Journal of Fish Health
Volume 5, Issue 4, November 2025
https://doi.org/10.29303/jfh.v5i4.8259

Climate-Resilient Biofloc Aquaculture: Energy Efficiency, System Robustness, and Operational Adaptations under Changing Environmental Conditions (2020–2025)

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Received:
September 18th, 2025
Accepted:
October 4th, 2025
Published:
November 7th, 2025

Keywords:
BFT, Energy Efficiency, OTE, Climate Change, Sustainability

ABSTRACT

Climate change poses a significant threat to the sustainability of global aquaculture, including biofloc-based aquaculture systems (BFT). While BFT improves nutrient use efficiency and reduces water consumption, energy efficiency remains a key challenge, especially in terms of energy intensity and oxygen transfer (OTE/SOTE). This study conducts a systematic literature review (SLR) using the PRISMA 2020 method, focusing on energy efficiency in tilapia cultivation with BFT and adaptation strategies to climate variability. Key findings emphasize the importance of aeration, design optimization, and C/N management in minimizing energy consumption without compromising production. Additionally, integrating technologies like IoT/AI for adaptive DO control shows great potential in reducing energy intensity. This research contributes a systematic framework that links energy metrics with aeration design and operational adaptation strategies, offering guidance for developing more efficient and climate-resilient BFT systems. The study also recommends implementing renewable energy and smart water quality monitoring technologies to enhance aquaculture sustainability.

INTRODUCTION

Aquaculture is now the world's primary source of aquatic food, and tilapia (*Oreochromis* spp.) is a key commodity that underpins the supply in technology-based, intensive aquaculture systems, especially in developing countries that have been the epicenter of production growth since 2020 (Bartley, 2022). Climate change is triggering an increase in the frequency of ocean heatwaves, changes in rainfall patterns, droughts, and extreme events, which increase risks to freshwater fisheries and aquaculture, thereby demanding evidence-based adaptation strategies at both system and operational levels (Jarraud & Steiner, 2023). Specifically, for tilapia (*O. niloticus*), ensemble modelling revealed a decline in the "highly suitable" habitat area under future climate scenarios, indicating the species' spatial vulnerability despite its reputation for adaptability (Esmaeili & Eslami Barzoki, 2023).

Biofloc technology (BFT) provides a pathway to sustainability through nutrient recycling by heterotrophic microbial communities, which reduces the need for water turnover and is often associated with improved growth performance, feed conversion, and survival in fish, including tilapia (Yu *et al*., 2023). Recent experimental evidence in dry, salinity-stressed environments suggests that the integration of saltwater into desert BFT systems can maintain the water quality, health, and performance of Florida red tilapia, thus confirming BFT's potential as an adaptation platform to water scarcity and saline intrusion (Abdel-Rahim *et al*., 2024). On the other hand, the cutting-edge integrative review emphasizes the importance of integrating BFT with other system models to balance the environmental and economic benefits in intensive cultivation, which is relevant to the design of climate-resilient systems (Li *et al*., 2025).

The energy dimension is often overlooked as a determinant of sustainability, and electricity intensity in aquaculture is commonly expressed as kilowatt-hours (kWh) per kilogram of biomass produced, with a wide range of values between species and between system configurations; therefore, this metric is crucial for cross-study evaluation (Rodríguez-Hernández *et al*., 2025). In intensive operations, aeration components often account for a significant portion of energy consumption—for example, in intensive shrimp farming, it is reported to reach around 90–95%, which underscores the importance of optimizing oxygen supply at the equipment and control strategy levels (Tien Nguyen *et al*., 2024). Beyond total consumption, oxygen transfer efficiency (OTE) is a crucial performance indicator that describes the fraction of oxygen transferred from the gas phase to water by an aeration device under standard conditions, thereby directly linking mass transfer performance with energy costs (Kelestemur *et al*., 2024). The intensity of aeration physically modulates the size and distribution of bubbles, which in turn affect OTE, biofloc formation, and water environmental conditions. Therefore, the tuning of the aeration intensity configuration becomes a sensitive efficiency lever (Han *et al*., 2024). Engineering advances, such as venturi-assisted confined jet aerators, demonstrate a standard aeration efficiency (SAE) of up to ~0.74 kg O_2/kWh, illustrating the close link between aerator design, oxygen transfer performance, and energy savings (Mahmud *et al*., 2024).

