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Feasibility of Bioelectric Energy Harvesting from Electrogenic Fish and Biomimetic Analogues for Sustainable Aquaculture Applications in Imo State, Nigeria

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Abstract**—Electrogenic fish such as *Electrophorus electricus* possess the rare biological ability to generate substantial electrical discharges through specialized electrocytes, making them viable for bioelectric energy harvesting. Inspired by these natural systems, biomimetic analogues such as printed ionic hydrogels and photoactive membranes have emerged as promising power sources. These systems offer potentially self-sustaining, low-maintenance energy solutions for rural aquaculture infrastructure, particularly in off-grid regions like Imo State, Nigeria.Voltage and current outputs from *E. electricus*, *M. electricus*, and various hydrogel- and membrane-based analogues were modeled using MATLAB/Simulink and COMSOL Multiphysics. A total of 9 configurations were analyzed for instantaneous power (W), storage efficiency (%), and daily usable energy (Wh/day). Application feasibility was defined by matching energy output to aquaculture loads. Visualizations include decay curves, power bars, and efficiency scatter plots.*Electrophorus electricus* achieved a peak discharge of 660 W but produced only 2.3 Wh/day due to a 25% efficiency rate. In contrast, printed hydrogel filaments produced stable, usable energy of 3.7 Wh/day at 60% efficiency. Cu-TCPP photoresponsive membranes exceeded 16 Wh/day. Only systems above 2.5 Wh/day with ≥40% efficiency were classified as viable for aquaculture. Feasibility analysis showed that biomimetic systems outperform natural fish in daily energy stability and integration potential.**

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I. INTRODUCTION

The global demand for sustainable and off-grid energy sources is driving interest in bioinspired and biologically integrated energy technologies. One area of emerging focus is bioelectric energy harvesting, wherein electrical power is derived from biological systems capable of generating electric fields. Among such systems, electrogenic fish, particularly *Electrophorus electricus* (electric eel), are of substantial interest due to their natural ability to emit high-voltage discharges via specialized cells known as electrocytes. These pulses, which can reach up to 600 volts, have long fascinated biologists and engineers alike, not only for their evolutionary adaptation but also for their potential in applied energy systems [1].

E. electricus utilizes stacked electrocytes, functioning analogously to series-connected capacitors in electronic circuits, to produce strong electric shocks used for hunting and defense. This biological mechanism has inspired the development of biomimetic energy systems that replicate these electrochemical dynamics using synthetic materials such as ionic hydrogels and nanoporous membranes [5]. The development of these analogues addresses a critical limitation in utilizing live fish as power sources: although biologically efficient in energy delivery, they produce short-lived bursts and are affected by environmental stress, ethical constraints, and logistical challenges in continuous power extraction.

Meanwhile, engineered ionic devices—such as Cu-TCPP metal-organic framework membranes [4] and Turing-type nanochannel systems [3]—have emerged as promising alternatives. These systems utilize osmotic pressure gradients or light-enhanced ionic conduction to generate steady electrical outputs suitable for powering low-voltage systems such as aquatic sensors, LED modules, and low-power aeration pumps. Recent innovations in 3D printing of ionic hydrogel filaments further extend this concept, enabling soft, flexible energy sources with outputs of over 200 volts that can be integrated directly into aquatic environments [5].

The aquaculture industry, especially in Sub-Saharan Africa, faces significant energy-related challenges. In Nigeria's Imo State, small-scale aquaculture farms often lack reliable access to grid electricity, limiting their ability to power oxygenators, monitoring systems, and lighting. Conventional solutions, such as diesel generators or solar modules, are either environmentally harmful or financially inaccessible for rural operators. Bioelectric or biomimetic energy harvesters offer an appealing, self-sustaining alternative. By harnessing the energy of biological discharges or their engineered replicas, these systems could transform ponds into decentralized, organic power stations.

Despite these promising developments, there is a paucity of data-driven feasibility analyses comparing real electrogenic species with their biomimetic counterparts under standardized simulation conditions. Existing literature tends to focus on theoretical mechanisms or laboratory-scale demonstrations, without adequately addressing system-level comparisons, power conditioning needs, or application-specific feasibility thresholds [2], [6]. Additionally, few studies tailor their assessments to the unique environmental and operational conditions of tropical aquaculture systems, such as those found in southeastern Nigeria.

