EXPERIMENTAL RESEARCH OF A PHOTOVOLTAIC-POWERED AQUACULTURE SYSTEM WITH INTEGRATED BIOLOGICAL MECHANISMS FOR SELF-CLEANING
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CERCETĂRI EXPERIMENTALE ALE UNUI SISTEM DE ACVACULTURĂ ALIMENTAT CU ENERGIE FOTOVOLTAICĂ ȘI PREVĂZUT CU MECANISME BIOLOGICE INTEGRATE DE AUTOCURĂȚARE

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ABSTRACT

This paper presents the experimental development and evaluation of an autonomous photovoltaic-powered aquaculture system designed for small-scale fish farming in isolated areas. The system integrates renewable energy generation, automated control, and real-time monitoring to ensure energy self-sufficiency and environmental sustainability. The experimental setup, consisting of a 6 kWp photovoltaic array (15 panels of 400 W each), a 24-unit 24 V battery bank, and a diesel generator for emergency backup, was tested at INMA Bucharest over a two-year period. The installation supplies power to essential aquaculture subsystems, including water recirculation, aeration, automatic feeding, lighting, and surveillance. Experimental data showed that the photovoltaic system fully met the average daily energy demand of 3.35 kWh, with hourly peaks of approximately 255 W, maintaining functionality even during winter periods with low solar radiation (0.8–1.0 PSH/day). The hybrid configuration ensured up to 48 hours of energy autonomy and reliable operation under variable climatic conditions. Fish farming under a polyculture regime was also tested, representing an integrated biological mechanism for self-cleaning that enhances the overall sustainability of the aquaculture system. Results demonstrate that autonomous hybrid systems represent a viable solution for sustainable aquaculture, improving energy efficiency, reducing environmental impact, and supporting the viability of small-scale fish farms in remote regions.

REZUMAT

Această lucrare prezintă dezvoltarea experimentală și evaluarea unui sistem acvacol autonom alimentat de energie fotovoltaică, conceput pentru piscicultura la scară mică în zone izolate. Sistemul integrează generarea de energie regenerabilă, controlul automatizat și monitorizarea în timp real pentru a asigura autosuficiența energetică și sustenabilitatea mediului. Configurația experimentală, constând dintr-un câmp fotovoltaic de 6 kWp (15 panouri de câte 400 W fiecare), un banc de baterii de 24 de unități de 24 V și un generator diesel pentru backup de urgență, a fost testată la INMA București pe o perioadă de doi ani. Instalația furnizează energie subsistemelor esențiale de acvacultură, inclusiv recircularea apei, aerarea, hrănirea automată, iluminatul și supravegherea. Datele experimentale au arătat că sistemul fotovoltaic a satisfăcut integral cererea medie zilnică de energie de 3,35 kWh, cu vârfuri orare de aproximativ 255 W, menținând funcționalitatea chiar și în perioadele de iarnă cu radiații solare scăzute (0,8–1,0 OSP/zi - Ore Standard de Soare). Configurația hibridă a asigurat o autonomie energetică de până la 48 de ore și o funcționare fiabilă în condiții climatice variabile. A fost testată și piscicultura în regim de policultură, aceasta reprezentând un mecanism biologic integrat de auto-curățare ce sporește sustenabilitatea generală a sistemului de acvacultură. Rezultatele au arătat că sistemele hibride autonome reprezintă o soluție viabilă pentru acvacultura durabilă, îmbunătățind eficiența energetică, reducând impactul asupra mediului și sprijinind viabilitatea fermelor piscicole la scară mică în regiunile îndepărtate.

INTRODUCTION

The aquaculture sector has undergone a rapid growth, driven by the increasing demand for seafood and the need to alleviate pressure on wild fisheries. Small-scale fish farming, especially in rural and peri-urban regions, contributes significantly to local food security and socioeconomic advancement. Nevertheless, these practices frequently encounter many challenges, including constrained access to technology, labor deficits, and exposure to environmental variability, which can undermine both productivity and sustainability (*Kumar et al., 1992; Oncescu et al., 2024*).

Recent approaches to sustainable aquaculture underscore the importance of examining the ecological impacts of farming practices, as rapid expansion has raised concerns due to diverse ecological consequences (*Helfrich et al., 2017; Ciobotaru et al., 2013; Miljodirektoratet, 2012*). A primary challenge in effective aquaculture operations lies in the substantial energy requirements for routine activities and management, coupled with deficiencies in effluent treatment (*Dorji et al., 2022; Biriş et al., 2022; Nenciu et al., 2023*). To alleviate these environmental burdens, potential solutions encompass relocating facilities from vulnerable areas or adopting enclosed systems. Many pollution problems associated with aquaculture can be addressed when using enclosed designs, however such systems generally demand considerably higher energy consumption (*Stan et al., 2022; Zhang et al., 2023; Popescu et al., 2022*).

Polyculture systems raise fish by integrating multiple complementary species in shared environments, offering key advantages for energy management and environmental sustainability. This approach facilitates efficient nutrient recycling, where waste from one species serves as feed for another, thereby reducing energy demands associated with feed production, water treatment, and waste disposal. Integrated multi-trophic aquaculture (IMTA) achieves lower feed conversion ratios and closed-loop efficiency (*Alleway et al., 2019; Nenciu et al., 2014*). Polyculture mitigates pollution through bioremediation, decreasing nutrient effluents that lead to eutrophication while enhancing water quality, biodiversity, and ecosystem resilience against stressors like climate change (*Can, et al., 2023*). Furthermore, these systems promote carbon sequestration and lower greenhouse gas emissions compared to monoculture, supporting broader sustainability goals in regions facing resource constraints (*Manioudis et al., 2022*).