In the context of tilapia in BFT, environmental sustainability studies have reported high survival rates, good feed efficiency, and a minimal water footprint. However, the process energy requirements remained significant—for example, the energy requirement of 114.59 MJ per kilogram of product in a closed BFT unit—which underscores the need for an energy-efficient approach without sacrificing water quality stability (Blatt *et al*., 2025). In line with this, regional assessments indicate that freshwater shortages, salinization, and rising temperatures will further exacerbate the pressure on tilapia cultivation in production hotspots, such as the Nile Delta, making the design of systems more resilient to climate variability a policy and research priority (Yacout *et al*., 2025). Automation-based "intelligent biofloc" frameworks—including real-time DO control for aeration—are proposed to stabilize water quality while suppressing energy consumption through sensor- and algorithm-based adaptive operation (Matishov *et al*., 2025). At the same time, the latest literature highlights the need for a more energy-focused assessment of BFT, including standardized measurement and reporting for key metrics across studies and configurations (Matishov *et al*., 2025).

Departing from these gaps, this systematic literature review (2020–2025) explicitly limits the objects to indigo in the BFT system and focuses on two interrelated energy–oxygen metrics, namely energy intensity ($kWh \cdot kg^{-1}$) and OTE, while linking them to the dimensions of system resilience and operational adaptation to climate-related environmental variability.

Without summarizing here, the manuscript continues to map the scientific progress of the past five years, examines technical and operational strategies that improve energy efficiency and system robustness, and identifies knowledge gaps for the research and development of more climate-resilient BFT technologies on indigo.

LITERATURE REVIEW

The concept of biofloc technology (BFT) is rooted in aquatic microbial ecology, which involves utilizing heterotrophic communities to assimilate inorganic nitrogen into microbial biomass that can be consumed by fish, thereby reducing water turnover and waste load in intensive systems. State-of-the-art reviews of the past five years confirm that BFT reduces dependence on fishmeal, improves FCR, and improves the sustainability of the farming environment (Raza *et al*., 2024). At the microbiological level, communities of "biofloc organisms" (BFOs)—heterotrophic bacteria, nitrifiers, microalgae, protozoa, and small zooplankton—play a key function in maintaining water quality and providing additional nutrients, with compositions influenced by salinity, carbon sources, C/N ratios, and aeration intensity (Khanjani *et al*., 2022). Recent metagenomics studies show that BFT has markedly "reshaped" the water column microbiome through the dominance of functional bacterial taxa that recycle dissolved compounds—a mechanism that links water quality stability to the system's resilience to environmental variability (Yang *et al*., 2025). On the theoretical side, the resilience of socio-ecological systems requires a multidimensional approach (ecological, socio-economic, and governance) and indicators that can be used to address climate disruptions in aquaculture (Baird *et al*., 2024; Subramaniam et al., 2023). In the energy–oxygen dimension, standard oxygen transfer efficiency (SOTE/OTE) describes the fraction of oxygen from aeration that is absorbed into water under standard conditions and is the direct link between mass transfer performance and electrical load; hence, OTE is a key metric in addition to energy intensity ($kWh \cdot kg^{-1}$ biomass) (Tauviqirrahman *et al*., 2024).

Mapping the results of previous studies on indigo in BFT shows a spectrum of adaptation strategies and performance outcomes. In the context of water scarcity and saline intrusion, desert mariculture experiments integrating saltwater have proven the maintenance of water quality and the health of Florida red tilapia in BFT across various salinity levels, thus validating BFT as an adaptation platform to hydrological stresses (Abdel-Rahim *et al*., 2024). Research on red tilapia broodstock has demonstrated the impact of salinity on reproductive performance, digestive enzymes, and immune–antioxidant responses in an integrated BFT scheme, confirming the relevance of BFT for critical physiological functions under environmental variability (Sallam *et al*., 2024). At the system integration level, the latest study summarizes the BFT-integrated model (e.g., BFT-RAS, BFT-aquaponics), which improves resource efficiency and tilapia growth performance, while highlighting the challenges of energy monitoring (Li *et al*., 2025). Experimental evidence on tilapia in BFT shows that C/N management practices (e.g., 12:1) spur floc formation while maintaining water quality, but the process's energy requirements remain substantial (Blatt *et al*., 2025). From an economic and energy perspective, an analysis of solar-based commercial BFTs for red tilapia indicates that photovoltaic schemes can reduce energy costs without compromising production performance, provided that aeration is the dominant electrical load (Cala-Delgado *et al*., 2024). Geographically, the context of slapstick production in Egypt—a major contributor to global tilapia—exhibits vulnerability to warming and salinization, making a climate-resilient approach to freshwater-intensive systems even more urgent (Yacout *et al*., 2025).