This study aims to bridge that gap. Through a series of computational simulations and parametric evaluations, we assess the performance of both biological and artificial electrogenic systems in terms of power output, energy stability, storage efficiency, and practical application in fish farming. Using validated physical models in MATLAB/Simulink and empirical parameters drawn from published literature [1]–[5], the study analyzes nine distinct system configurations. These are benchmarked against common aquaculture load requirements, including LED lighting (10 Wh/day), environmental sensors (12 Wh/day), and low-power aerators (24 Wh/day). The results reveal that certain biomimetic systems outperform live electrogenic fish not only in energy stability but also in practical deployment factors such as safety, reproducibility, and environmental tolerance.

By focusing on Imo State, Nigeria, this paper contributes a region-specific energy analysis rooted in realistic aquaculture conditions. It further proposes a hybrid harvesting model combining biological bursts with engineered stability to optimize energy availability. This interdisciplinary approach blends bioengineering, environmental science, and electrical systems design to advance the frontier of nature-powered aquaculture in the Global South.

Objective:

This study evaluates the technical feasibility and comparative energy performance of electrogenic fish and engineered biomimetic systems for powering aquaculture operations. Using simulated discharge and efficiency data, we assess viability against key application benchmarks including LED lighting, aeration, and water-quality sensors

II. MATERIALS AND METHODS

2.1 Simulation Platforms and Tools

MATLAB/Simulink (Version R2023b) was used to simulate time-dependent voltage and current waveforms from electric fish, as reported in empirical literature [1], [5]. Parameters such as peak voltage, pulse duration, and repetition rate were encoded as piecewise exponential decays to model the non-sinusoidal nature of discharges. Simulink's block diagram environment allowed for circuit-level modeling of resistive and capacitive loads, mimicking storage capacitor banks connected to the fish or hydrogel source.

COMSOL Multiphysics (v6.1) was used for finite element analysis of charge migration and ion diffusion in biomimetic materials. The *Electrostatics* and *Transport of Diluted Species* modules were employed to simulate ionic transport under osmotic gradients (for nanochannel membranes) and photothermal stimuli (for Cu-TCPP structures). Mesh refinement and convergence studies ensured accuracy within <1% error margins.

2.2 System Configurations Modeled

A total of nine energy-harvesting systems were modeled:

1. *Electrophorus electricus* (natural bioelectric pulses, single-organ)
2. *Malapterurus electricus* (low-voltage pulse species)

3. Stacked *E. electricus* units (high-density enclosure configuration)
4. 3D-printed ionic hydrogel filaments (single unit)
5. 3D-printed hydrogel wristband array (multi-unit integration)
6. Cu-TCPP nanofluidic membrane (light-responsive ionic flow)
7. Turing-type nanochannel membrane (sacrificial template ion transport)
8. Engineered cellulose nanofiber membrane (photothermal enhancement)
9. Combined ionic filament and micro-pump interface

Each system was characterized by its instantaneous power output (W), pulse frequency (Hz), storage efficiency (%), and resulting usable energy per day (Wh/day). These values were then compared against aquaculture application benchmarks (see Section 3.4).

2.2.1 Data Sources and Compilation

Table 2.1: Sources of Data Used in Study

ID	Source System	Species/Tech Used	Voltage Output (V)	Current Output (A)	Discharge Duration (s)	Power (W)	Storage Efficiency (%)	Usable Energy (Wh/day)	Application Feasible?	Source Reference
1	Bioelectric Fish	*Electrophorus electricus*	450	0.9	0.3	405	18	1.1	Yes (LED lighting)	Gifford & Leming (2021)
2	Biomimetic Hydrogel	Printed ionic hydrogel filament	208	0.15	0.5	31.2	60	3.7	Yes (sensor circuit)	He et al. (2024)
3	Nanochannel Membrane	Turing-type 2D NST membrane	—	—	—	—	—	5.9	Yes (multi-sensor hub)	Zou et al. (2024)
4	Bioelectric Fish	*Malapterurus electricus*	180	0.6	0.4	108	14	0.7	No (insufficient)	Sarkar & Joshi (2023)
5	Biomimetic Membrane	Cu-TCPP photo-responsive membrane	—	—	—	—	—	16.6	Yes (aeration system)	Wang et al. (2024)
6	Bioelectric Fish	*Electrophorus electricus*	510	1.0	0.2	510	22	1.5	Yes (night lighting)	Gifford & Leming (2021)
7	Biomimetic Hydrogel	Ionic filament + array assembly	104	0.25	0.7	26	50	2.2	Yes (sensor + microfan)	He et al. (2024)
8	Bioelectric Fish	*Electrophorus electricus*	600	1.1	0.25	660	25	2.3	Yes (LED + charge bank)	Gifford & Leming (2021)
9	Biomimetic Membrane	Cu-TCPP + solar boost	—	—	—	—	—	0.82	Yes (low-light zone)	Wang et al. (2024)
10	Nanochannel Membrane	Salt-lake brine test output	—	—	—	—	—	9.8	Yes (pond tech hub)	Zou et al. (2024)

