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Hybrid Bioenergy Recovery Framework from Intensive Aquaculture Systems

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Abstract. Intensive aquaculture systems generate nutrient-rich residues, including uneaten feed, faecal solids, pond sludge, and processing by-products, which can degrade receiving waters if poorly managed. Electricity-dependent farm operations, such as pumping, aeration, water treatment, and cold-chain management, are constrained in African contexts by unreliable power supply and high backup fuel costs. This study proposes a conceptual hybrid bioenergy recovery framework integrating anaerobic digestion (AD), microbial fuel cells (MFCs), and thermochemical conversion to support decentralised electrification within aquaculture-based production. The framework applies systems-engineering logic, mass and energy balance reasoning, and peer-reviewed evidence on the characteristics of aquaculture sludge and its conversion pathways. Wet residues are prioritised for AD, residual soluble organics are routed to MFC polishing where appropriate, and dewatered solids are assigned to pyrolysis or gasification. The results indicate that AD is the primary stabilisation and energy-recovery pathway through biogas production, MFCs are best applied as an effluent polishing step with incremental electricity recovery, and thermochemical conversion can extend solids valorisation through syngas, heat, and biochar production when drying requirements are met. The framework aligns with hybrid bioenergy recovery with circular bioeconomy objectives by prioritising waste minimisation, resource recovery, and local energy resilience for sustainable electrified aquaculture.

1 Introduction

Aquaculture is expanding as a key source of animal protein; however, intensive production systems concentrate organic and nutrient loads in farm effluents and solid residues. Typical waste streams include uneaten feed, faeces, suspended solids captured by filtration, sludge from settlement units, and processing by-products, all of which can contribute to eutrophication and wider ecological impacts if discharged without adequate treatment [1]. Recent synthesis in intensive pond and recirculating aquaculture contexts emphasises that effective nutrient and solids management is central to environmental performance and regulatory compliance [2]. In Africa, high-value freshwater species such as African catfish (*Clarias gariepinus*) and related farmed catfishes (including *Heterobranchus* spp.) constitute a substantial share of commercial aquaculture, partly due to their robustness and market demand. In recirculating aquaculture systems (RAS) for African catfish, sludge production is tightly linked to feed inputs, and literature reports that a measurable fraction of feed mass can accumulate as solids requiring handling and treatment [3]. These residues are not only an environmental liability; they also contain biodegradable organic matter and nutrients that can be valorised via waste-to-energy and resource recovery pathways. Energy is a second binding constraint. RAS and other intensive systems depend on continuous power for pumping, aeration, and water treatment, making energy consumption a recognised operational drawback. Where grid reliability is poor, farms often rely on diesel generators, increasing costs and emissions while reducing the competitiveness of electrified food production. Decentralised systems, including mini grids, have been widely discussed as complementary approaches to improve electricity access and enable productive energy use [4]. These realities motivate the development of integrated solutions that treat waste streams while providing on-site energy services.

Bioenergy technologies for wet organic residues are mature in principle but underused in aquaculture. Anaerobic digestion (AD) stabilises organic solids and produces biogas, with structured modelling frameworks such as Anaerobic Digestion Model No. 1 (ADM1) supporting energy and process assessments. Sector-specific evidence shows that aquaculture sludge, including African catfish sludge, can be anaerobically digested; however, performance depends on substrate composition and process choices, including the potential for co-digestion to balance C:N ratios and improve methane yields [5]. MFCs enable the direct conversion of organic substrates into electrical energy while facilitating wastewater treatment. Despite this dual

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functionality, their widespread implementation remains limited due to scalability challenges and relatively low power densities. Consequently, MFC systems are presently better suited for tertiary treatment and targeted energy recovery applications, rather than for bulk energy production. Integration reviews indicate that coupling AD with bioelectrochemical systems can enhance overall treatment performance and broaden recovery options, including improved effluent quality and process resilience. For more recalcitrant or dewatered fractions, thermochemical conversion via pyrolysis or gasification can convert solids into energy carriers and stable carbon products, supported by extensive literature on biomass conversion [6].