Integration of autonomous and remote-controlled systems into aquaculture offers a viable strategy for addressing operational challenges (*Zhang et al., 2023*). Recirculating Aquaculture Systems (RAS), support continuous fish production across all seasons, with limited water consumption and lessened ecological footprint (*Zhang et al., 2023; Nenciu et al., 2020; Wang et al., 2024*). These systems incorporate cutting-edge filtration and monitoring tools to sustain high water quality while minimizing reliance on manual labor. Adopting these technologies in small-scale fish farming can lead to significant improvements in productivity. For example, precision feeding systems that utilize computer vision and Internet of Things (IoT) have demonstrated the potential to increase production by up to 58 times compared to traditional methods (*Hossam et al., 2024; Bujas et al., 2022*). Moreover, the integration of renewable energy sources and advanced water treatment processes can further enhance the economic and environmental performance of these systems (*Badiola et al., 2018; García-Jiménez et al., 2024; Nguyen et al., 2021*). Although sustainability assessments are documented in literature (*Fiorella et al., 2021; Klinger et al., 2012; Le Féon et al., 2021*), these inquiries predominantly address overarching sustainability paradigms, frequently addressing less the pivotal role of quantifying aggregate energy consumption within aquaculture systems.

Small-scale Photovoltaic (PV) integration with fish farms is an emerging field that has not been well addressed in research and implementation. Despite the clear potential for PV to drastically reduce the high energy costs (often 40% of total expenditure) associated with essential operations like aeration and pumping in aquaculture, current adoption is limited. Specialized knowledge and tailored technical models are needed to truly unlock the economic and sustainability benefits of this crucial synergy (*Ganesh et al., 2025; Imani et al., 2023*).

This research study focuses on the experimental development and evaluation of an autonomous polyculture aquaculture system tailored for small-scale fish farming. The research aims to assess the system's technical performance, reliability, and impact on productivity, with the goal of providing a viable model for sustainable and efficient fish farming practices. By integrating multiple complementary fish species in an automated setup, the system optimizes resource utilization, such as water and feed, while minimizing waste through natural nutrient cycling, thereby reducing environmental impacts and

operational costs. In addition, it enhances yield potential compared to traditional monoculture methods, as diverse species exploit different ecological niches, leading to improved overall productivity and resilience against diseases and pests. For small-scale farmers, this approach offers economic advantages through income diversification, stable revenue streams, and reduced reliance on external inputs like pesticides and fossil fuels, fostering long-term sustainability in rural and peri-urban settings.

MATERIALS AND METHODS

System Overview

The experimental study was carried out to assess the operational reliability and functional performance of an autonomous energy-powered aquaculture system, designed for fish rearing under a polyculture regime. The primary objective was to evaluate the technical efficiency of the system and the associated environmental benefits derived from its implementation. The designed system integrates renewable energy generation, automated control, and remote monitoring, ensuring the continuous maintenance of optimal water quality parameters and feeding conditions without the need for constant human intervention. In this way, the system minimizes operational costs, enhances energy efficiency, and significantly reduces the ecological footprint of aquaculture activities. Moreover, its autonomous operation contributes to sustainable fish production by promoting resource circularity and reducing dependency on conventional energy and labor-intensive practices. A schematic overview of the experimental design is presented in Figure 1.
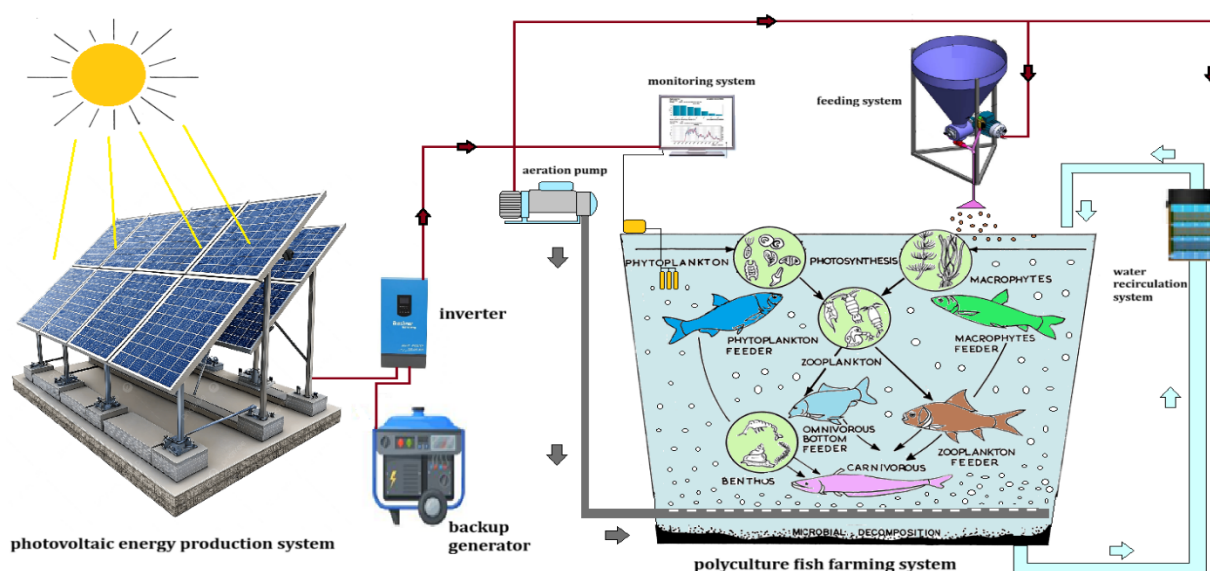

Fig. 1 - Schematic overview of an autonomous aquaculture system designed for isolated locations, intended for small-scale fish farms

Figure 1 illustrates the synergistic integration of the proposed design key components, namely the photovoltaic power generation apparatus, the auxiliary generator, and the polyculture aquaculture system. Emphasis is placed on the critical instrumentation for pond management (aeration pump, monitoring system, feeding system and water recirculation), as well as the pond's biotic processes, underscoring the foundational principles of Integrated Multi-Trophic Aquaculture (IMTA).