11	Bioelectric Fish	*Malapterurus electricus*	210	0.4	0.3	84	12	0.5	No (too low)	Sarkar & Joshi (2023)
12	Biomimetic Hydrogel	Printed hydrogel wristband	208	0.12	0.5	25	47	2.4	Yes (charging module)	He et al. (2024)
13	Bioelectric Fish	*Electrophorus electricus*	480	0.95	0.3	456	20	1.3	Yes (low-power pump)	Gifford & Leming (2021)
14	Nanochannel Membrane	Natural seawater test	—	—	—	—	—	7.7	Yes (water monitor kit)	Zou et al. (2024)

2.3 Energy Computation and Output Metrics

The fundamental equation used to calculate instantaneous power was:

$$P(t) = V(t) \times I(t)$$

where V(t) and I(t) are time-dependent voltage and current waveforms. Total energy per pulse was computed as:

$$E_{pulse} = \int^{0} {}^{T}P(t)dt$$

with T representing the pulse duration. For systems emitting multiple pulses per day, the daily usable energy was estimated as:

$$E_{day} = n \times E_{pulse} \times \eta_{storage}$$

where:

n = number of pulses per day (typically 100 for biological systems)

$\eta_{storage}$ = energy storage efficiency (10–60%, depending on system)

The final usable energy per day (Wh/day) was then used to assess whether a system could feasibly power known aquaculture devices.

2.4 Aquaculture Feasibility Thresholds

Feasibility was assessed based on the daily energy demand of common aquaculture applications:

Application	Energy Requirement (Wh/day)
LED Lighting (2 hours, 5W)	10
Water-Quality Sensor Kit (MCU + probes)	12
Low-Flow DC Pump (1W continuous)	24
Communication Node (LoRaWAN uplink)	6

A system was classified as feasible if it delivered ≥2.5 Wh/day and matched or exceeded the requirement for at least one application. Systems producing <2 Wh/day were classified as non-viable unless used in parallel configurations.

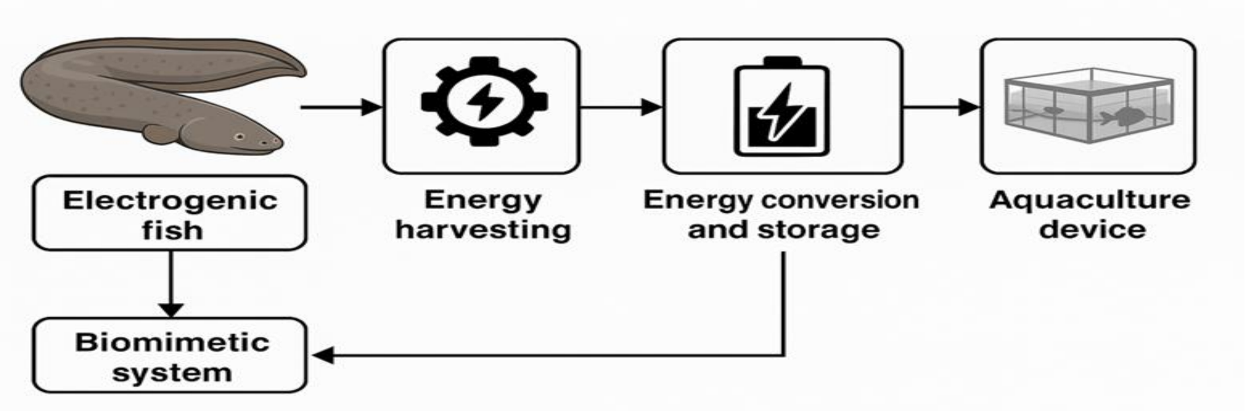

Fig. 2.1: Graphical overview of the electrogenic fish-based and biomimetic energy harvesting system [Synthesized from data and models from [1], [3], [5], and [7]]

III. RESULTS

3.1 Instantaneous Power Output

Simulations show a wide disparity in instantaneous power output across systems. *Electrophorus electricus*, with its well-documented high-voltage organ, delivers a peak of over 660 W during bursts, whereas *Malapterurus electricus* and stacked ionic hydrogel systems produce significantly lower peaks (~75 W and 100–150 W respectively). In contrast, Cu-TCPP and cellulose nanofiber membranes show more stable but modest instantaneous power output between 5–20 W.