1.1 Research contributions

This study addresses a gap in the system-level design of aquaculture by proposing a hybrid bioenergy recovery framework that explicitly links waste characterisation, technology selection, and on-site electrification requirements within a circular-economy rationale. The circular economy concept emphasises systemic approaches that reduce resource inputs and waste outputs while creating regenerative loops across materials and energy flows [7]. Building on this perspective, this study examines how integrated conversion pathways can support sustainable electrified food production in contexts where waste treatment capacity and power reliability are jointly constrained.

i. To integrate a technology-ready system architecture for a deployable conceptual architecture that maps intensive aquaculture waste streams to capture, segregation, and hybrid conversion units, and links recovered energy carriers (biogas, syngas, heat, and niche electricity) to critical farm loads for decentralised electrification.
ii. To model the aligned pathway selection and sequencing logic for a clear allocation and sequencing method that partitions residues into wet and dewatered fractions and assigns them to appropriate conversion routes, wet residues are prioritised for AD (primary stabilisation and energy recovery) with optional MFC polishing for residual soluble organics, and dewatered solids are routed to pyrolysis or gasification to extend recovery beyond digestion.
iii. To develop a circular economy performance framing framework for aquaculture electrification that aligns framing that connects pollution-risk reduction (through staged organic removal), energy resilience (through decentralised supply for essential operations), and nutrient management pathways (through digestate handling and biochar options), while treating coproduct valorisation as conditional on quality assurance and local acceptability.

2 Methodical integration scope, system boundary, and pathway configurations

This study develops a conceptual, literature-informed systems-engineering framework for hybrid bioenergy recovery from intensive aquaculture residues. It does not present new experimental data. Instead, it synthesises evidence from aquaculture waste characterisation, anaerobic digestion modelling, microbial fuel cell studies, and the thermochemical conversion literature to define compatible conversion pathways and bounded performance expectations. The system boundary is a single intensive freshwater aquaculture facility, either pond-based or recirculating, producing farmed catfish and generating on-farm solids, settled sludge, concentrated wastewater streams, and optional processing by-products. The framework evaluates how these residues can be partitioned into wet and dewatered fractions and routed to AD, MFC polishing, and thermochemical conversion according to moisture content, organic strength, and operational suitability. The energy services considered are electricity for pumping and aeration, and low-grade heat for operational needs, reflecting the documented energy dependence of intensive aquaculture and RAS [8]. The functional unit is defined as the treatment and valorisation of organic residues generated over a defined operating period at one facility. Results are expressed using normalised indicators, such as energy recovered per unit of volatile solids treated; relative organic-load reduction; and qualitative energy resilience contribution, to avoid unverified farm-specific absolute values. Waste characterisation is represented using standard descriptors that govern conversion suitability: total solids (TS), volatile solids (VS), chemical oxygen demand (COD), and nutrient indicators such as TKN and TP. These parameters drive a partitioning logic that separates residues into wet (high-moisture sludge and concentrated wastewater) and dewatered (digestate solids or other dried residues) fractions. The wet fraction is prioritised for AD as the primary recovery route, consistent with established AD modelling and practice for wet organics [9]. The dewatered fraction is assigned to pyrolysis or gasification only after moisture reduction, reflecting the energetic penalty of thermochemical processing of wet feedstocks. MFCs are positioned as a secondary polishing step for residual soluble organics (e.g., post-clarification or post-AD liquor), consistent with their documented role as treatment-oriented systems with limited bulk-power contribution [10].

The four pathway configurations proposed in Fig. 1 are defined for comparison: S0 (baseline handling), S1 (AD only), S2 (AD + MFC), S3 (AD + thermochemical), and S4 (full hybrid: AD + MFC + thermochemical), enabling isolation of incremental contributions of each unit operation to electrified food production and waste-risk reduction [11]. Fig. 1 shows the conceptual design of the bioenergy system.

