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Exploring a Self-Sufficiency Approach within a Sustainable Integrated Pisciculture Farming System

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Abstract: The pandemic crisis has created significant challenges for small farms, leading to increased energy costs, higher prices for feed and nutrients, unreliable supplies of chemical fertilizers, and disruptions in product sales markets. These factors have collectively compromised the operational viability and economic sustainability of small-scale agricultural enterprises. To address these challenges, this paper explores the concept of a self-sufficient farming system, focusing on locally producing most of the resources needed to sustain operations and reduce dependence on external sources. A self-sufficient integrated pisciculture farming system is proposed and evaluated, promoting an autonomous circular model that prioritizes environmental sustainability. This system incorporates the integration of local livestock into fish diets, production of renewable energy sources, and efficient water and sludge management to reduce reliance on external resources. The detailed methodology used to evaluate sustainability indicators objectively demonstrates that the proposed system can be self-sustainable and autonomous; however, it requires considerable initial investments that can be recovered within at least six years. Optimizing the energy management plan can reduce daily power consumption by up to 25%. However, local conditions may challenge the efficiency of photovoltaic–hybrid energy production, requiring slight oversizing of the system. The research indicated that rearing carp with cereal-based feed mixtures produces growth results comparable to those achieved with commercially purchased feed. The indicators of resource efficiency, reliability, flexibility, productivity, environmental impact, and social impact were met as expected. The weakest indicator was the technology's potential for scalability, due to its strong dependence on various regional factors.

Keywords: sustainable agriculture; resource security; hybrid energy production systems; autonomous fish farming; self-sufficiency strategy

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1. Introduction

1.1. Enhancing Farm Autonomy, Self-Sufficiency and Waste Management Strategies

Aquaculture has a significant potential to enhance its role in global protein production. Given the current complex and uncertain global economic landscape, it is increasingly important for farms to achieve self-sufficiency in resource production [1–3]. This highlights the need for resilient and sustainable aquaculture practices that ensure long-term environmental health and economic viability. Some research studies [4,5] have emphasized that focusing on technological innovations, efficient resource use, and effective waste management is essential for developing a robust aquaculture sector that can endure global economic uncertainties and environmental pressures. However, these new technologies present significant implications and concerns, underscoring the need for developing and implementing adaptation techniques [6–8]. Modern aquaculture systems should offer a controlled environment that enables precise management of water quality, prevention of disease outbreaks, and control of pollutants, all of which are crucial for maintaining the health and wellbeing of aquatic species [9–11].

1.2. Self-Sustaining Agricultural Practices

Self-sustaining agricultural practices aim to establish long-term sustainable production models, promoting the preservation of a balanced ecological system [12,13]. However, the pursuit of self-sustaining aquaculture encounters several challenges, including limited resource availability, insufficient external inputs, lack of qualified local workforce, and decreased productivity [14]. Despite the risks, many researchers [15] consider autonomous aquaculture systems, capable of self-sustaining through on-site production, to be highly promising for future development. They provide notable benefits, including increased productivity, reduced water consumption, and improved sustainability targets. Nevertheless, it has been found that renewable energy production and consumption in aquaculture are influenced by many dynamic variables, making accurate representation or prediction challenging [16].

Synergies between aquaculture and cereal crop production offer substantial potential to enhance productivity and reduce waste [12,17–20]. Integrating these systems promotes innovative resource management practices, yielding advantages for both sectors. For example, fish wastes and byproducts can serve as natural fertilizers for cereal crops, enriching soil nutrients and improving production [21]. Conversely, crop residues can be utilized as feed or habitat enhancements for many aquaculture species, thereby promoting a circular model and minimizing waste. This reciprocal relationship not only increases productivity but also reduces the environmental footprint associated with both aquaculture and crop production [22,23]. However, there is a lack of empirical research on the effects of resource self-sufficiency on farms' economic performance [24].

1.3. Approaches towards Sustainable, Resilient and Innovative Systems in Fish Farming

Sustainable, resilient, and innovative systems in fish farming represent the future of aquaculture, addressing the critical challenges of food security, environmental impact, and economic viability [25]. By integrating advanced technologies such as precision aquaculture, renewable energy sources, and eco-friendly feed options, these systems aim to optimize fish health and growth while minimizing resource use and pollution. Innovations in water quality management, disease control, and breeding practices further enhance the sustainability and resilience of fish farming operations. This holistic approach ensures that aquaculture can meet the growing global demand for seafood in a way that is both environmentally responsible and economically sustainable, paving the way for a more secure and efficient food production system [26,27].

Some research studies [28,29] challenge the current concept of sustainability in fishing practices, highlighting the strong correlation with long-term economic exploitation. This exploitation, however, can cause unknown damage to ecosystem processes. Therefore, the research calls for further ecological, social, and economic modeling to better understand these impacts. Ensuring productive and sustainable fisheries requires understanding the complex interplay of biology, environment, politics, management, and governance [30]. Failing to understand and sustain ecosystem processes, including humans' impact, continues to drive significant biodiversity loss worldwide [31,32].

The fishery sector serves as an important global source of protein and nutrients, while in Romania, the common carp species (*Cyprinus carpio*) is among the most valuable species [33]. Nutrition and farming methods are pivotal aspects under constant research and development to ensure sustainable, profitable and healthy fish production. Artificial feeding of carp is fundamental to modern aquaculture, exerting a significant influence on the growth, health, and quality of fish meat.

1.4. Current Integration of Renewable Energy in Aquaculture Practices

The development of renewable energy management systems and time-based energy consumption models represents a relatively recent advancement in aquaculture [34]. This integration offers significant benefits, including reduced environmental impact, enhanced financial competitiveness, and sustainable development [35]. However, there is a lack of economic and energy optimization models for the design and operation of such systems. A major challenge is addressing the intermittence and instability of renewable energy sources, which can threaten the system's safe and stable operation. Optimal integration requires careful planning to determine the best hourly operation strategy and the appropriate capacity and design of units, considering specific constraints.

Another research study [36] evaluated a hybrid energy system incorporating photovoltaic (PV) panels, wind turbines, and energy storage to sustain the functioning of a fishing farm, while optimizing the net present cost. The study provided high-level estimations and assessed all possible combinations of the selected technologies. Another renewable energy production system was proposed [37] to produce pure oxygen, for the purpose of stabilizing dissolved oxygen levels. The proposed system optimized the life cycle cost and demonstrated that integrating PV panels and wind turbines could achieve energy self-sufficiency with minimal environmental impact. Another study [38] evaluated the economic benefits of fish production across different energy usage and aquaculture systems. A detailed review of energy consumption in recirculating aquaculture systems [39] identified renewable energy integration as a potentially more cost-effective approach than current practices.