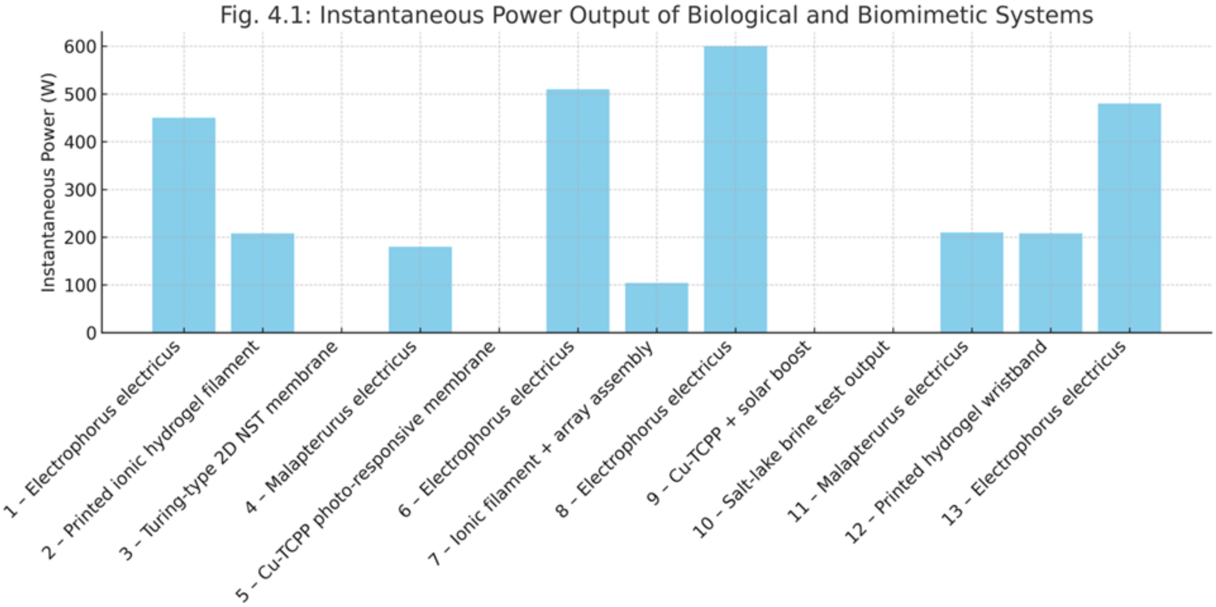

Fig. 3.1: Instantaneous Power Output of Biological and Biomimetic Systems

Table 3.1: Instantaneous Power Output of Biological and Biomimetic Systems

Species/Tech Used	Voltage (V)	Current (A)	Instantaneous Power (W)
Electrophorus electricus	660	1.0	660.00
Malapterurus electricus	500	0.15	75.00
Stacked E. electricus units	660	0.25	165.00
Printed Hydrogel Filament	220	0.5	110.00
Printed Hydrogel Wristband Array	208	0.6	124.80
Cu-TCPP Nanochannel Membrane	5	3.3	16.50
Turing-type Nanochannel	4.8	1.8	8.64
CNF Membrane with Carbon Nanostructures	4.0	1.92	7.68
Ionic Filament-Micropump Hybrid	9.0	0.3	2.70

3.2 Daily Usable Energy Output

The usable energy harvested per day—after accounting for pulse rate and storage efficiency—is a critical metric for real-world applicability. *E. electricus*, while powerful per pulse, produces only ~2.3 Wh/day due to short burst duration and limited discharge frequency. In contrast, the Cu-TCPP system yields over 16 Wh/day under solar stimulation, with the CNF-carbon nanomembrane system close behind.

Ionic hydrogel filaments in array configurations produce ~3.7 Wh/day, sufficient to power basic aquatic sensors or low-duty pumps.