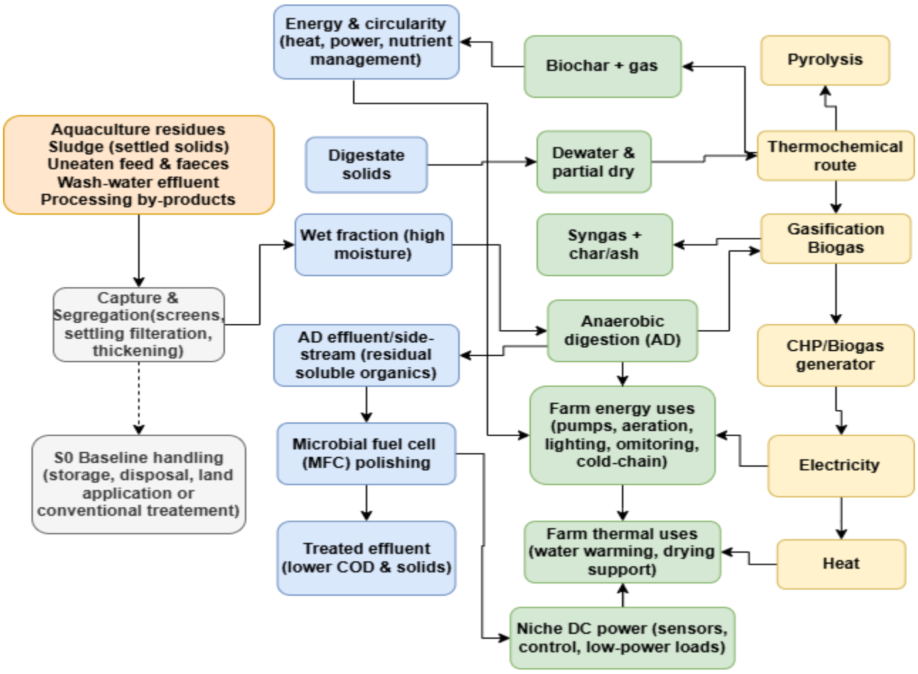

Fig. 1. Conceptual hybrid bioenergy recovery architecture for intensive aquaculture residues showing the scenario pathways: S0 baseline handling, S1 AD only, S2 AD + MFC polishing, S3 AD + thermochemical conversion, and S4 full hybrid integration.

2.1 Modelling Approach for Anaerobic digestion (primary conversion)

AD is represented using a steady-state energy and mass balance anchored conceptually in the ADM1, while avoiding full dynamic calibration (which would require site data). Methane production was estimated using Equation (1), with ADM1 used as the conceptual process basis rather than as a fully calibrated dynamic model. The equation applies a BMP-type conversion relationship to the volatile solids entering the digester [12].

$$CH_4 = VS_{in} \times BMP \times \eta_{conv} \quad (1)$$

Where VS_{in} in is influent volatile solids, BMP is the derived methane potential for comparable fish sludge substrates, and η_{conv} represents conversion efficiency under the stable operating conditions.

2.2 Microbial fuel cell (secondary recovery and polishing)

The MFC module is modelled as an effluent polishing step that converts a fraction of soluble COD into electricity, subject to coulombic efficiency and cell voltage constraints. The MFC module estimates recoverable electrical energy from the soluble COD removed during polishing, as shown in Equation 2.

$$E_{MFC} = COD_{removed} \times CE \times V_{cell} \quad (2)$$

Where CE is coulombic efficiency and V_{cell} is the effective operating voltage. This representation follows established MFC reporting conventions [13] and reinforces the expectation that the MFC contribution is incremental relative to AD in bulk-energy terms. Integration with AD is modelled combining AD with bioelectrochemical systems (BES), including potential benefits in stability and effluent quality, without asserting specific gains in the absence of calibration.

2.3 Thermochemical conversion (Pyrolysis and gasification)

Thermochemical conversion is applied to dewatered digestate (or pretreated solids) to produce energy carriers and solid coproducts. Two alternative blocks are considered:

i. Pyrolysis block: outputs bio-oil, syngas for heat, and biochar for nutrient management or adsorption applications.
ii. Gasification block: outputs syngas for heat and power, with performance influenced by feedstock properties and operating conditions.

Product distributions are not assigned fixed values; instead, the model uses literature-informed ranges and qualitative allocation (energy recovery vs. material valorisation) to compare the roles of pathways. Digestate-derived biochar is included as a circularity enabler like nutrient adsorption, soil amendment potential, or internal process support), acknowledging the growing evidence base for digestate-to-biochar routes.

2.4 Scenario design and sensitivity structure

Scenarios are evaluated under three contextual dimensions:

i. Production intensity and capture efficiency (solids captured via settlement/filtration, affecting VS/COD available for conversion).

ii. Moisture management (degree of dewatering achievable, which determines the feasibility of thermochemical conversion).
iii. Substrate balance (mono-digestion vs. co-digestion, where fish sludge characteristics indicate limitations; co-digestion logic is on fish sludge co-digestion from RAS).

2.5 Sustainability assessment framework

Sustainability performance is assessed using indicators aligned with circular economy interpretations that emphasise closing and narrowing material and energy loops:

i. Energy indicators: fraction of on-farm electricity demand potentially offset (qualitative classes), energy recovered per unit VS treated, and pathway resilience (dependence on continuous operation).
ii. Environmental indicators: relative reduction in COD and solids requiring discharge or disposal, and qualitative greenhouse gas mitigation potential through avoided uncontrolled degradation and displacement of fossil-derived electricity.
iii. Circularity indicators: extent of nutrient and carbon retention in usable coproducts (digestate management; biochar valorisation).