Energy optimization modeling offers a valuable tool for minimizing power consumption while maximizing production efficiency in aquaculture. By considering energy consumption factors and simulating various scenarios, these models can identify the most energy-efficient configurations and management strategies while also taking into account economic and environmental considerations. However, generating such models presents many challenges, including integrating data at different scales, solving scheduling for highly interconnected systems, mathematically optimizing nonlinear systems with multiple and conflicting objectives, and developing accurate prediction models.

Although many studies address sustainability approaches in aquaculture, significant gaps remain in the development of functional self-sufficient systems for fish farming. Innovative, cost-effective, and environmentally friendly solutions are still lacking in practical implementation. Although the literature covers various aspects of fish nutrition and feed efficiency, including alternative feeds and the reduction of fishmeal use, there is limited research on optimizing feed conversion ratios and producing fodder for small-scale aquaculture systems. Comprehensive studies on the cumulative environmental impacts of aquaculture practices, particularly in changing climates, are still needed.

Although waste management is a key concern, innovative, cost-effective, and environmentally friendly solutions are still lacking in practical application.

The present paper explores a self-sufficiency approach within a sustainable integrated pisciculture farming system. The research aims to develop a management model for fish farms that emphasizes autonomy and sustainability. The proposed model integrates crop establishment and livestock for fish diet, efficient water management, and renewable energy sources to reduce dependence on external inputs. By adopting a circular economy framework, the system seeks to reutilize all generated waste, thereby enhancing resource efficiency and minimizing environmental impact.

2. Materials and Methods

2.1. Self-Sufficient and Sustainable Farming System and Model Design

To facilitate an effective transition from conventional pisciculture to a self-sufficient and sustainable farming system, the objective was to integrate various components—such as energy production and consumption, feed production, improved fish farming practices, and resource and waste management strategies—into a cohesive and sustainable business model (Figure 1). This design facilitates on-site production of essential resources for farm operations, including energy, water, and fish feed, while ensuring the reutilization of all generated waste within the production streams. All technological processes are closely interconnected to optimize resource utilization and minimize dependence on external sources.

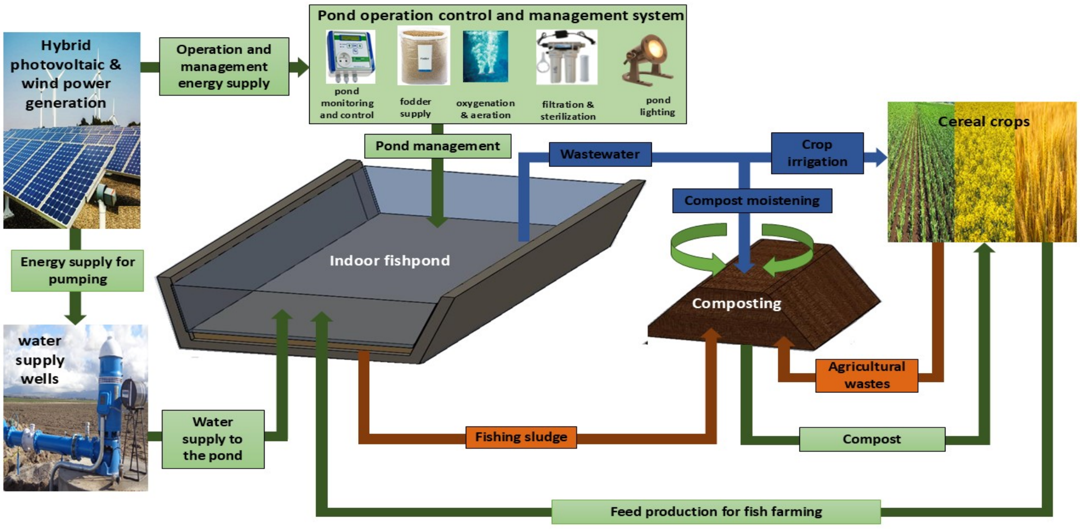

Figure 1. Self-sufficient and sustainable resource and waste management approach.

To prove the viability of a self-sustaining fishing system, we conducted an evaluation that demonstrates how the system can operate efficiently, generate sufficient revenue, and provide a reasonable return on investment.

The photovoltaic–wind hybrid energy power supply, equipped with storage capacity in accumulators, must be capable of meeting the energy needs of all associated systems. This includes powering the processes of water addition, sludge evacuation, and pond management. Vegetable waste from agriculture and sludge from fish farming create an excellent composting mixture due to their favorable carbon–nitrogen ratio. The resulting compost serves as a biofertilizer in agriculture, while the wastewater from the pond is used for crop irrigation. By cultivating agricultural crops for producing fish feed, we effectively close the loop of resources and wastes at the farm level.

To accurately assess the characteristics of self-sufficiency and sustainability, this article focuses on four main pillars: renewable energy management, feed efficiency, waste and resource management, and pond productivity, as illustrated in Figure 2.

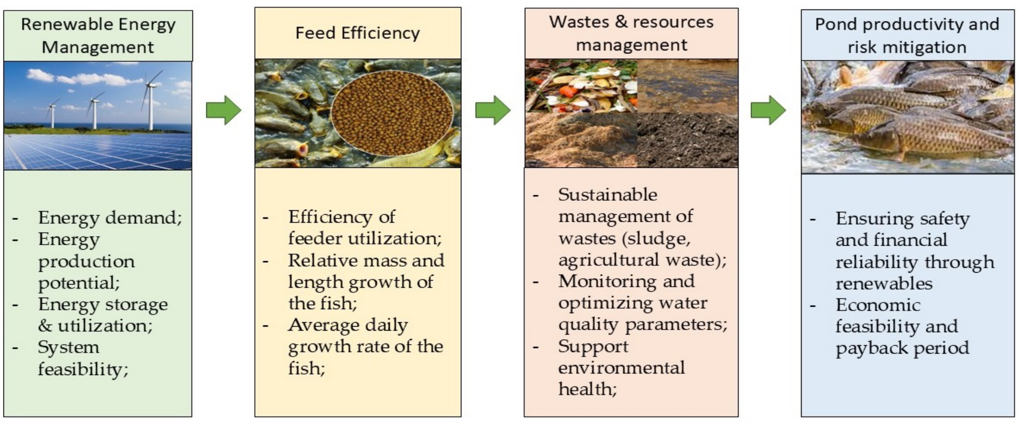

Figure 2. Approach to analyzing self-sustaining capacity using four main pillars (renewable energy management, feed efficiency, waste and resource management, and pond productivity) and risk mitigation.

2.2. Equipment and Resources Required for the Experimental Fish Pond

For the experiment, we managed a concrete fish pond designed for carp farming, with a water capacity of 400 cubic meters (Figure 3). Closed fishing ponds offer the advantage of reducing the environmental impact, by minimizing the release of sludge and wastewater into the rivers. However, these systems tend to accumulate substantial amounts of wastewater and nutrient-rich sludge, which need to be efficiently managed within the production cycle. Some approaches propose applying these byproducts directly to agricultural fields; however, we found that using unprocessed sludge as a fertilizer may carry some risks for crops and does not always leverage their full nutritional potential.