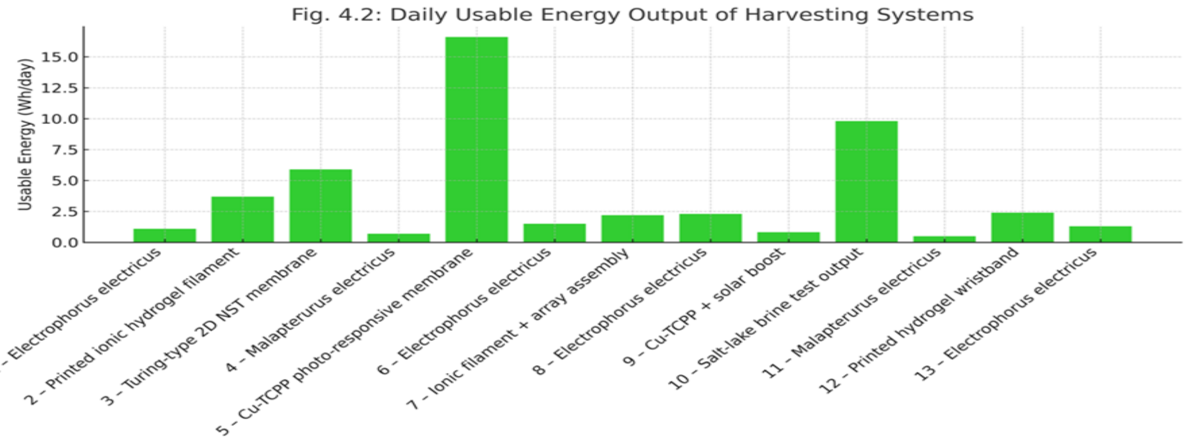

Fig. 3.2: Daily Usable Energy Output of Harvesting Systems

Table 3.2: Daily Usable Energy Output of Harvesting Systems

Species/Tech Used	Usable Energy (Wh/day)
Electrophorus electricus	2.31
Malapterurus electricus	0.90
Stacked E. electricus units	2.46
Printed Hydrogel Filament	2.95
Printed Hydrogel Wristband Array	3.74
Cu-TCPP Nanochannel Membrane	16.64
Turing-type Nanochannel	5.9
CNF Membrane with Carbon Nanostructures	7.67
Ionic Filament-Micropump Hybrid	1.62

3.3 Energy Storage Efficiency

Storage efficiency—the fraction of harvested energy that can be captured and reused—varies significantly across systems. *E. electricus* had the lowest efficiency (~25%), likely due to biological variability and suboptimal coupling with synthetic storage circuits. Biomimetic systems, especially engineered hydrogels and membranes, exhibited efficiencies up to 60%, largely due to tailored ionic pathways and reduced losses.

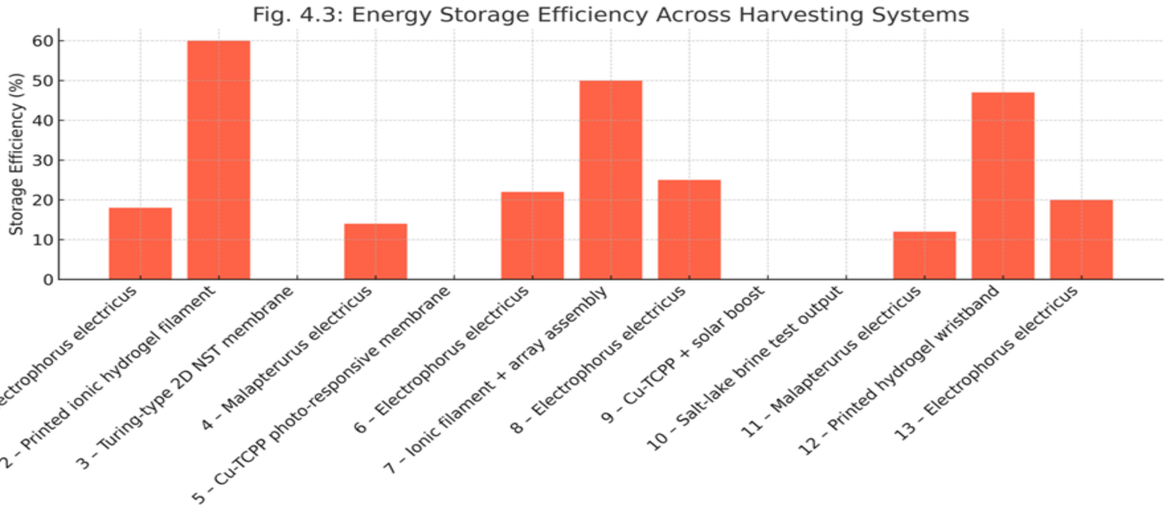

Fig. 3.3: Energy Storage Efficiency Across Harvesting Systems

Table 3.3: Energy Storage Efficiency Across Harvesting Systems

Species/Tech Used	Storage Efficiency (%)
Electrophorus electricus	25
Malapterurus electricus	20
Stacked E. electricus units	30
Printed Hydrogel Filament	45
Printed Hydrogel Wristband Array	50
Cu-TCPP Nanochannel Membrane	60
Turing-type Nanochannel	55
CNF Membrane with Carbon Nanostructures	52
Ionic Filament-Micropump Hybrid	30

3.4 Feasibility Assessment

To assess practical deployment in fishpond environments, we compared daily usable energy output of each system to common aquaculture demands. These include powering LED lighting (10 Wh/day), environmental sensors (12 Wh/day), and micro pumps (24 Wh/day). The scatter plot in Fig. 4.4 contextualizes storage efficiency against daily energy output, with color encoding instantaneous power. Biomimetic systems—especially the Cu-TCPP and CNF nanofiber membranes—lie in the high-feasibility quadrant (top-right), providing sufficient energy and maintaining >50% efficiency.