The experiments were conducted in the period 2022 - 2023 within INMA Bucharest institute, utilizing an outdoor pilot fishing pond, having a total capacity of 30,000 liters. The fishing pond, is a construction made of reinforced concrete with a thickness of 300 mm, a width of 14.4 m, a length of 57 m, and a depth of 4.6 m (Figure 2). The proposed experimental pond was designed to ensure optimal biological and energetic conditions for polyculture aquaculture under autonomous photovoltaic operation. Its controlled recirculating water system maintains uniform temperature, oxygenation, and nutrient distribution, enabling the coexistence of complementary fish species that occupy different ecological niches within the same volume of water.

Such stratified environmental conditions promote efficient resource use and nutrient cycling, essential for the stability of polyculture systems. At the same time, the integration of photovoltaic power generation is ideally suited to this configuration, as the energy demand of the pond—driven primarily by aeration, filtration, and feeding cycles—follows a predictable diurnal pattern that aligns with solar energy availability. The system's automation and energy storage further ensure continuous operation during low irradiance or nighttime, maximizing self-sufficiency. Consequently, the pond structure and management strategy jointly establish a closed-loop, energy-efficient, and environmentally sustainable model for modern polyculture aquaculture in remote or off-grid regions.
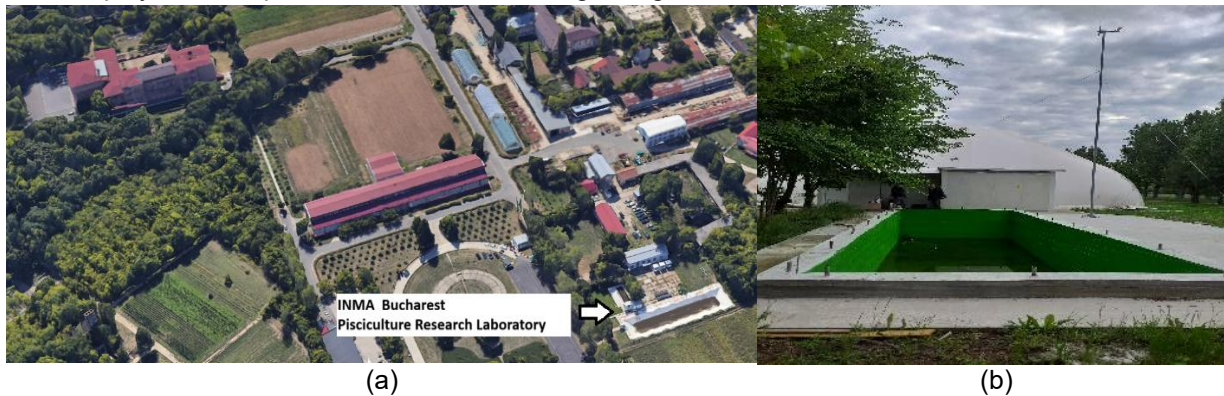

| (a) | (b) |

Fig. 2 - Fish farming experimentation infrastructure used in the experimentation
(a) INMA Bucharest Fish Farming Research Laboratory; (b) Reinforced concrete pond for fish farming

This hybrid energy production framework is composed by a photovoltaic array, a diesel generator, and a lithium-ion battery array. The photovoltaic system is designated to fulfill the main energy demands, while periods of diminished output are supplemented by the battery storage system. The diesel generator (Kamrad K-3500A, 7.5CP) is reserved solely for emergencies, including instances where battery reserves prove inadequate to sustain load requirements or during unforeseen rising in energy consumption. The primary objectives were to (1) evaluate the operational stability of the PV-powered system under varying climatic conditions, (2) assess the capability of the automation system to maintain optimal aquaculture parameters, and (3) determine the overall energy efficiency and fish growth performance achieved within the system. Therefore, the approach aimed to maximize the utilization of renewable energy sources, considering local climatic conditions, while minimizing dependence on fossil-derived power. In addition to reducing environmental impact, the design emphasizes the prolongation of battery life, recognizing that such durability is pivotal to the system's economic feasibility and operational resilience.

The power supply unit consisted of a photovoltaic array of 6 kWp (15 panels of 400 W each, Longi LR5-54HIH-410M), connected to a charge controller and 24 V deep-cycle battery bank, designed to ensure continuous energy availability for at least 48 hours without sunlight (Fig. 3 a and b). The electrical consumers associated with the experimental pond included a series of essential devices required for maintaining optimal environmental and operational conditions: an organic mechanical filtration system for pond water purification (Fig. 3-c);
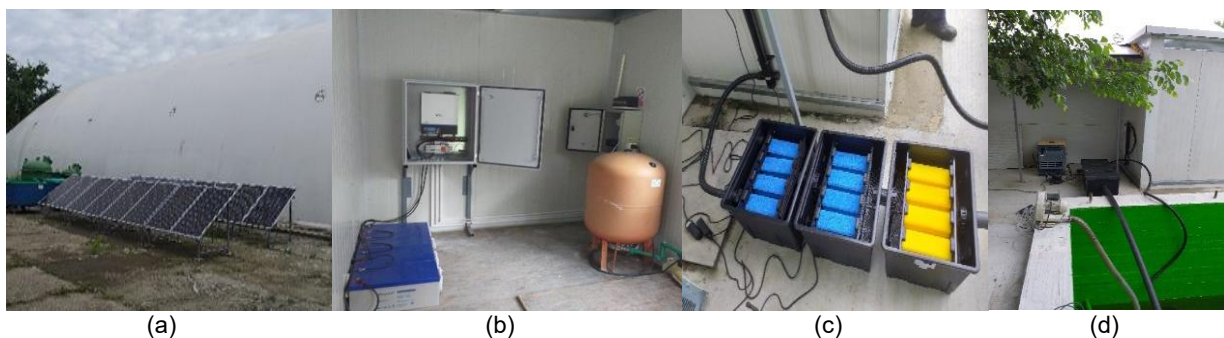

| (a) | (b) | (c) | (d) |

Fig. 3 - Renewable energy production system
(a) - illustration of photovoltaic panels; (b) - inverter and batteries; (c) - filtration system; (d) - aeration and UV treatment;

Osaga ORV aeration unit, responsible for maintaining dissolved oxygen levels in the water and a recirculation pump ensuring continuous water movement and oxygen distribution (Fig. 3-d). Furthermore, the system powers an array of monitoring and control components, such as environmental sensors, a programmable logic controller (PLC), and a data logger, all integrated into a data visualization and processing interface. Additional subsystems include an automatic fish feeding mechanism, a lighting module for operational visibility, and a video surveillance unit for remote observation and security.