(**a**) (**b**) (**c**)

Figure 3. Reinforced concrete pond for raising fish in a closed system, with a capacity of 400 cubic meters: (**a**) exterior view of the pond; (**b**) interior view of the pond, showing water evacuation for better fish harvesting; (**c**) decanting and pumping the sludge after harvesting's completion.

2.2.1. Power Requirements Analysis and Designing Energy Consumption Plan

The aim was to determine the total energy usage of the fish production facility and to create an efficient energy consumption plan that does not compromise productivity or harm the environment. Creating an effective energy consumption plan involves a comprehensive analysis of the power requirements for all operational activities and align energy use with available renewable resources. We adjusted and programmed energy consumption patterns to ensure the sustainable use of resources. This approach aims to optimize energy efficiency while minimizing environmental impact and operational costs. Implementing this strategy involves incorporating advanced technologies and best practices to optimize energy use and continuously improve system performance.

The energy consumers considered for the experiments in the fishing pond include two aeration pumps used for water oxygenation (Osaga ORV 370-60 Aerator), an UV-C sterilizer (Osaga 55), an organic mechanical filter (gravity pond filter IAZZ), a water recirculation pump, two pumps for water addition (DRK Water pump) and sludge evacuation (Furiatka sludge discharge water pump), various monitoring sensors, a PLC, a data logger, a data-processing system, automatic fish feeding equipment (Eurohunt automatic digital feed), a lighting system, and a surveillance system. These pieces of equipment work together to create and sustain optimal conditions for fish development and growth.

2.2.2. Power Production and Energy Storage Installations

The hybrid power supply system consists of 21 photovoltaic panels, each with a maximum power output of 310 W (DBsolar Monocrystalline 310) and a 600 W wind turbine (ATO-WT-600M4). However, their maximum power output is affected by various local factors such as solar radiation, wind conditions, shading, nearby buildings, and seasonal variations. Consequently, some measurements were taken to evaluate both the theoretical maximum energy input using the Voltcraft PL-110SM digital pyranometer and the real energy accumulated, based on data recorded by the MPP Solar PIP 8048 MAX solar inverter. This ensures a comprehensive assessment of energy production and helps in fine-tuning the system to better match real-world conditions. Figure 4 illustrates some of the equipment used for renewable energy production, storage, and management.

(**a**) (**b**) (**c**)

Figure 4. Hybrid renewable energy production system: (**a**) inverter and batteries; (**b**) partial illustration of photovoltaic panels; (**c**) wind turbine.

The energy storage system capacity (using rechargeable batteries) required to ensure a continuous power supply during periods of low solar and wind energy generation was also determined. This involved assessing the energy demands of the facility, evaluating the typical fluctuations in solar and wind energy availability, and calculating the storage necessary to maintain operations without interruption. The analysis ensured that the storage system could handle extended periods of low renewable energy output, thereby guaranteeing reliability and efficiency in the power supply for the fish production facility.

Energy storage capacity in the batteries (B_{cap}) is considered an assumption of the autonomous days of the system functioning at full capacity ($Days_{\text{autonomy}}$) and energy demand (E_{demand}); it is found using Equation (2).

$$B_{cap} = Days_{\text{autonomy}} \times E_{demand} \quad (1)$$

2.2.3. The Effect of Locally Produced Feed on the Growth of Three Carp Species

Determining the self-sufficiency of a fishing pond considering only feed management involves evaluating the effectiveness and efficiency of feeding practices in meeting the nutritional needs of the fish without overfeeding or relying excessively on external feed inputs. To explore the concept of a self-sufficient farming model, it is essential to locally produce the resources needed for feed, thereby reducing dependence on external sources. By examining the complexities of this approach, including its potential benefits and challenges, we aim to provide valuable insights into the feasibility and implementation strategies necessary for achieving greater autonomy and sustainability in fish farming practices.

The experiment assessed the influence of locally produced food on the growth and development of Common carp, Frasinet carp, and Salonta carp, grown in nine experimental pools. These carp subspecies have been selected due to their high commercial potential within the Romanian market. Many farmers prefer cultivating these species, which has led to heightened interest in assessing sustainability in practical terms.

Each pool measured 2 × 2 × 1 m and contained three cubic meters of water. Three fish breeding tanks were allocated to each species, accommodating 100 fish per pond with an average weight of 107 g each. The fish tanks, functioning within a recirculating system, were equipped with the filtration unit Hailea G12000 (Guangdong Hailea Group Co.,Ltd., Foshan, China), the automated feeding system Eheim Twin Duo (EHEIM GmbH & Co. KG., Deizisau, Germany), and the water-quality-monitoring system Atlas Scientific Wi-Fi Hydroponics Kit (Atlas Scientific Environmental Robotics, New York, NY, USA). Over a period of 4 months, the growth of the fish being fed three different diets was monitored.

Feed was administered three times daily, with rations adjusted based on fish size and water temperature. Throughout the research period, daily food intake was maintained at 2% to 5% of the fish body weight. This protocol was applied uniformly for all feed recipes, while growth conditions (temperature, oxygen levels and water quality parameters) were kept the same for all tanks (Figure 5).

(**a**) (**b**) (**c**)

Figure 5. Technological installations designed for raising fish fry from the carp family: (**a**,**b**) small tanks working in a recirculating system, equipped with aeration and monitoring equipment; (**c**) depiction of fish raised in small ponds.

The feed recipes were formulated using locally available grains and took into account specific nutritional percentages.

The first feed recipe (R1) was acquired from local distributors, while the other three recipes (R2–R4) were produced locally using cereals cultivated in the experimental fields of INMA Bucharest Institute and two partner research stations. Given the use of varying technologies and cultivation methods for growing cereals, this study focused exclusively on the effects of the feed formulations, without addressing the economic aspects of feed production. The primary objective was to demonstrate that feed recipes produced locally by farmers can attain nutritional characteristics comparable to commercial alternatives.

Fish feed recipe R1 (control commercial recipe Evialis carp feed): crude protein 17%; vitamin A 12,000 IU/kg; fat 4.0%; vitamin D3: 2400 IU/kg; crude cellulose 6.0%; vitamin E 40 mg/kg; crude ash 7.0%; phosphorus 0.7%; calcium 1.5%; sodium 1.5%; lysine 0.9%; methionine 0.30%.

Fish feed recipe R2: proteins: 30%; fats: 6%, crude fibers: 5%; cereals used in the recipe R 2: wheat flour: 35%; oat flour: 25%; rye flour: 20%; soy flour: 20%.

Fish feed recipe R3: proteins: 28%; fats: 6%; crude fibers: 5%; cereals used in the recipe R 3: barley flour: 30%; ground corn: 30%; wheat flour: 25%; pea flour: 15%.