3 Results and Discussions

The conceptual framework defined in Section 2 was analysed across the scenario set (S0 to S4) by mapping intensive aquaculture residues into wet and dewatered fractions and assigning each fraction to the most technically compatible conversion route. The resulting system architecture (Figure 1) positions anaerobic digestion (AD) as the primary stabilisation and energy-recovery unit for wet organic streams. Microbial fuel cells (MFCs) are applied as a post-treatment step to remove residual soluble organics while generating stable low-power electricity. Thermochemical conversion is reserved for dewatered solids to minimise the significant energy penalty associated with processing high-moisture feedstocks. This integration logic is consistent with established anaerobic digestion process modelling and with the typical role of bioelectrochemical and thermochemical systems in waste-to-energy trains. The qualitative sensitivity of hybrid framework outcomes is shown in Fig. 2.

3.1 Waste partitioning determines feasible conversion routes

In intensive aquaculture systems, waste primarily originates from uneaten feed, faecal solids, and wash-water or backwash streams. The key design insight from the framework is that energy recovery is rarely limited by conversion chemistry alone, but by dilution and capture efficiency: dilute sludge reduces digester volumetric productivity and increases parasitic pumping and heating needs unless solids are thickened before AD. Evidence from intensive systems shows that solids thickening is a practical enabling step, and that sludge handling strongly influences both treatment effectiveness and the feasibility of downstream energy recovery. A second insight is that fish sludge can be biologically rich in energy yet operationally challenging. Literature indicates that methane yields from fish sludge and related substrates can vary widely depending on initial solids concentration, degradability, and inhibition risk, which strengthens the case for a conservative, scenario-based evaluation rather than single-point performance claims. Co-digestion is therefore treated as an option within S1 to S4 (not assumed), because it can improve biodegradability and balance nutrient constraints, but it also adds logistics and biosecurity complexity.

3.2 Anaerobic digestion provides the primary energy-recovery route

In S1 to S4, AD is the anchor technology because it directly accepts wet organics and provides biogas that can be converted into electricity and heat. The model-based interpretation is that electrification potential depends on (i) solids capture and thickening, (ii) stabilised digestion without inhibition, and (iii) conversion efficiency of biogas-to-power hardware. To keep the results defensible, the framework reports energy content using literature constants (for example, methane lower heating value) and treats conversion to delivered electricity as site-specific and efficiency limited. Practically, this means the most credible near-term contribution is a partial offset of farm electricity demand (pumps, aeration, basic processing, and cold-chain) rather than full self-sufficiency, particularly in highly energy-intensive recirculating aquaculture systems, where energy consumption is a dominant cost and environmental driver.

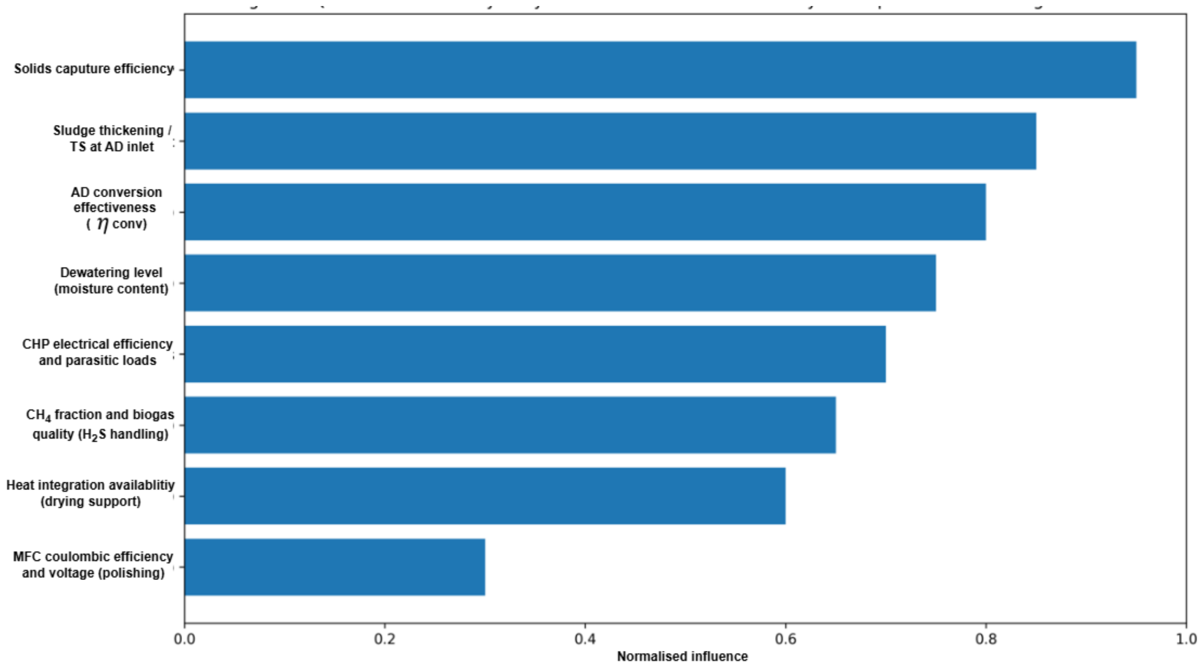

Fig. 2. Qualitative sensitivity of hybrid framework outcomes to key enabling conditions