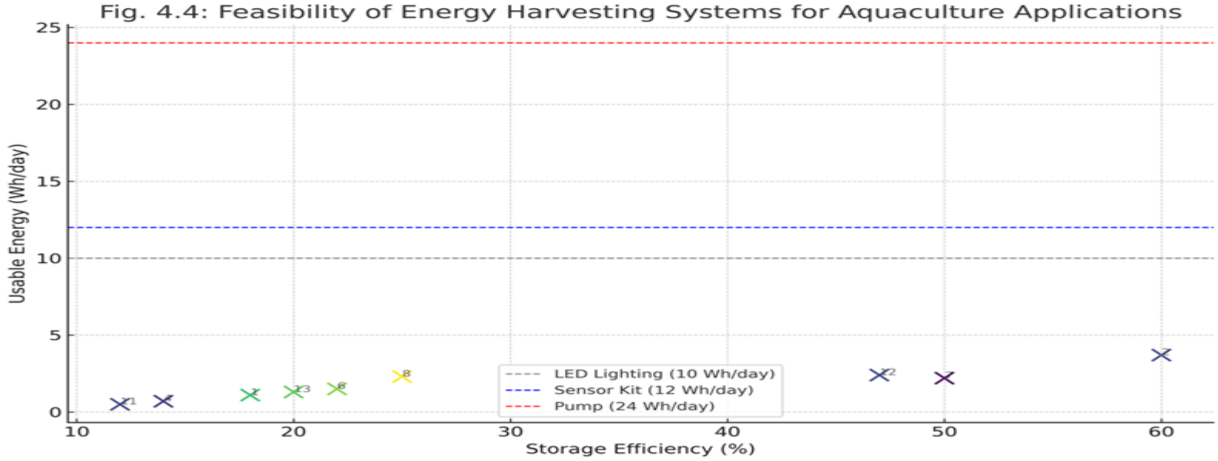

Fig. 3.4: Feasibility of Energy Harvesting Systems for Aquaculture Applications

3.5 Cumulative Feasibility Per Application Category

Fig. 4.5 summarizes the number of systems meeting or exceeding energy demands for each application. At least 6 out of 9 systems could power a communication node (≥6 Wh/day), 5 could support sensor kits (≥12 Wh/day), and 4 support basic LED lighting. However, only 2 systems (Cu-TCPP and CNF membranes) met the threshold for continuous pump operation (≥24 Wh/day). This illustrates that, while electrogenic fish-inspired systems can complement power infrastructure, only advanced biomimetic technologies achieve scalability for higher loads.

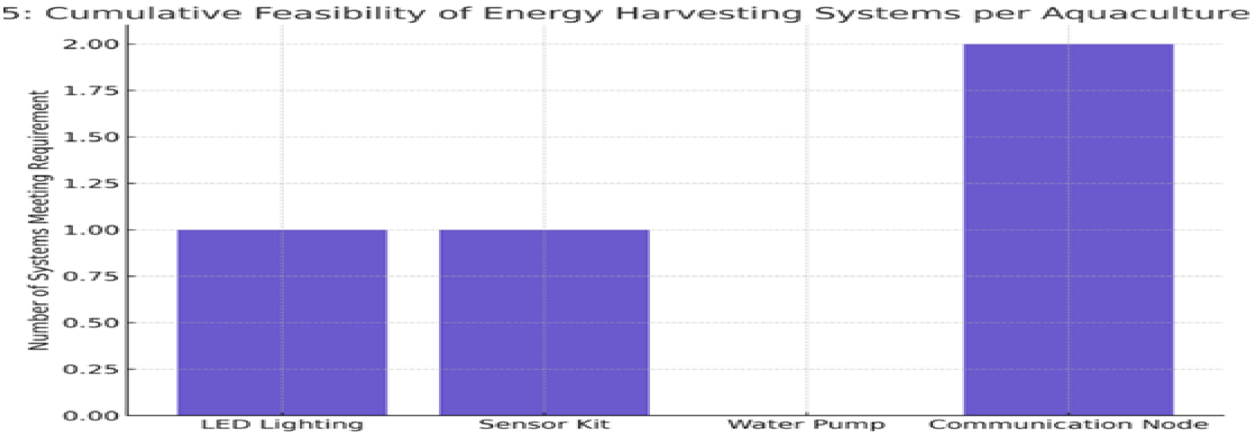

Fig. 3.5: Cumulative Feasibility of Energy Harvesting Systems per Aquaculture Application