Fish feed recipe R4: proteins: 25%; fats: 4%; crude fibers: 7%; cereals used in the recipe R 4: wheat flour: 35%; sorghum flour: 25%; millet flour: 20%; pea flour: 20%.

To ensure high-quality feed for the fish, extruding equipment was used, which involves treating the ingredient mixture with steam and high temperatures, followed by compression at controlled pressures. This method enhances nutrient digestibility and absorption while reducing water pollution, as the compacted pellets minimize the release of unused nutrients.

Pelletized feed production involved several phases to ensure good nutritional value and feed efficiency. The ingredients were weighed then ground using a hammer mill and mixed to achieve a homogenous blend (Figure 6a,b). The mixture was conditioned with heat and moisture to improve pellet formation, then extruded using specialized equipment (Figure 6c). The pellets were cooled, dried, and stored in containers.

The extruder features the following specifications: a power supply voltage of 230 V, power rating of 2.8 kW, a maximum speed of 1400 rpm, and a production capacity of 150 kg of pelleted feed per hour. It weighs 94 kg and has die hole diameters ranging from 2 to 12 mm (adjustable according to the size of the fish).

(**a**) (**b**) (**c**)

Figure 6. Setup for the production of pelletized feed for carp family: (**a**) grinding and (**b**) mixing cereals; (**c**) production of different extruded pellets.

Pelletized feed was dispensed automatically using specialized equipment (EvoFeed—Evolution Fish Feed), while pool oxygenation was facilitated by dedicated aerators (Tetra Tetratec APS 50). Monitoring of water parameters such as dissolved oxygen levels was conducted using an Atlas Scientific Wi-Fi Aquaponics Kit. The fish tanks were positioned indoors in an experimental hall designed for aquaculture research, allowing for more efficient temperature control. The feed ration for carp (*Cyprinus carpio*) varies depending on several factors, including the size of the fish, rearing conditions, water temperature and the type of feed used. During the studied months, the daily food intake ranged from 2% to 5% of the total body weight. The monthly average weight of the feed for each pool is illustrated in Figure 7.

Recype type	Fe 1			Fe 2			Fe 3			Fe 4		
Fish type	CC	CS	CF	CC	CS	CF	CC	CS	CF	CC	CS	CF
May 1– May 31	14.8	15.3	16.2	14.9	15.2	15.8	14.3	15.1	15.9	14.5	15.5	15.9
June 1– June 30	31.8	34.9	35.2	31.2	34.3	34.3	29.8	33.7	33.8	29.4	33.7	33.5
July 1– July 31	50.0	53.5	52.9	49.1	52.8	51.8	47.5	51.8	51.2	46.9	51.4	50.6
August 1–August 31	70.1	72.7	70.1	69.0	71.6	68.0	67.8	70.7	67.2	66.8	69.7	66.4

Figure 7. The average monthly amount of feed administered for each pool under monitoring.

The primary growth indicators used for analyzing the development of the three fish types are outlined below, in Equations (1)–(3).

The feed conversion ratio (FCR) indicates the efficiency of feed utilization and is calculated using Equation (2).

$$FCR = \frac{FI}{WG} \quad (2)$$

where FI = feed intake, which is the total amount of feed consumed by the fish, and WG = weight gain, which is the increase in the fish's weight over a specific period.

The relative mass growth (RMG) for fish provides the relative mass growth as a percentage and is calculated using Equation (3).

$$RMG = \left(\frac{W_f - W_i}{W_i}\right) \times 100 \quad (3)$$

where W_f is the final weight of the fish and W_i is the initial weight of the fish.

The specific growth rate (SGR) for fish indicates the average daily growth rate of the fish and is calculated using Equation (4).

$$SGR = \left(\frac{ln\left(W_f\right) - ln(W_i)}{t}\right) \times 100 \tag{4}$$

where W_f is the final weight of the fish, and W_i is the initial weight of the fish; t is the time period over which the growth is measured.

2.2.4. Assessment of Statistically Significant Differences among Feed Recipes

A one-way ANOVA was employed to assess if there are statistically significant differences between the four feed recipes in terms of their impact on fish growth. The aim was to determine if different feed recipes lead to significant differences in fish growth rates. The calculation was made for each of the analyzed months using the growth data of the three species depending on the feeding recipes. The chosen significance level was 0.05, the groups were set Fe 1–Fe 4, and the null hypothesis was that mean weights for the three carp subspecies would be equal for all types of feed.

2.3. Water and Sludge Management and Conservation

Effective water management is critical in closed fish pond systems, particularly in terms of quality, quantity, and sludge management. The feed production system includes technologies for monitoring and optimizing water quality parameters such as oxygen levels, pH balance, and temperature. This proactive approach minimizes stress on fish and enhances overall productivity. Additionally, the pond is constructed from reinforced concrete, preventing any leakage into the ground. The water is either recirculated or repurposed for agricultural use after sludge removal. The sludge is composted together with other waste materials, such as leaves and straw, and utilized as organic fertilizer in agriculture. The water supply is sourced from wells and added to the pool without prior filtration.

2.4. Economic Viability

Beyond environmental benefits, the self-sustaining feed production system enhances economic viability for fish farmers. By reducing operational costs through efficient feed utilization and minimizing resource inputs, farmers can achieve higher profitability while maintaining sustainable practices. However, the expenses of implementing the system must be amortized over time and are calculated using Equation (5).

$$Payback = \frac{Cost}{Annual\ savings} \tag{5}$$

2.5. Composting Phase for Ecological Waste Management and Fertilizer Production

Vegetable waste from agriculture (Figure 8a) was mixed with sludge from fish farming, being combined to create an excellent composting mixture (Figure 8b). The resulting mix was highly valuable due to its ideal carbon-to-nitrogen ratio. Carbon-rich vegetable waste provided energy for microorganisms, while nitrogen-rich fish sludge supported their growth and accelerated decomposition over 3 months of composting (Figure 8c).

This synergy enhances microbial activity, leading to faster and more efficient composting. The resulting compost is nutrient-enhanced, improving soil health and boosting crop yields. By using these organic byproducts, in addition to waste reduction, the method also promotes a circular economy, reusing resources within the system. This sustainable approach exemplifies modern farming practices that support environmental health and agricultural productivity. Compost was produced in simple and inexpensive windrow piles, controlling moisture content and aeration.

(**a**) (**b**) (**c**)

Figure 8. Sustainable management of waste by composting agricultural vegetable waste, fish farming sludge, and wastewater: (**a**) vegetable waste predominantly composed of leaves and straws; (**b**) composting process using aeration mixing equipment pulled by an agricultural tractor; (**c**) maintaining optimal composting conditions for at least 3 months.