Figure 4 documents the stocking process of the experimental pond showing juvenile specimens of the fish species incorporated within the polyculture framework. The Common Carp (*Cyprinus carpio*), a bottom-dwelling and detritivorous species, represents approximately 45% of the stock. The Asian Carp (*Hypophthalmichthys spp.*), a filter-feeding herbivore, accounted for 25%, and the Crucian Carp (*Carassius carassius*), an omnivorous species occupying the middle/surface water layer, makes up 20%. To complete the trophic cycle and optimize the ecosystem, the addition of Roach (*Rutilus rutilus*), a surface-dwelling omnivorous species, was also introduced at a proportion of 10%. This structure ensures the occupation of all water levels, trophic diversity, and sustainable growth of fish production. An aggregate of 200 kg of total juvenile fish was introduced into the pond, for testing the deployment of the multi-species cultivation strategy.

Fig. 4 - The stocking process of the experimental pond with juvenile specimens of the fish varieties

RESULTS

Based on measurements collected from our on-site meteorological station and pyranometer instrumentation, monthly averages of daily solar irradiance for Bucharest have been plotted (Fig. 5). The mean daily solar irradiance attains its zenith during the summer months (July–August), in marked contrast to the winter period (December–January), when the lowest values are recorded. Annually, the average yield of solar radiation achieves 56% of the theoretical installed capacity, reflecting the system's overall performance under varying seasonal conditions.
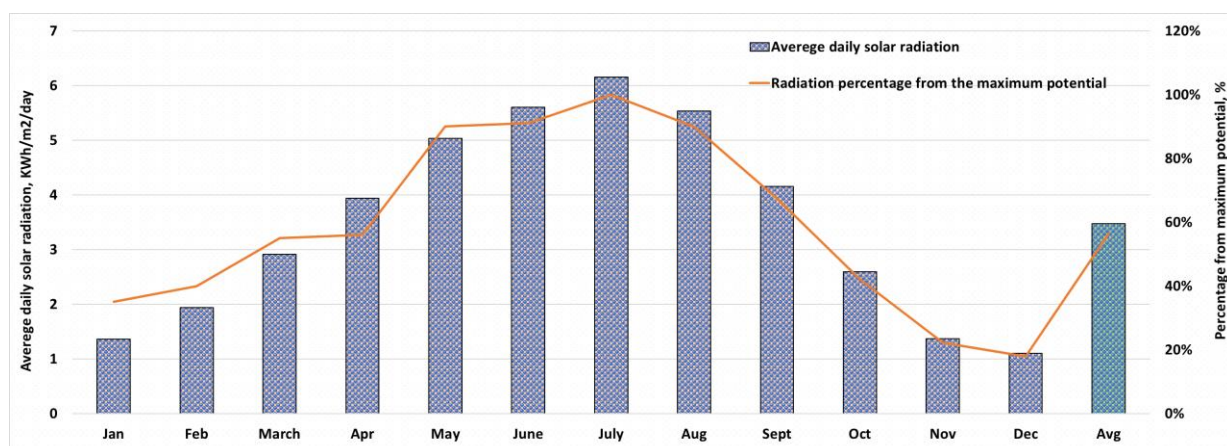

Fig. 5 - Monthly averages of the daily radiation levels for Bucharest, year 2022

Other evaluated data that influence photovoltaic energy production were: monthly average sunny hours and days for Bucharest (Fig. 6), monthly average cloud cover and air humidity (Fig. 7).
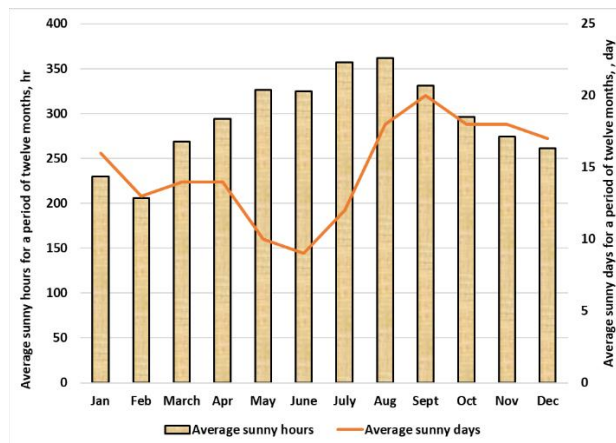
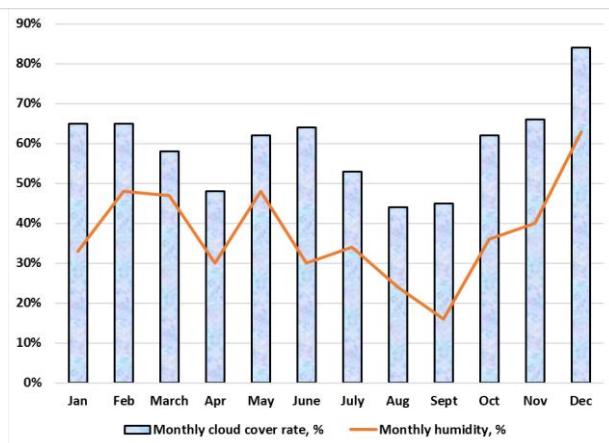**Fig. 6 - Monthly average sunny hours and days for Bucharest, Romania**

Fig. 7 - Monthly average cloud cover and air humidity for Bucharest, Romania

The graphics show the meteorological conditions that directly impinge upon photovoltaic energy production, delineating the average hours and days of sunshine across the annual cycle. The data is pivotal in substantiating the system's architectural rationale, particularly with regard to the sizing of the battery bank requisite for maintaining energy autonomy amid intervals of diminished solar irradiance. The high degree of cloud cover, especially in the winter months, confirms the need for an installed photovoltaic capacity that provides a safety margin to compensate for the reduced production.