From the corpus, several research gaps emerged. First, climate change studies on aquaculture have highlighted numerous biophysical impacts and general adaptation strategies; however, rigorous operational measurements of energy-oxygen metrics ($kWh \cdot kg^{-1}$ and OTE) in the context of tilapia BFT are still sporadic, making it difficult to compare results across studies and scales (Maulu *et al*., 2021). Second, the energy efficiency literature focuses heavily on RAS, with an intensity range of 15–30 $kWh \cdot kg^{-1}$, thus forming a strong baseline for RAS. In contrast, the specific intensity curve of tilapia BFT has not been standardized and is often partially estimated (Kashem *et al*., 2023). Third, advanced aeration (CFD, soft computing) research yields predictive models/tools for oxygen transfer, but these are rarely linked to real-time load control strategies, reported as $kWh \cdot kg^{-1}$ savings at the cultivation scale (Puri *et al*., 2025). Fourth, evidence of declining productivity due to extreme climatic events in freshwater aquaculture justifies the need for a system design that is energy-responsive while being resistant to disturbances for tilapia (Jiang *et al*., 2025). Fifth, the latest OTE/SAE studies are primarily based on bench-scale "clean water" tests (e.g., pool aerators with high SAE); therefore, in situ verification is still needed on BFTs rich in suspended solids (Roy *et al*., 2024).

This article aims to bridge these gaps by systematically compiling the 2020–2025 literature, extracting and normalizing the reporting of energy metrics ($kWh \cdot kg^{-1}$) and OTE on tilapia-BFT, and then linking them to indicators of system resilience and operational adaptation under environmental variability. The PRISMA 2020 approach is implemented so that the transparency of data selection, extraction, and synthesis can be replicated and aligned with the latest SLR reporting practices (Page *et al*., 2021). Thus, the main contribution of this study is to present an evidence-to-operations framework that links aeration design, DO control strategies, and C/N management practices with energy-oxygen output and resistance indicators in tilapia-BFT. This perspective is still rarely explicitly articulated in the literature.

The most relevant approaches and trends from the last five years reveal two significant trends. First, the emergence of AIoT-based "smart aquaculture" for real-time monitoring of DO, pH, temperature, TSS, and ammonia that underpins adaptive aeration control and smart feeding, but the evaluation of their impact on $kWh \cdot kg^{-1}$ and OTE in the context of tilapia BFT is still limited (Tina *et al*., 2025; Zamnuri *et al*., 2024). Second, at the methodological level of the literature review, the practice of science mapping and bibliometrics, using Bibliometrix (R) and VOSviewer, is increasingly prevalent for mapping the evolution of biofloc themes and author collaboration, providing a quantitative foundation for thematic synthesis (Gencer, 2024; Melo *et al*., 2025). However, the analytical guidelines also emphasize the importance of metadata curation and indicator harmonization, ensuring that keyword maps (co-occurrence), co-citation networks, and thematic evolution have clear procedural traceability in SLR scripts (Melo *et al*., 2025).

The conceptual synthesis of this study links three main building blocks: (i) the IPCC adaptation framework—which views risk as a function of hazard, exposure, and vulnerability—to assess the need for operational adaptation in the NPF; (ii) energy-oxygen technical metrics ($kWh \cdot kg^{-1}$ and OTE) as core performance indicators sensitive to aerator design, DO control strategies, and C/N management; and (iii) the principle of socio-ecological resilience to weigh the trade-offs and capacity of the system to recover against environmental shocks (Adam *et al*., 2024; Jarraud & Steiner, 2023). From this foundation, the SLR pipeline will extract and normalize energy-oxygen reporting, map themes and bibliometric evidence networks, and then craft a thematic synthesis that informs design decisions and controls for indigo operations that are both energy-efficient and resilient to climate variability—without closing the gap for metrically scalable intelligent technology integration.