3. Results

3.1. Power Requirements Analysis for Fish Pond Operations and Energy Consumption Plan Design

An operational management strategy for the fish pond was designed in order to optimize energy consumption hours for all the energy-consuming equipment. This approach aims to flatten consumption peaks while ensuring that each piece of equipment within the system performs its intended function effectively (Figures 9 and 10).

				Dayly operational power consumtion																									
System	Equipment	Equipment nominal powe	UM	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Total energy consumtion per equipment	
Water aeration system	Osaga ORV 370-60 Aerator 1	0.25	KW		0.25			0.25				0.25			0.25			0.25			0.25				0.25			1.75	KWh
	Osaga ORV 370-61 Aerator 2	0.25	KW			0.25					0.25								0.25			0.25						1	KWh
Water filtration, sanitation and recyrculation system	Water recirculation and mechanical filtering	0.15	KW									0.15				0.15				0.15				0.15				0.6	KWh
	UV-C sterilizer	0.6	KW									0.60				0.60												1.2	KWh
Monitoring and control system	Sensors, PLC, data logger	0.1	KW	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	2.4	KWh
	Display and processing system	0.11	KW							0.11	0.11																	0.22	KWh
Automatic fish feeding system	Eurohunt automatic digital feeder	0.3	KW						0.30					0.30					0.30				0.30					1.2	KWh
Auxiliary systems	Lighting system	0.2	KW	0.20	0.20	0.20	0.20	0.20	0.20														0.20	0.20	0.20	0.20	0.20	2.2	KWh
	Surveillance system	0.2	KW	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	4.8	KWh
Watter adition and evacuation from the pond	DRK Water pump	1	KW										1.00															1	KWh
	Furiatka sludge discharge water pump	1.5	KW														1.50											1.5	KWh
Hourly energy consumed by the system				0.5	0.8	0.8	0.5	0.8	0.8	0.4	0.7	1.3	1.3	0.6	0.6	1.1	1.8	0.6	0.9	0.5	0.6	0.6	0.8	0.7	0.8	0.5	0.5	17.87	KWh

Figure 9. Energy management plan for fish basin functioning.

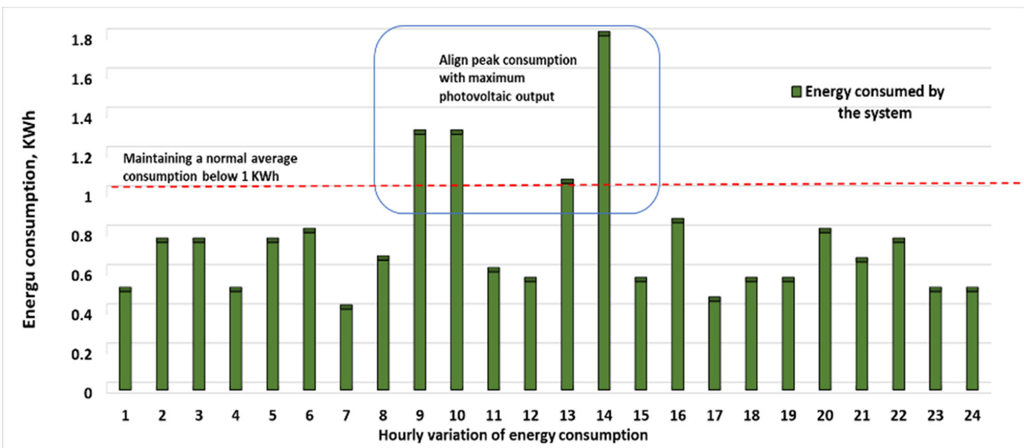

Figure 10. Key constraints on hourly power consumption used for operating the fish pond.

After evaluating the energy requirements and optimizing the consumption peaks, a site assessment was conducted to evaluate the real potential of solar and wind power generation.

3.2. Power Production and Energy Storage

Both the global radiation specific to the area using the pyranometer (Figure 11) and the real radiation produced by the annual photovoltaic panels (Figure 12) were recorded.

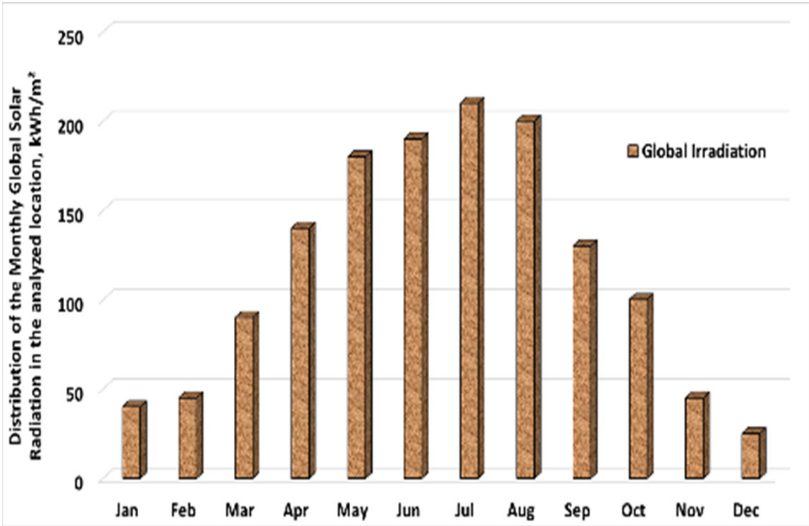

Figure 11. Monthly average global solar radiation (GSR), monitored in the pond's location using a pyranometer.

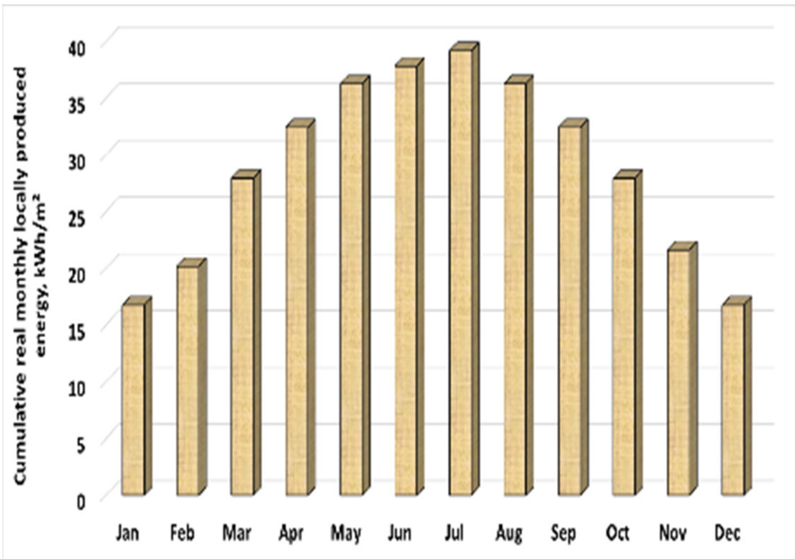

Figure 12. Cumulative monthly energy produced per square meters, monitored in the location.