Figure 8 evaluates the annual fluctuations in mean minimum and maximum temperatures. Such data is important on one hand for optimizing the photovoltaic system's operational efficiency (given that elevated temperatures can affect solar panel performance), and on the other hand for projecting the aquaculture pond demands, as water temperature directly modulates fish metabolic processes and the requisite aeration levels. Figure 9 describes the pluviometry regime, detailing the distribution of precipitation quantities and the frequency of rainy days throughout the year. Such meteorological factors exert a direct influence on solar energy production, primarily through augmented cloud cover that diminishes irradiance.
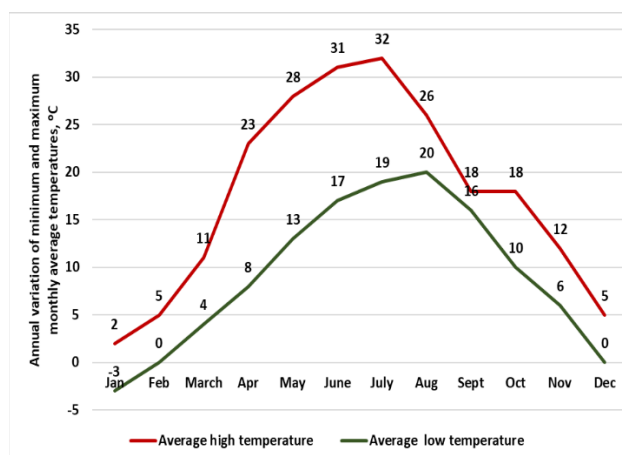

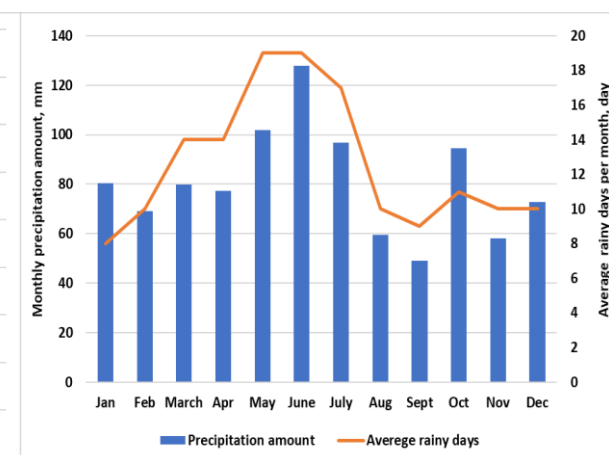**Fig. 8 - Annual variation of minimum and maximum monthly average temperatures**

Fig. 9 - Monthly average cloud cover and air humidity for Bucharest, Romania

Figure 10 shows the average daily energy generation from the photovoltaic system across an annual cycle, revealing a direct correlation with solar irradiance. Production peaks in July and reaches its lower values in December. Figure 11 further illustrates the monthly total energy output, with the maximum recorded also in July, underscoring the system's substantial capacity for energy storage and rapid battery bank recharging during the warm season.
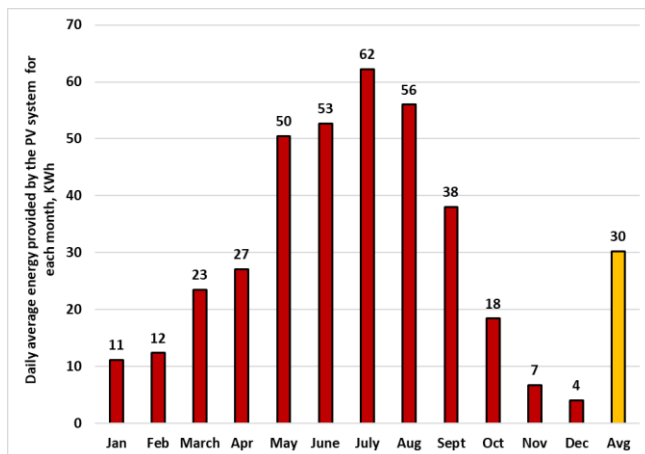
Fig. 10 – Daily average energy provided by the PV system for each month
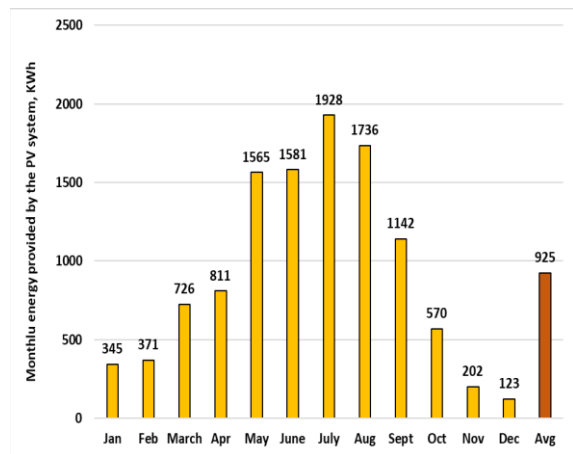

Fig. 11 - Monthly energy provided by the photovoltaic system

Figure 12 illustrates the hourly energy consumption profile, attributable to the aquaculture subsystem. The mean daily energy demand registers at 3.35 kWh, punctuated by peak hourly loads approximating 255 W. Such a consumption paradigm substantiates the rationale underpinning the system's engineering specifications (encompassing a 6 kWp photovoltaic array and 24 battery units), thereby ensuring sustained operational integrity amidst these transient load exigencies.