METHODS

The study employs the Systematic Literature Review (SLR) framework, utilizing the PRISMA 2020 reporting standard, as it provides cutting-edge checklists, selection flows, and reporting items to enhance the transparency and replicability of systematic reviews *(Page et al*., 2021). The search and documentation strategy for terms, filters, and deduplication processes is designed following the PRISMA-S guidelines, ensuring that bibliographic searches can be reported in a complete and searchable manner (Rethlefsen *et al*., 2021). The SLR protocol is registered in the Open Science Framework (OSF), and reporting adheres to the PRISMA item related to registration. Registration links/DOIs will be included in the final manuscript to ensure procedural traceability (Page *et al*., 2021).

The sources and types of data are secondary to the Scopus-indexed open-access scientific literature for the period 1 January 2020–15 August 2025, with a specific focus on biofloc technology (BFT) for indigo (*Oreochromis* spp.) and the energy-oxygen dimension, so that all units of analysis are peer-reviewed research/review articles that present relevant methodological and/or numerical information (Rethlefsen *et al*., 2021). In addition to primary/review articles, methodological guidelines (e.g., PRISMA 2020 and PRISMA-S) are used as a process reference, not as evidence of substantive findings, to maintain the integrity of the SLR methodology (Page *et al*., 2021; Rethlefsen *et al*., 2021).

Literature search protocols are compiled and recorded according to PRISMA-S, including the following Boolean combinations (field tag and wildcard adjustments are performed per database):(biofloc OR "bio-floc" OR BFT) AND (tilapia OR Oreochromis) AND (energy OR aeration OR oxygen OR kWh OR "oxygen transfer" OR OTE OR SOTE) AND (climate OR "climate change" OR temperature OR salinity OR heatwave OR rainfall OR drought OR "extreme event*" OR variability); 2020–2025 limits, Article/Review document type, English, and full access OA documented in replicable search logs (Rethlefsen *et al*., 2021). The screening procedure was conducted in two stages (title–abstract and then full text) by two independent reviewers, with conflict resolution through consensus. Each inclusion/exclusion decision was recorded on a decision sheet mapped to the PRISMA 2020 flowchart (Page *et al*., 2021).

Inclusion criteria: (i) study of tilapia in BFT systems as a primary context (including indoor/outdoor, RAS-BFT hybrid, or greenhouse variations), (ii) present at least one of two target metrics—energy intensity ($kWh \cdot kg^{-1}$ biomass) or standard oxygen transfer efficiency/OTE/SOTE (%)—with measurable values, quantifiable derivatives, or valid measurement methodologies (Rodríguez-Hernández *et al*., 2025). Exclusion criteria: non-BFT or non-indigo studies as the main object, studies without data/methodology to lower $kWh \cdot kg^{-1}$/OTE, articles that are not fully OA, editor's notes/opinions/comments, and preprints that have not been peer-reviewed; exclusion decisions refer to the methodological justifications documented in the screening sheet (Rethlefsen *et al*., 2021). The JBI Manual for Evidence Synthesis guidelines are used to formulate question framing, define analysis units (studies), and structure data extraction forms, ensuring comparisons across studies are maintained (JBI, 2020).

Data extraction was carried out using a standardized form that contained: metadata (title, author, year, country, journal), technical characteristics of the system (BFT configuration, stocking density, DO/pH set-points, carbon source & C/N ratio), environmental parameters (temperature, salinity), as well as the following energy-oxygen outputs: total electricity consumption and/or energy intensity $kWh \cdot kg^{-1}$ (calculated as total kWh divided by harvested biomass/biomass increase if not explicitly reported) and OTE/SOTE (refers to the definitions and derivatives of K_L a, SOTR, and SOTE under standard conditions for oxygen transfer) (Rodríguez-Hernández *et al*., 2025). When the study only reported SOTR/K_L a or clean-water test results, SOTE values were calculated according to the standard approach described in the literature on clean-water oxygen transfer techniques, with the note that the limitations of the BFT water process were included in the quality record (Vera-Puerto *et al*., 2022).

Evidence quality assessment was carried out at the study level with a checklist of JBI Critical Appraisal Tools that was tailored to the design type (experimental, quasi-experimental, case series, observational), including design clarity, group/comparator equivalence, measurement validity (e.g. DO calibration), and reporting of energy-oxygen metrics, so that the risk of technical bias could be identified before synthesis (JBI, 2020). For review studies included as secondary evidence, the quality and completeness of the reporting are assessed against the relevant items in the JBI guidelines to prevent duplication and double-counting of findings (JBI, 2020).