Figure 13 depicts the average wind speed at the turbine location, while Figure 14 illustrates energy conversion efficiency, which is notably influenced by local conditions and wind turbine limitations.

Calculating the appropriate size of the energy storage system in batteries is crucial to ensuring the safety and reliability of the energy production system. To cover an energy requirement of 17.87 kWh over a period of two days, a minimum of 18 batteries with a capacity of 250 Ah each are needed. Experiments have revealed that the energy storage system is utilized primarily during the night, (because wind generation does not always function at night), as well as during certain winter periods. Snow removal from the photovoltaic panels was a necessary task throughout the winter for the proposed dimensioning.

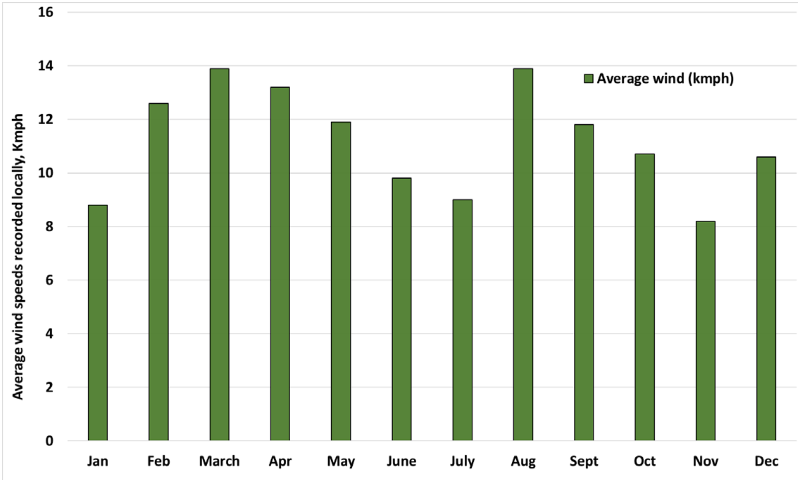

Figure 13. Monthly average wind speeds recorded in the pond location using an anemometer.

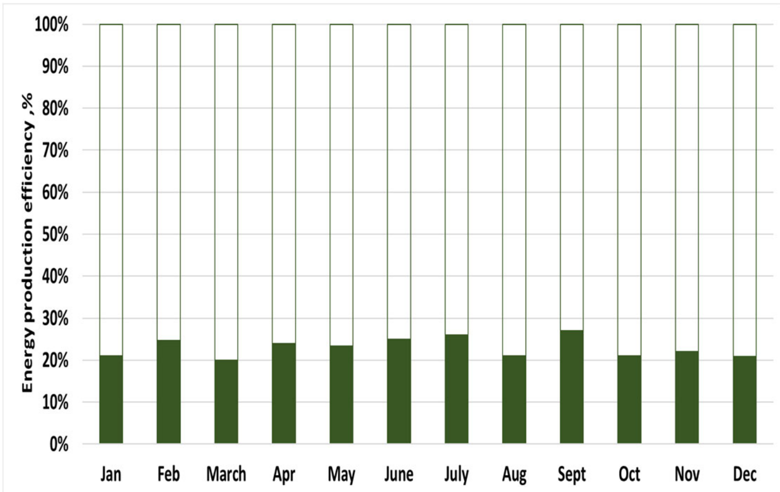

Figure 14. Energy production efficiency for the wind turbine under local environmental conditions.

The purchase costs of the hybrid energy production and storage system (photovoltaic panels, wind turbine, invertor, batteries and accessories) were 11,000 EUR without assembly.

Considering an average local energy price of electric energy of EUR 0.26 per kWh and cumulative energy production (photovoltaic and wind) of 7243 kWh per year, the annual savings will be EUR 1883. Therefore, the payback period for the EUR 11,000 investment is approximately 6 years.

3.3. Self-Sustaining Feed Production System for Raising Carp in Fish Ponds

The growth of fish when fed with three types of locally produced feed (Fe 2, Fe 3, and Fe 4) as well as one type of purchased feed (Fe 1) is illustrated in Figures 15 and 16.

The efficiency of feed utilization was calculated using the feed conversion ratio (FCR), and the values for the four recipes and three fish types are shown in Figures 16–18.

The specific growth rate found for the three fish species over the May–August period is depicted in Figure 19.

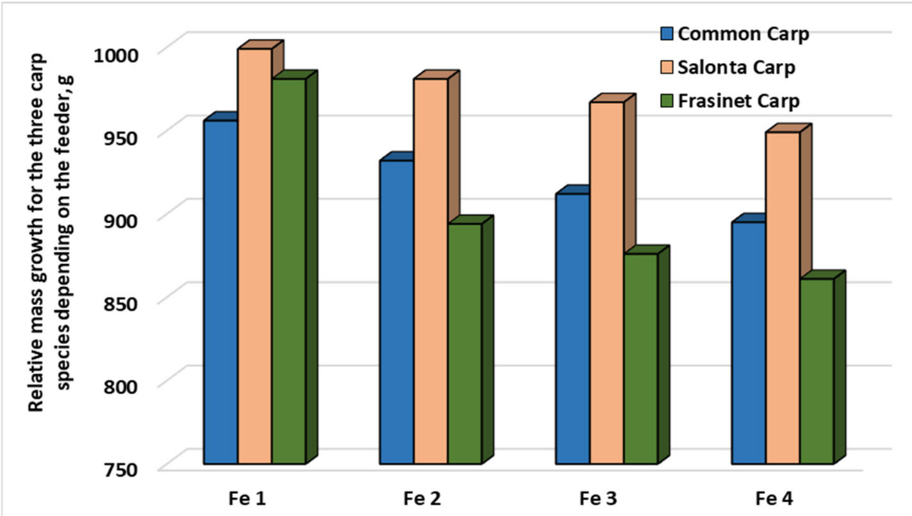

Figure 15. Relative mass growth for the three carp species depending on the feed recipes.

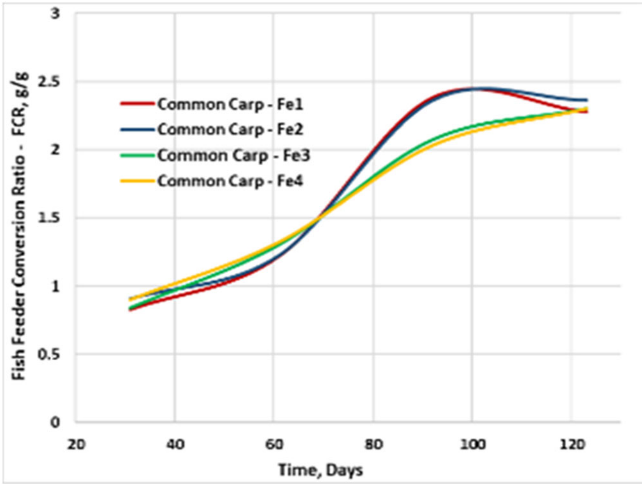

Figure 16. Variation in feed conversion ratio (FCR) over 120 days for common carp fed with the four different recipes.