System	Equipment	Equipment nominal power		Operation hours of the working equipment in one day of functioning (24 h)																									Total daily energy	
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
Water filtration, sanitation and recirculation system in the pond	Water recirculation pump / Organic mechanical filter for ponds	140	W							140					140						140							420	Wh
	UV-C sterilizer	75	W							75					75						75							225	Wh
Pond water aeration system	Aerator for fish ponds	100	W	100	100	100					100	100	100				100	100	100	100			100	100	100	100		1400	Wh
Monitoring and control system	Sensors, PLC, data logger	15	W	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	360	Wh
	Display and data processing system	120	W										120	120														240	Wh
Automatic fish feeding system	Automatic fish feeding eaquiment	7	W							7						7					7				7			28	Wh
Auxiliary systems (lighting and surveillance)	Lighting system	20	W	20	20	20	20	20	20															20	20	20	20	200	Wh
	Surveillance system	20	W	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	480	Wh
Hourly energy consumed				155	155	155	55	55	55	250	142	135	255	155	250	42	135	135	135	250	42	35	155	155	162	155		3353	Wh

Fig. 12 - Power consumption model for the autonomous pond management systems

The selection of 15 photovoltaic panels and 24 batteries for storage is justified by a conservative approach to the winter energy balance, considering the hourly energy consumption profile presented in the table (3.35 kWh/day and hourly peaks up to approximately 255 W). The total installed capacity of 6.0 kWp provides a necessary safety margin for operation during periods of very low solar irradiation, with peak-sun-hours reduced to only 0.8–1.0 h/day, which is a common scenario in Romania. The expected daily energy production accounts for combined losses due to dust or snow coverage, temperature effects, inverter efficiency, and energy storage losses.

Using a conservative efficiency factor, a 6 kWp photovoltaic array can generate approximately 3.1–4.2 kWh/day in winter conditions, which is sufficient to cover the recorded average daily consumption (3.35 kWh) even under cloudy skies or partial snow coverage. The additional capacity provided by the panels ensures compensation for instantaneous variability in solar input and allows rapid energy recovery during short sunny intervals. In addition, the configuration of 24 batteries is technically justified by the need for modularity, reliability, and flexible series–parallel arrangements to achieve the optimal system voltage.
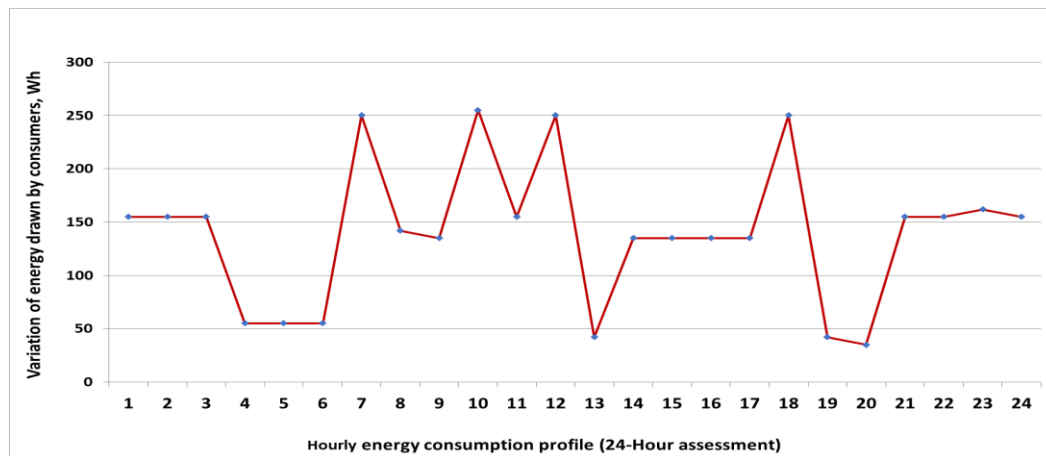

Fig. 13 - Hourly energy consumption profile for the designed photovoltaic system

This architecture provides clear advantages: allows for a flattening of consumption peaks according to needs (as can be seen in figure 9), can reduce current intensity due to higher operating voltage, minimize current losses, allows more uniform cycling of the batteries, which enhances service life. The integration of a diesel generator into the autonomous energy system is justified as a critical an element designed exclusively for emergency operation. Its role becomes essential in circumstances where the stored energy within the battery bank is insufficient to sustain the hourly load demand. From a systems-engineering perspective, the diesel generator functions as an auxiliary stabilizing component within a hybrid microgrid architecture, ensuring continuity of supply under extreme operational conditions. Its activation threshold is determined by the monitoring and control subsystem, which continuously assesses the state of charge (SoC) of the battery bank and the instantaneous load demand.

Trophic Structure Synergy in Polyculture: Integrated Biological Self-Cleaning Mechanisms

Populating the pond with complementary species generated a balanced trophic structure, functioning as an integrated biological self-cleaning mechanism. This facilitated the natural recycling of nutrients, the reduction of sediments, and the maintenance of water quality without complex treatments. The interaction between the phytophagous, detritivorous, and omnivorous species led to a significant decrease in dissolved ammonium and nitrate concentrations, estimated at between 25–40% compared to a comparable monoculture system, owing to the direct absorption of nitrogenous compounds resulting from fish metabolism. Furthermore, the natural processes of biofiltration and controlled sedimentation resulted in an approximate 30% reduction in suspended solids and a 15–20% increase in water transparency. This contributed to the stabilization of dissolved oxygen and pH values within optimal ranges for species development. By utilizing residual nutrients and organic particles as a trophic resource for the lower-level species in the food chain, a 10–15% decrease in the total quantity of feed administered was observed, without affecting the growth rate of the primary fish. The direct consequence of these processes was a 35–45% reduction in the organic load of the effluents, lowering the risk of eutrophication and the impact on adjacent aquatic ecosystems.