The data analysis technique combines three layers: (i) bibliometrics using a bibliometrix package in R to map publication trends, authors/productive institutions, and thematic evolution 2020–2025, following the standard steps of collecting, cleaning, and modeling citation/keyword metrics; (ii) science mapping with VOSviewer for keyword co-occurrence, author/institution collaboration network, and co-citation network with association strength normalization; and (iii) thematic-narrative synthesis on three axes—energy efficiency, system resilience, and operational adaptation—linking DO aeration/control design, C/N management, and climate variability contexts (Passas, 2024; Puri *et al*., 2023). For heterogeneous quantitative $kWh \cdot kg^{-1}$ and OTE data across studies, descriptive summaries use median and interquartile ranges, accompanied by quality-weighted vote-counting. If a meta-analysis is not feasible, reporting follows SWiM guidelines to maintain transparency and audibility in synthesis without meta-analysis (Campbell *et al*., 2020).

As a procedural reinforcement, when aeration studies report OTEs based on specific clean water or hydraulic tests, the normalization and interpretation steps are associated with the latest hydraulic aeration efficiency review to ensure that the definition and limitations of standardized tests remain consistent in the context of suspended solid-rich BFTs (Puri *et al.*, 2023). All data cleansing scripts, search logs, extraction codebooks, and bibliometric/VOSviewer workflows are planned to be included as reproducible research attachments in the OSF repository of this manuscript (Page *et al*., 2021).

RESULTS

The range of inclusive publications is dominated in 2024–2025 with a focus on oxygenation efficiency, system resilience, and climate adaptation; This is reflected in BFT-based aeration studies on intensive aquaculture, biofloc efficiency articles in aquaculture fisheries, and climate risk analysis on aquaculture feed systems *(*Han *et al.,* 2024; Matishov *et al*., 2025; Yacout *et al*., 2025). The red tilapia experiment, which integrates saltwater in BFT, emerged as a prominent theme in 2024, featuring a multi-salinity design that monitors both water quality and the health and immune response of fish (Abdel-Rahim *et al*., 2024).

Energy intensity measurements in tilapia BFT (*Oreochromis niloticus*) analyzed through mass balance-based sustainability indicators, were reported to be 114.59 MJ per kilogram of production (Blatt *et al*., 2025). With a standard SI conversion, this value is equivalent to ~31.83 $kWh \cdot kg^{-1}$ (1 kWh = 3.6 MJ) (Milton, 1977). Economic analysis of tilapia-BFT networks shows that the application of photovoltaics lowers operational energy costs but increases investment costs and initial depreciation (Cala-Delgado *et al*., 2024). A study on the cost of producing tilapia in an intensive system confirms the significant portion of energy in the cost structure and compares BFT with RAS and aquaponics in terms of profitability *(Rodríguez-Hernández et al*., 2025).

Standard oxygen transfer performance (SOTE) in a pond-scale fine-pore aeration pipe layout was reported to be up to 29.30% with a SOTR of 19.20 kg $O_2 \cdot h^{-1}$ in a straight-line configuration, as determined by CFD modeling (Tauviqirrahman *et al*., 2024). The enclosed tubeled venturi aerator exhibits a peak SAE of 0.74 kg $O_2 \cdot kWh^{-1}$ and a ~20% increase in performance at larger injector diameters (Mahmud *et al*., 2024). A perforated, pooled, circular, stepped cascade (PPCSC) aerator delivers an SAE of 2.16–2.70 kg $O_2 \cdot kWh^{-1}$ in tangka-based intensive aquaculture testing (Roy *et al*., 2024). Venturi optimization of aerators with an artificial neural network (ANN) combined with PSO/GA improves aeration efficiency under operating conditions tested in the experimental tub (A. Yadav *et al*., 2024).

In the context of operational adaptation, the integration of saltwater in BFT enhances water quality, controls pathogenic bacteria, and improves health indicators of Florida red tilapia fish at various salinity levels (Abdel-Rahim *et al*., 2024). Seven-month experiments with red tilapia broodstock in BFT at salinities of 18–36‰ showed improved reproductive performance, increased hatchability, and enhanced larval tolerance to sudden transfer to high salinity (Sallam *et al*., 2024). A study of Egypt's aquaculture food systems documents the decline of the Nile River flow, saltwater intrusion, and sea level rise as key environmental pressures for aquaculture, which is a relevant background for the adoption of BFT practices in saline environments (Yacout *et al*., 2025).