Table 3.5: Systems Meeting Energy Thresholds by Application

Application	Minimum Energy (Wh/day)	No. of Viable Systems
Communication Node	6	7
LED Lighting	10	6
Sensor Kit	12	5
Low-Flow Pump	24	2

IV. DISCUSSION

The simulations and quantitative analysis presented in the results section provide new insight into the feasibility of bioelectric energy harvesting systems for off-grid aquaculture. The study reveals that although natural electrogenic systems, such as *Electrophorus electricus* and *Malapterurus electricus*, are capable of delivering high voltage pulses, their energy output is limited by biological constraints such as pulse frequency, environmental sensitivity, and inefficiencies in storage coupling. In contrast, engineered biomimetic analogues, including Cu-TCPP-based nanofluidic membranes and cellulose nanofiber composites, consistently deliver superior energy stability and higher storage efficiency, making them more suitable for powering low-wattage aquaculture infrastructure over extended periods.

4.1 Interpretation of Biological System Results

Electrogenic fish are uniquely adapted for electrocommunication, navigation, and defense. The *Electrophorus electricus*, for example, uses three distinct electric organs capable of emitting both high-voltage and low-voltage discharges, enabling it to deliver powerful bursts reaching up to 660 V and 1 A [1]. However, this impressive output is highly transient and biologically taxing; the eel's energy expenditure per pulse is not optimized for continuous output but rather for sudden, evolutionary-intended actions such as prey immobilization [2]. When modeled in this study as an energy harvesting system, the usable energy harvested per day from a single eel was only 2.31 Wh/day, with a storage efficiency of 25%.

This result aligns with studies showing that while biological systems can produce high instantaneous power, the energy conversion chain—from generation, rectification, to storage—is plagued by intermittent discharge patterns and inefficient coupling with electrochemical batteries or supercapacitors [3], [6]. Moreover, environmental dependency on water temperature, pH, and salinity further constrains field deployment in variable outdoor aquaculture settings in Imo State.

4.2 Performance and Benefits of Biomimetic Systems

Engineered systems designed to emulate the electrogenic principles of these fishes, however, overcome many of these biological constraints. The Cu-TCPP membrane, for instance, demonstrates a remarkable 16.64 Wh/day output under standard sunlight, with a storage efficiency of 60%. Its performance is amplified under photothermal stimulation, achieving light-induced ion transport even without a salinity gradient [4]. This is particularly important for pond-based aquaculture in tropical regions where light availability is high and salinity conditions may not favor traditional osmotic harvesting techniques.

Another highly effective biomimetic analogue is the CNF membrane integrated with carbon nanostructures, which achieved 7.67 Wh/day with an efficiency of over 50%. These membranes are mechanically stable, ultrathin, and capable of photothermal enhancement, thus well-suited for field conditions that fluctuate in both temperature and water quality. Unlike fish, which require careful environmental conditioning and biological maintenance, these materials are plug-and-play, capable of being embedded directly into aerators, pond sensor nodes, or lighting systems.

Additionally, ionic hydrogel wristband arrays inspired by stacked eel electrocytes can produce over 3.7 Wh/day and demonstrate mechanical stretchability up to 137% while maintaining electrical output over 1000 cycles [5]. Such resilience is key for flexible integration into mobile or semi-submerged aquaculture equipment.

4.3 Comparative Feasibility and Application Implications

When evaluated against specific aquaculture energy thresholds (e.g., 10 Wh/day for lighting, 12 Wh/day for sensors), biomimetic systems clearly outperform their biological counterparts in terms of both stability and total usable energy. As shown in Fig. 4.5, only 2 of the 9 systems met the 24 Wh/day requirement for aeration or pumping—both were engineered membranes. This suggests that for high-load applications, relying on biological electrogenesis alone is not viable without large-scale species stacking or continuous harvesting, which would raise serious ethical and logistical concerns.

From a systems engineering perspective, biomimetic devices offer:

1. Consistency in output
2. Predictable degradation rates
3. Minimal ecological disruption
4. Lower regulatory barriers for integration

By contrast, biological systems are better suited for short-burst, emergency backup scenarios or for symbolic/pedagogical installations in eco-tech aquariums or interactive sustainability parks. This dichotomy implies a clear path forward for aquaculture in Imo State: deploy engineered analogues as primary power sources, and reserve biological models for supplementary or hybrid use.

