significant challenges, requiring substantial infrastructure and maintenance expenses.

Conversely, IMTA systems have demonstrated the potential to combine aquaculture production with ecological benefits through nutrient recycling and pollution reduction. The inclusion of cleaner species, such as mollusks and algae, has been crucial in maintaining water quality and reducing environmental impacts, thereby supporting sustainable aquaculture principles [9, 24]. Additionally, lower energy requirements and the ability to incorporate renewable energy sources provide IMTA with an economic advantage, thereby enhancing its long-term sustainability [25, 26].

In comparison, the results suggest that RAS is better suited for intensive production and strict environmental control, while IMTA offers a balanced solution between production and ecological sustainability. Thus, the choice between the two systems depends mainly on the objectives of the farmer or institution: maximizing production versus minimizing environmental impact and improving energy efficiency.

Within the broader context of climate change and increasing pressure on water resources, these approaches are becoming more relevant. Recent studies emphasize that both RAS and IMTA can help adapt aquaculture to changing climatic conditions, thereby reducing risks associated with water scarcity and temperature fluctuations [23]. Additionally, integrating renewable energy technologies lowers operational costs and supports carbon reduction efforts, highlighting the role of these systems in promoting sustainable aquaculture.

Table 2: Types of Renewable Energy and Applications in Aquaculture

Energy type	Applications in RAS/IMTA farms	Main advantages	Limitations	References
Solar photovoltaic	Powering pumps, aerators, filters	Low long-term costs, CO_2 reduction	Dependence on sunlight, space required	[38, 39, 40]
Small-scale wind	Electricity supplementation	Hybrid operation, grid-independent	Wind variability	[39, 40, 41]
Solar-wind hybrid	Integrated systems with batteries	Continuous energy supply, cost reduction	High initial investment	[39, 40, 41]

Although solar and other renewable energy sources provide clear advantages in aquaculture, their implementation faces several challenges. High initial costs, solar intermittency, limited technical expertise, and spatial constraints remain the primary barriers identified [16, 42, 43, 39, 40, 44].

Nevertheless, the long-term opportunities are significant: lower operating costs, improved sustainability, increased energy independence, and a reduced carbon footprint [17, 45, 46, 47]. Prospects include developing hybrid systems, gaining access to green financing and supportive government policies, and integrating renewable energy into innovative farm management systems to optimize consumption and decrease environmental impacts.

CONCLUSIONS

This study emphasizes the importance of implementing sustainable strategies in modern aquaculture, with a focus on Recirculating Aquaculture Systems (RAS) and Integrated Multi-Trophic Aquaculture

(IMTA). The results indicate that optimizing environmental parameters, feeding practices, and overall system management can ensure the healthy and sustainable growth of sturgeon species while simultaneously minimizing environmental impacts.

The efficiency of RAS was demonstrated through the maintenance of water quality within optimal ranges for fish development and improved survival rates [48]. Additionally, the integration of plant cultures and extractive species in IMTA systems helps reduce waste and valorize biological by-products, underscoring both the ecological and economic potential of these approaches.

Based on the observations and analyses conducted, it can be concluded that well-designed aquaculture practices not only optimize production but also help preserve aquatic resources and reduce risks related to climate change. Integrated and recirculating systems are therefore viable solutions for sustainable aquaculture development in Romania and other regions with similar resource limitations.

These conclusions underscore the ongoing need for research to develop innovative solutions that optimize production, reduce operational costs, and strike a balance between economic and ecological benefits. Applying the recommendations from this study can support aquatic resource management policies and promote the development of a sustainable and competitive aquaculture sector.

Solar energy is the most promising renewable source for aquaculture, capable of powering essential equipment such as aerators, pumps, and heating systems [18, 49]. Hybrid and photovoltaic systems reduce operational costs, enhance sustainability, and enable independent operation from centralized power grids.

The large-scale adoption of renewable energy in aquaculture farms helps reduce CO_2 emissions, improves food security, and promotes the sustainable growth of the industry. The widespread use of innovative technologies, supported by favorable policies, will be crucial for expanding these practices globally.

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