In terms of water quality and microbial communities, environmental genomics studies have shown that BFT significantly reshapes the aquatic microbiome and is associated with improved cultivar survival. Meanwhile, microbiota diversity studies have confirmed the role of heterotrophic communities in TAN mitigation and systemic nitrogen cycles (Choi *et al*., 2024; Yang *et al*., 2025). BFT's integrated application review confirms the origins of the concept of zero-water-exchange and activated sludge processes in BFT, with the main functions of nutrient recycling and waste discharge reduction in cultivation units (Li *et al*., 2025).

In terms of metric reporting, the literature uses SOTR, SOTE, overall oxygen transfer coefficient, and SAE parameters under standard conditions of 20 °C and 1 atm to assess the performance of aeration (Puri *et al*., 2023). Paddlewheel field testing in intensive ponds reported DO-based OTR for 1–2 HP aerators as a reference for practical oxygen supply capacity (Ariadi *et al*., 2023). Development and testing of aeration devices for pond RAS demonstrate a diffusion/air spray-based design aimed at improving DO and operating efficiency in aquaculture environments (Tong *et al*., 2024).

DISCUSSION

Affirmation of the Primary Outcome of the Problem Formulation

The synthesis reveals that some indigo biofloc systems exhibit high energy intensity per unit of biomass, making energy efficiency a key lever in operational resilience and sustainability under climate pressures (Blatt *et al*., 2025). Variations in aeration design and layout contribute to the wide distribution of oxygen transfer performance, as measured by OTE/SOTE, which directly affects electricity consumption per kilogram of crop yield (Tauviqirrahman *et al*., 2024). Field tests on pool systems demonstrate that effective aeration system modifications can enhance oxygenation efficiency, indicating significant optimization potential in intensive practice (Kelestemur *et al*., 2024). On the other hand, hydraulic devices such as perforated, pooled, circular, stepped cascades exhibit high SAE and SOTR under standard conditions, which conceptually confirms the close link between aerator design, OTE, and energy load (Roy *et al*., 2024). Micro/nanobubble advances enhance oxygen transfer coefficients (kLa) and OTR in bench-scale tests, expanding technical options to reduce energy intensity without compromising oxygen supply (K. On the digital adaptation horizon, the integration of IoT/AI for DO and feed control indicates an acceleration towards energy-responsive operations that are relevant to fluctuating biofloc systems (Rodríguez *et al*., 2025). The pressures of climate variability—including extreme events—have been proven to systematically reduce the productivity of freshwater aquaculture systems, making energy efficiency and oxygenation stability inseparable adaptation dimensions for tilapia farming (Jiang *et al*., 2025).

Interpretation in Theoretical and Conceptual Frameworks

Within the framework of the IPCC, risk is a function of hazard, exposure, and vulnerability; Thus, energy-efficient tilapia bioflocs can be positioned as a vulnerability reduction intervention that strengthens adaptive capacity at the system level (Jarraud & Steiner, 2023). The cutting-edge literature positions BFT as a production practice that enhances circularity and resource efficiency by recycling microbial nutrients, with implications for increasing the resilience of aquaculture ecosystems to environmental variability (N. K. Yadav *et al*., 2025). Integration models (e.g., BFT–RAS/aquaponics) are shown to be able to balance environmental and economic benefits, allowing technical decision-making regarding aeration and DO control to be directed towards dual outputs: high OTE and low $kWh{\cdot}kg^{-1}$ intensity (Li *et al*., 2025).

Comparison with the Findings of Previous Studies (Consistent and Opposite)

Cost-performance studies of intensive production reveal a wide range of energy intensities between species and configurations (e.g., RAS 2.9–81.48 $kWh{\cdot}kg^{-1}$), highlighting the importance of standardized reporting to distinguish "technological effects" from "contextual effects" on indigo bioflocs (Rodríguez-Hernández *et al*., 2025). On the hardware side, venturi-flume optimization yields discharge- and geometry-sensitive SOTE enhancements, facilitating a parameter-based design strategy to achieve higher oxygenation efficiency at the pond/tank scale (Tiwari & Panwar, 2024). However, it should be noted that many OTE/SAE values originate from clean water testing, so an α-factor correction is required between clean water and process water to ensure that interpretations of biofloc solid-rich media are not biased (Schwarz *et al*., 2022). In the area of innovation, FAO's guidelines on nanobubbles highlight opportunities for improved oxygen distribution and bubble stability; however, complete translation to biofloc process conditions requires in situ verification with uniform energy metrics (Griffiths *et al*., 2022).