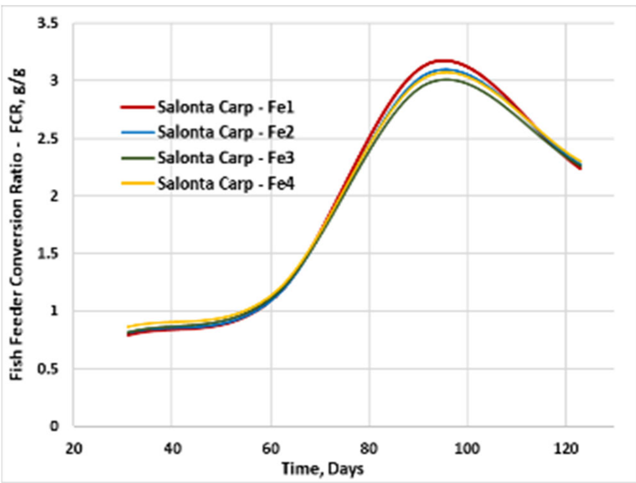

Figure 17. Variation in feed conversion ratio (FCR) over 120 days for Salonta carp fed with the four different recipes.

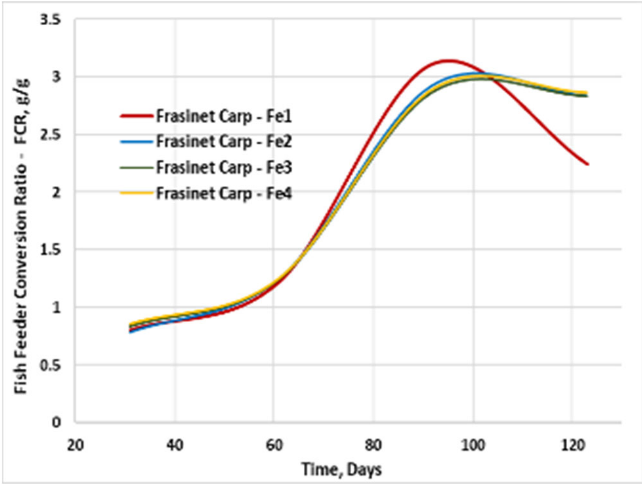

Figure 18. Variation in feed conversion ratio (FCR) over 120 days for Frasinet carp fed with the four different recipes.

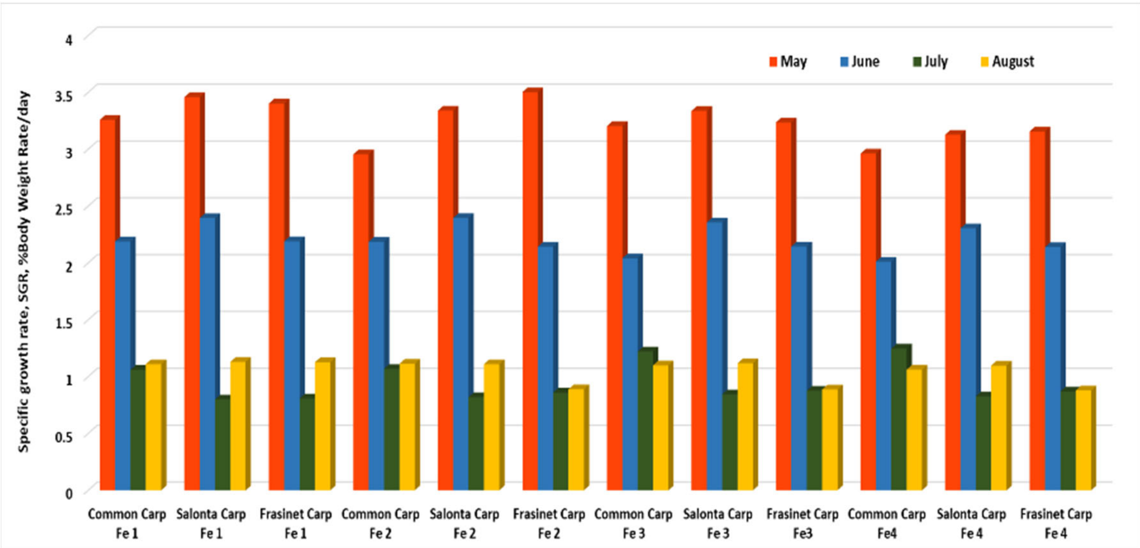

Figure 19. Specific growth rate evaluated for the three fish species over the May–August period.

3.4. Assessment of Statistically Significant Differences among Feed Recipes

For all evaluated months, the F-statistic was lower than the critical value and the *p*-value was greater than 0.05; there was no statistically significant difference in the fish growth rates among the different feed recipes. This implies that all feed recipes have a similar effect on fish growth, and any observed differences in growth rates are likely due to random variation rather than significant differences between feed recipes. This finding is important as it demonstrates that farmers are capable of producing high-quality fish feed at the farm level, thereby reducing reliance on external suppliers.

3.5. Developing an Evaluation Model to Assess the Self-Sustainability of the Aquaculture System

We aimed for stakeholders in fish production systems to objectively assess the sustainability and autonomy indicators of the presented aquaculture system. To achieve this, we developed an evaluation model based on experimental results, clearly defining performance indicators evaluated across multiple dimensions to provide a comprehensive view of the system's performance. Five fish farmer management representatives participated in the scoring process, evaluating each indicator on a scale from 1 to 5 (with 1 indicating unsatisfactory performance and 5 indicating excellent performance). This grading enabled the identification of strengths and areas for improvement (Table 1).

Table 1. Evaluation of the method using specific indicators.