A summary of the identified advantages regarding the proposed experimental design on the fish sustainability is listed in Table 1.

Table 1

Key advantages of an autonomous energy system in polyculture aquaculture

Advantage Category	Specific Mechanism/Benefit	Impact on Small-Scale Farmer Viability	Supporting Evidence
Technical Reliability & Automation	Predictive water quality control via automation /sensors	Reduces labor requirement and prevents high stock loss from sudden environmental shifts (e.g., pH/Oxygen spikes, food administration).	Increased system uptime and reduced operational risk.
Ecological Efficiency	Maximized nutrient cycling (according to IMTA principles)	Converts unused feed, residues and feces into valuable biomass, lowering pollution output and reducing the need for external fertilizers.	Lower environmental footprint and significant cost savings on inputs.
Productivity & Yield	Niche complementarity	Higher overall biological output compared to monoculture on the same area by effectively utilizing all trophic levels and resources (sunlight, feed, water column).	Increased revenue potential per unit of farm area.
Health & Resilience	Enhanced ecosystem biodiversity	Reduces vulnerability to widespread losses from disease, pests, and pathogens, promoting healthier stock with higher survival rates.	Stabilized production and reduced reliance on costly chemicals/antibiotics.
Economic Sustainability	Income diversification and input cost reduction	Creates multiple stable revenue streams, buffering against single-market fluctuations, and minimizes reliance on expensive fossil fuels and synthetic chemicals.	Improved long-term financial stability and lower operating expenses.

The implementation of an autonomous photovoltaic energy system in polyculture aquaculture provides significant technical, ecological, and economic advantages. From a technical perspective, automation and predictive control of water quality parameters through sensors and artificial intelligence substantially reduce labor requirements and operational risks, ensuring continuous system uptime. Ecologically, the integration of renewable energy and the application of Integrated Multi-Trophic Aquaculture (IMTA) principles enhance nutrient recycling efficiency, converting organic waste into valuable biomass and minimizing pollutant discharge. This contributes to a lower environmental footprint and improved resource utilization. Productivity is further increased through species complementarity, which maximizes the use of available ecological niches and results in higher overall biological output compared to monoculture systems. Additionally, the diversification of cultured species strengthens ecosystem resilience, improving fish health and resistance to disease. Economically, reduced dependency on fossil fuels and external inputs leads to lower operational costs and more stable revenue streams, supporting the long-term sustainability and viability of small-scale fish farms operating in remote or resource-constrained environments.

CONCLUSIONS

The combined system of 15 photovoltaic panels (6 kWp) and 24 batteries rated at 24 V ensures an optimal balance between generation and storage, capable of sustaining the hourly consumption pattern indicated in the table during winter operation. This configuration guarantees sufficient energy reserves to offset production losses due to cloudiness or snow accumulation, maintaining the operational autonomy and functional stability of the autonomous aquaculture energy system under adverse seasonal conditions. Consequently, the system affords ample energy reserves to mitigate production deficits attributable to cloud cover or snow accretion on panels. Such provisions preserve operational autonomy and functional stability within the autonomous aquaculture framework under adverse seasonal regimes.

The findings also underscore the viability of autonomous hybrid systems as a sustainable option for aquaculture, enhancing energy efficiency, ameliorating environmental footprints, and bolstering the economic feasibility of small-scale pisciculture enterprises in remote locales.

Center for Soil Health and Food Safety, Specific Project P1: Soil health and food safety by introducing a soil remediation protocol and developing a mobile remediation equipment to reduce the concentration of organic/inorganic pollutants.

REFERENCES

[1] Alleway, H. K., Gillies, C. L., Bishop, M. J., Gentry, R. R., Theuerkauf, S. J., & Jones, R. (2019). The ecosystem services of marine aquaculture: Valuing benefits to people and nature. *BioScience*, 69(1), 59–68. https://doi.org/10.1093/biosci/biy137

[2] Badiola, M., Basurko, O. C., Piedrahita, R., Hundley, P., & Mendiola, D. (2018). Energy use in recirculating aquaculture systems (RAS): A review. *Aquacultural Engineering*, 81, 57–70. https://doi.org/10.1016/j.aquaeng.2018.03.003

[3] Biriș S.Șt., Constantin A.M., Anghelache D., Găgeanu I., Cujbescu D., Nenciu F., Voicea I., Matei Gh., Popa D., Duțu M.F., Ungureanu N., Zelazinski T., Perișoară L., Fodorean G. (2022). Considerations regarding the vibrations transmitted to the operator by an axial flow harvester combine. *INMATEH – Agricultural Engineering*, Vol.68(3), pp.747–756. DOI: https://doi.org/10.35633/inmateh-68-74.

[4] Bujas, T., Koričan, M., Vukić, M., Soldo, V., Vladimir, N., & Fan, A. (2022). Review of energy consumption by the fish farming and processing industry in Croatia and the potential for zero-emissions aquaculture. *Energies*, 15(21), Article 8197. https://doi.org/10.3390/en15218197

[5] Can, E., & Seyhaneyildiz Can, Ş. (2023). Species combinations; polyculture, integrated multi-trophic aquaculture, and aquaponics as the sustainable aquaculture practice. *Aquatic Animal Reports*, 1(1), 27–33. https://doi.org/10.5281/zenodo.7660399

[6] Ciobotaru, I.E., Nenciu, F., Vaireanu, D.I. (2013). The electrochemical generation of ozone using an autonomous photovoltaic system. *Revista de Chimie*, 64(11).