Scientific Contribution of Articles to Theory and Practice

This article contributes an evidence-to-operations framework that binds two core metrics—$kWh \cdot kg^{-1}$ and OTE—with operational levers (aeration design, diffuser layout, and sensor-based DO control) on the nitra–BFT, so that technical conclusions can be generalized across configurations with explicit reporting rules (Flores-Iwasaki *et al*., 2025). The framework enriches the biofloc literature by centralizing measurable and comparable energy–oxygen indicators, while placing energy efficiency as a dimension of operational system resilience within the IPCC adaptation framework (Jarraud & Steiner, 2023).

Limitations of Research in Proportion

The available evidence base remains fragmented on the energy reporting side for indigo–BFT, which poses a risk to cross-study comparison estimates due to the heterogeneity in design, scale, and definition of production outputs (Rodríguez-Hernández *et al*., 2025). Much of the OTE and SAE reporting relies on clean water and laboratory-scale assays, which can overestimate performance in high-TSS biofloc media without factor-α correction and field validation (Schwarz *et al*., 2022). Evidence of increased efficiency through oxygenated nanobubbles is still primarily based on controlled tests and sectors other than aquaculture, so the application to indigo biofloc requires water-process testing consistent with energy–oxygen indicators (Mamun & Islam, 2025).

Implications and Recommendations for Research–Practice–Policy

For practitioners, the technical priority is to adopt a high-OTE aeration configuration (e.g., venturi/cascade with parameter optimization), accompanied by a diffuser layout that minimizes head losses and improves the distribution of DO in biofloc suspended solids (Tiwari & Panwar, 2024). For operators, IoT/AI integration—from real-time DO–ammonia sensing to adaptive aeration control logic—can be a $kWh \cdot kg^{-1}$ reduction strategy while maintaining water quality stability under fluctuating loads (Kanwal *et al*., 2024). For policymakers, support for the integration of renewable energies (e.g., on- or near-water PV and scenario-based energy management systems) has the potential to lower energy costs and carbon footprints in intensive aquaculture facilities (García-Jiménez *et al*., 2024) in the context of limited land–water resources. Floating solar offers high energy density on the water surface with manageable module temperature sensitivity, thereby synergizing with aquaculture infrastructure (Manolache *et al*., 2025).

CONCLUSION

This study highlights key findings on energy efficiency and system resilience in tilapia cultivation using biofloc technology (BFT) under climate change. While BFT enhances sustainability through nutrient recycling and reduced water change, challenges persist in managing energy consumption, particularly in energy intensity ($kWh \cdot kg^{-1}$) and oxygen transfer (OTE/SOTE). Efficient aeration design and C/N management strategies are crucial for minimizing energy use while maintaining productivity. The study emphasizes the need for further verification of advanced aeration technologies like venturi-assisted and nanobubbles in particle-dense BFT systems. Additionally, integrating renewable energy and IoT/AI for automated management offers promising operational adaptations to climate variability. The research develops a framework linking energy and oxygen metrics with aeration design and C/N management, providing insights for optimizing BFT systems for climate change resilience and sustainability. Future research should focus on advanced technologies and real-world field experiments to enhance system efficiency and robustness.

ACKNOWLEDGEMENT

We sincerely thank all those who contributed to this study, "Climate-Resilient Biofloc Aquaculture: Energy Efficiency, System Robustness, and Operational Adaptations under Changing Environmental Conditions (2020–2025)." Our gratitude goes to the faculty and colleagues at the Study Program of Aquaculture, University of Mataram, for their support and insights. We also appreciate the researchers whose work informed and shaped this study. Finally, we acknowledge the importance of advanced technologies like IoT and AI in addressing energy efficiency challenges in biofloc aquaculture and hope this research will contribute to the development of more sustainable and resilient aquaculture systems.

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