Indicators Achieved to Meet Sustainability and Self-Sustaining Requirements			**Grading ***				
Objectives	**Indicator**	**Requirement Fulfillment**	**1**	**2**	**3**	**4**	**5**
Resource Efficiency	Energy Use	-Highly efficient in energy consumption, providing a customized consumption regime that flattens power consumption peaks; -Renewable energy sources such (hybrid photovoltaic–wind turbines, coupled with energy storage system for safety.					
	Water Utilization	-The wastewater coming from fish farming is used entirely for irrigation in agriculture, and there is no pollution of the emissary (rivers); -Due to the special construction of the fishing pond (waterproof reinforced concrete), there is no pollution of the underground waters; -There is high efficiency in using water per unit of food and endowments regarding water recycling and purification systems.					
	Nutrient Management	-Feed produced locally using local technology and ingredients demonstrates fish growth comparable to that achieved with purchased feed; -Wastes generated from feed production are reintegrated back into the system.					
System Reliability	Operational Stability	The system operates consistently under normal and stress conditions, including ability to handle variations in weather, resource availability, and potential system failures. The carp is a species that does not show a high sensitivity to the technological problems that may arise.					
	Low Maintenance Requirements	-Low frequency and cost of maintenance are needed to keep the system functioning optimally. Maintenance costs can increase over time, due to the high level of automation.					
Flexibility and Scalability	Adaptability	-The system has an increased ability to adapt to different environments, scales of operation, and changing resource conditions. However, local climatic conditions can negatively influence energy production.					
	Expansion Potential (scale up or down)	-The technology can be scaled up or down to meet varying demands or to integrate into larger production systems. However, there is a strong dependance on several factors such as climatic conditions, type of fish raised, and fertility of the soil for feed production.					
	Ease of Operation	-Easy for operators to use, with simple management tasks and minimal expertise required.					
	Integration with Existing Systems	-The system integrates with existing agricultural or energy systems, ensuring compatibility with current infrastructure and technologies.					
Productivity	Yield	-Achieving a substantial yield of products and energy relative to the inputs utilized, considering factors such as growth rates, harvest times, and overall productivity per unit volume.					
Environmental Impact	Carbon Footprint	-Reducing the GHG emissions, including direct and indirect emissions associated with energy use, production processes, and waste management and transportation (compared to conventional systems).					
	Biodiversity and Ecosystem Health	-Highly positive impact on local biodiversity and ecosystem services, including substantial benefits such as reducing surface and underground water pollution and mitigating river nitrification.					
	Climate Resilience	-Ability to withstand and adapt to climate-related challenges, including extreme weather events and long-term climate change.					
	Renewability	-Reliance on renewable resources and capacity to minimize depletion of non-renewable resources.					
Social Impact	Community Benefits	-System may support local communities, including job creation, food security, and social equity (especially in the production of cereals). However, the increased level of automation reduces the effort with the farm's labor force, therefore not contributing to the creation of new jobs.					
	Resource Resilience	-High capacity to manage resource scarcity or variability, including fluctuations in energy, water, and nutrient availability					
	Local Economy	The system contributes to the local economy, including impacts on local businesses, markets, and economic resilience.					

* In the evaluation, green color represents the fulfillment of the score, while orange color indicates the non-fulfillment of the score.

4. Discussion

The research indicated that rearing carp fish with cereal-based feed mixtures yields growth results comparable to those achieved with commercially purchased feed. This finding aligns with similar observations reported in other studies [40–42]. However, a notable limitation of the study is the absence of a financial evaluation of feed production.

Without this analysis, it remains unclear whether domestically produced feed might incur higher costs compared to commercially purchased alternatives.

Integrating renewable energy systems into aquaculture has demonstrated significant reductions in operating costs and carbon emissions, while also enhancing autonomy and self-sustainability. A combination of various energy types and storage systems can address some uncertainties and maintain system stability. This conclusion was also a significant finding in several studies examining fish systems that incorporated renewable energy production [24,43]. However, the initial capital cost for renewable energy installations proved to be quite significant, and factors such as energy demands, fish species, pond automation level, and location introduce numerous variables. Consequently, it is essential to develop an optimization model that balances both economic and sustainability goals for the design, planning, scheduling, operation, and control of aquaculture systems. Studies on fish systems utilizing renewable energy production typically maintain a connection to the power grid to ensure increased safety and reliability [44,45].

Given the total energy requirement of 17.9 kWh per day for the fish pond, the hybrid energy production system was designed with a power-buffer, directing at least 10% extra energy into the battery storage system. This stored energy was reserved for emergency situations. The system includes 21 photovoltaic panels, (310 W each), having an estimated average production time of 3.5 h per day and operating at 75% efficiency (accounting for losses due to the inverter, cabling, dust, and high temperatures). The photovoltaic system generated an average of approximately 17.1 kWh daily (only 56% of the theoretical power production, due to the location's shading). Additionally, the wind turbine, operating at an average wind speed of 4 m/s with a 20% capacity factor, contributed an additional 2.88 kWh per day. Altogether, the hybrid system produced a combined total average energy of 19.98 kWh daily, ensuring the supply for the fishing pond, while maintaining a reliable backup.

It can be observed that for some months, the energy production system was oversized. In this period, energy production exceeds the estimated energy consumption levels. This excess electricity was utilized to extend the operating hours of the aerators. This is particularly beneficial in summer, as higher water temperatures tend to reduce dissolved oxygen values. The additional aeration helps maintain optimal oxygen levels in the pond. The temperature increase is directly linked to higher photovoltaic energy production, since longer daylight hours and greater insolation during summer enhance solar panel output. The hybrid photovoltaic–wind power system implemented at this fishing farm has demonstrated the ability to function as a self-sustaining and sustainable system. Combining photovoltaic panels and wind turbines ensured the energy self-sufficiency necessary for all operational processes of the farm. This means that the entire energy requirement for operating pumps, aeration systems, lighting, and other essential equipment was fully covered by the energy produced from local renewable sources. While other studies have explored hybrid renewable energy production [46–48], no research has been identified that focuses on optimizing energy consumption based on sustainability indicators.

The photovoltaic–wind combination brings benefits, because photovoltaic panels capture solar energy during the day, while wind turbines generate energy throughout the day, including in low-light conditions or at night, when the wind may be stronger. This combination allows the system to compensate for the variability of each source (providing a better energy balance). For example, on a sunny day without wind, the photovoltaic panels provide the necessary energy, while on a windy and cloudy day, the wind turbines take over the main generation load.

To ensure operational continuity and maintain a self-sustaining system, the energy generated by the photovoltaic panels and wind turbines is stored in batteries. This storage guarantees the availability of energy during periods of high demand or when energy generation is lower. It maintains the uninterrupted operation of the fish farm even under variable weather conditions or at night.

This system not only ensures energy autonomy, but also does so in a sustainable way, contributing to reducing the carbon footprint and protecting the environment (the system contributes to reducing pollution and combating climate change, ensuring a minimal impact on the environment). In addition, the system uses natural energy sources available on site, reducing dependence on external resources and minimizing the need for energy transportation, which can be expensive and unsustainable.

5. Conclusions

The system operating with hybrid photovoltaic–wind power has demonstrated not only self-sufficiency in covering the energy requirement for all operational processes of the fish pond, but also the ability to maintain this autonomy in a sustainable way. The energy storage system in batteries provided a reliable backup, maintaining stability and continuity of operations even in conditions of varied natural resources.

The methodology used by the stakeholders to assess the sustainability indicators objectively demonstrated that the fish system is self-sustainable and autonomous. Indicators such as resource efficiency, reliability, flexibility, productivity, environmental impact, and social impact were met as expected.

However, self-sustaining approaches come with certain drawbacks, including higher investment costs, the need to diversify production portfolios, and the requirement for qualified personnel.

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Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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