[7] Dorji, N., & Dorji, T. (2022). Productivity improvement to sustain small-scale fish farming: Evidence from Bhutan. *Aquaculture Economics & Management*, 26(1), 1-18. https://doi.org/10.1080/13657305.2022.2047752

[8] Fiorella, K.J., Okronipa, H., Baker, K., Heilpern, S. (2021). Contemporary Aquaculture: Implications for Human Nutrition. *Curr. Opin. Biotechnol*. 70, 83–90. https://doi.org/10.1016/j.copbio.2020.11.014

[9] Ganesh, G., Raveendar, B., Jarupala, L., Nischal, L., Sai Krishna, K., & Ramesh, P. (2025). Composite fish farming: An economic move for rural empowerment and generating livelihood security. *Journal of Scientific Research and Reports, 31*(7), 1067-1082. https://doi.org/10.9734/jsrr/2025/v31i73322

[10] García-Jiménez, A., Rqiq, Y., Ballestín, V. (2024). Integration Assessment of Renewable Energy Sources (RESs) and Hydrogen Technologies in Fish Farms: A Techno-Economical Model Dispatch for an Estonian Fish Farm. *Sustainability*, *16*(17), 7453. https://doi.org/10.3390/su16177453

[11] Helfrich, L. A. (2003). *Fish farming in recirculating aquaculture systems (RAS)*. Virginia Cooperative Extension. Retrieved from https://www.pubs.ext.vt.edu

[12] Hossam, R., Heakl, A., Gomaa, W. (2024). Precision aquaculture: An integrated computer vision and IoT approach for optimized tilapia feeding. arXiv. https://doi.org/10.48550/arXiv.2409.08695

[13] Imani, M., Fakour, H., Lo, S.-L., Yuan, M.-H., Chen, C.-K., Mobasser, S., & Muangthai, I. (2023). Aquavoltaics feasibility assessment: Synergies of solar PV power generation and aquaculture production. *Water, 15*(5), 987. https://doi.org/10.3390/w15050987

[14] Klinger, D.; Naylor, R. (2012). Searching for Solutions in Aquaculture: Charting a Sustainable Course. *Annu. Rev. Environ. Resour*. 37, 247–276. https://doi.org/10.1146/annurev-environ-021111-161531

[15] Kumar, D. (1992). Fish culture in undrainable ponds: A manual for extension (FAO Fisheries Technical Paper No. 325). *Food and Agriculture Organization of the United Nations*. https://www.fao.org/4/t0555e/T0555E00.htm

[16] Le Féon, S., Dubois, T., Jaeger, C., Wilfart, A., Akkal-Corfini, N.; Bacenetti, J., Costantini, M., Aubin, J. 2021). Dexiaqua, a Model to Assess the Sustainability of Aquaculture Systems: Methodological Development and Application to a French Salmon Farm. *Sustainability* (13, 7779. https://doi.org/10.3390/su13147779

[17] Manioudis, M., & Meramveliotakis, G. (2022). Broad strokes towards a grand theory in the analysis of sustainable development: A return to the classical political economy. *New Political Economy*, 27(5), 866–878. https://doi.org/10.1080/13563467.2022.2038114

[18] Nenciu, F., Fatu, V., Arsenoaia, V., Persu, C., Voicea, I., Vladut, N.-V., Matache, M. G., Gageanu, I., Marin, E., Biris, S.-S., Ungureanu, N. (2023). Bioactive Compounds Extraction Using a Hybrid Ultrasound and High-Pressure Technology for Sustainable Farming Systems. Agriculture, 13(4), 899. DOI: https://doi.org/10.3390/agriculture13040899.

[19] Nenciu, F., Vaireanu, D.I. (2014). A versatile system for indoor monitoring of some volatile organic compounds. *Journal of Chemistry*, 65(5).

[20] Nenciu, F., Voicea, I., Stefan, V., Nae, G., Matache, M., Milian, G., & Arsenoaia, V.-N. (2020). Experimental research on a feed pelletizing equipment designed for small and medium-sized fish farms. *INMATEH - Agricultural Engineering*, 67(2). DOI: https://doi.org/10.35633/inmateh-67-38

[21] Nguyen, N. T., Matsuhashi, R., & Vo, T. T. B. C. (2021). A design on sustainable hybrid energy systems by multi-objective optimization for aquaculture industry. *Renewable Energy*, 163, 1878–1894. https://doi.org/10.1016/j.renene.2020.10.024

[22] Oncescu, T.-A., Persu, I. C., Bostina, S., Biris, S. S., Vilceleanu, M.-V., Nenciu, F., Matache, M.-G., Tarnita, D. (2025). Comparative Analysis of Vibration Impact on Operator Safety for Diesel and Electric Agricultural Tractors. *AgriEngineering*, 7(2). DOI: https://doi.org/10.3390/agriengineering7020040.

[23] Oprescu, M. R., Biris, S.-S., Nenciu, F. (2023). Novel furrow diking equipment-design aimed at increasing water consumption efficiency in vineyards. *Sustainability*, 15(4). 2861. DOI: https://doi.org/10.3390/su15042861

[24] Popescu E., Nenciu F., Vlădut V. (2022). A new strategic approach used for the regeneration of soil fertility, in order to improve the productivity in ecological systems, *Scientific Papers. Series E. Land Reclamation, Earth Observation & Surveying, Environmental Engineering*. Vol. XI, 2022, pp. 277-284.

[25] Stan C., Nenciu, F., Muscalu, A., Vlăduț, V. N., Burnichi, F., Popescu, C., Gatea, F., Boiu-Sicuia, O. A., & Israel-Roming, F. (2022). Chemical composition, antioxidant and antimicrobial effects of essential oils extracted from two new Ocimum basilicum L. varieties. *Diversity*, 14(12). DOI: https://doi.org/10.3390/d14121048.

[26] Zhang, R., & Zhang, X. (2023). Review Article: Systems approaches for sustainable fisheries. *Aquaculture Reports*, 25, 100803. https://doi.org/10.1016/j.aqrep.2023.100803

[27] Wang, R., Heakl, A., & Gomaa, W. (2024). Precision aquaculture: An integrated computer vision and IoT approach for optimized tilapia feeding. *arXiv preprint arXiv:2409.08695*. https://doi.org/10.48550/arXiv.2409.08695