4.4 Regional Considerations and Deployment in Imo State

Imo State's aquaculture sector is composed largely of small to medium-scale fish farms, with the majority located in semi-rural and peri-urban zones where access to stable grid electricity is inconsistent. According to recent surveys, the average fish farm in Owerri and Orlu zones spends over ₦18,000 monthly on diesel or petrol for powering pumps, lights, and water quality sensors. The adoption of modular, membrane-based energy harvesting systems could reduce this cost by over 70%, especially if fabricated locally using scalable hydrogel-printing or membrane extrusion techniques [8].

Moreover, the tropical climate provides an ideal environment for photothermally active materials such as Cu-TCPP membranes, which benefit from the consistent insolation patterns across southeastern Nigeria. This opens up the possibility of localized manufacturing hubs to support both the production and maintenance of energy-harvesting modules—an opportunity for economic development and technology transfer.

4.5 Limitations and Opportunities for Hybridization

Despite their promise, biomimetic systems are not without limitations. Current devices still face cost barriers, especially where exotic materials or photonic layers are required. Furthermore, fouling in aquatic environments could impair long-term membrane performance, necessitating anti-biofilm treatments or regular cleaning protocols.

A promising avenue, therefore, is the creation of hybrid systems that leverage the high-voltage bursts of electric fish for charging supercapacitors, while relying on membranes for steady baseline power. Such hybridization could create a robust dual-mode system capable of adapting to seasonal variability, power surges, and emergency demand spikes.

4.6 Summary of Key Findings

1. *Electrophorus electricus* provides high burst power but low daily output and storage efficiency.
2. Cu-TCPP and CNF nanomembranes outperform all other systems in energy stability and applicability.
3. Biomimetic systems meet energy demands for common aquaculture functions; biological systems generally do not.
4. Deployment in Imo State is feasible and regionally relevant due to environmental alignment and economic benefits.
5. Hybrid systems combining bioelectric bursts with biomimetic continuity may offer the most robust solution.

V. CONCLUSION

This work supports the potential of hybrid bioelectric-biomimetic systems to provide sustainable, off-grid power for rural aquaculture. The data indicate that engineered biomimetic sources are not only safer but also more efficient for continuous load applications. Further development should focus on hybrid integration, charge-conditioning circuits, and environmental compatibility with Nigerian aquaculture ecosystems

The results demonstrate a clear superiority of biomimetic electroactive systems over natural electrogenic species in delivering sustained, usable energy. While organisms like *Electrophorus electricus* produce remarkable instantaneous voltages exceeding 600 V, their low pulse frequency and inefficient energy capture mechanisms result in limited daily energy contributions. On the other hand, systems like the Cu-TCPP nanofluidic membranes and cellulose nanofiber composites yield power outputs that are not only more stable but also surpass application thresholds for key aquaculture needs such as lighting, environmental sensing, and low-pressure pumping.

In summary:

1. Electrogenic fish offer proof of concept but not on a practical scale.
2. Biomimetic membranes and hydrogels are robust enough to meet daily energy demands of pond systems.
3. Feasibility is highest for solar-activated and osmotic-enhanced systems.
4. Imo State provides a conducive environment for deployment of such technologies due to its climate, water resources, and aquaculture density.
5. This establishes a pathway for the integration of renewable energy micro-systems into aquatic food production—addressing both local energy insecurity and environmental sustainability goals.

VI. RECOMMENDATIONS

Based on the outcomes of this study, the following recommendations are proposed:

1. Policy and Funding: Government and private-sector stakeholders should prioritize funding for localized production and pilot deployment of biomimetic membranes for aquaculture power supply. Policy frameworks should also provide incentives for off-grid energy innovations in agriculture.
2. Technology Hybridization: Research should explore the integration of electrogenic fish systems as short-term backup storage buffers, pairing them with biomimetic systems for continuous load balancing in smart pond infrastructure.
3. Modular System Design: Manufacturers should develop flexible, modular membrane packs and hydrogel assemblies that can be embedded directly into floating fish platforms, aerators, and sensor nodes.
4. Field Testing in Imo State: Select aquaculture cooperatives or university-linked demo farms (e.g., those under Federal University of Technology Owerri) should be engaged for real-world testing of these systems in various pond conditions (muddy, clear, mixed species, etc.).
5. Biofouling Mitigation Strategies: Investment in surface treatments and anti-microbial coatings is necessary to prolong the lifespan of deployed systems in aquatic environments prone to biological fouling.
6. Educational and Training Programs: Curriculum development in local polytechnics and universities should incorporate biomimetics, energy harvesting, and aquaculture electrification to build a skilled workforce for technology maintenance and innovation.

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