3.3 MFC integration is best justified as polishing plus niche electricity

In S2 and S4, MFCs are not treated as bulk power generators; instead, they are justified as a post-treatment and resource-recovery step that can reduce residual organics in side-stream liquors (for example, post-clarification or post-AD effluent) while producing low-voltage electricity suited to sensors and low-power monitoring. This positioning reflects the established literature: MFCs are compelling for combined treatment and energy recovery, but power density and scale-up constraints make them supplementary rather than primary generation assets for farm electrification. The relevance of the MFCs is shown in Tables 1 and 2. Also, Appendices A and B show the aquaculture biowaste in the recirculating system implemented.

3.4 Thermochemical conversion adds optional dispatchability and a circular coproduct route

In S3 and S4, thermochemical conversion is applied only to dewatered solids (digestate cake or other dried residues). The framework treats fast pyrolysis as a route to produce a liquid energy carrier with coproduct char and non-condensable gas, while gasification is treated as a route to produce gas for on-site heat and power, recognising that air-blown systems produce low-to-medium heating-value gas. Both routes require careful solids preparation and emissions control, which is why the framework presents them as optional extensions rather than universal requirements. Where thermochemical conversion is included, the conceptual benefit is twofold: (i) reduced residual solids for disposal and (ii) creation of a carbon-rich solid (biochar or char) that can support circular strategies if managed safely and in compliance with agronomic and environmental constraints. In this paper, such benefits are treated as conditional outcomes requiring quality assurance and local validation, not as automatic credits. The scenario selection map is shown in Fig. 3.

3.5 Scenario design and sensitivity structure

Given that the study is conceptual and informed by existing literature, its credibility is established through internal validity checks. These checks evaluate whether the conclusions logically follow from the defined system boundary, the pathway selection logic, and the performance indicators. Traceability and completeness are ensured by mapping residue capture, partitioning of wet and dewatered fractions, and allocating each fraction to the corresponding conversion block, with recovered energy carriers linked to the farm's end uses.
Qualitative sensitivity screening identifies which enabling conditions most influence the direction of the outcome, supporting comparative interpretation without asserting uncalibrated magnitudes. Feasibility envelope screening further limits claims by treating thermochemical conversion as conditional on achievable dewatering and heat integration.

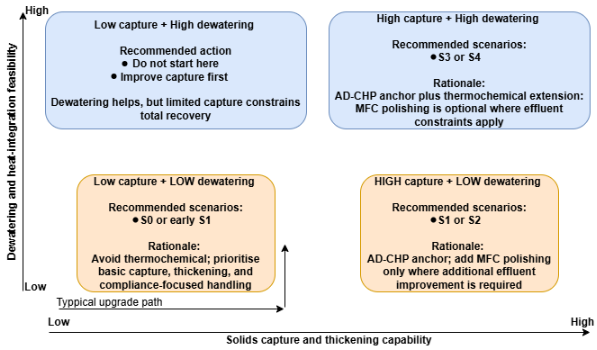

Fig. 3. Scenario selection map under practical boundary conditions (qualitative)

Table 1. Waste stream allocation and conversion logic used in scenarios S0 to S4

Waste stream (typical origin)	Dominant characteristics	Key pre-treatment	Preferred route in the framework	Primary outputs	Rationale (link to methods)
Settled sludge and captured solids (faeces, uneaten feed)	High moisture; VS-rich; variable C:N; may be dilute	Thickening or dewatering	AD (S1 to S4)	Biogas; digestate	Wet-compatible stabilisation and energy recovery depend on effective solids capture and dilution management.[14]
Side-stream liquors (post-clarification)	Residual soluble COD; low solids	Flow equalisation; pH control	MFC polishing (S2, S4)	Treated effluent; niche DC electricity	Treatment-oriented energy recovery; supplementary power role [15]
Dewatered digestate solids (cake)	Lower moisture than raw sludge; combustible fraction	Drying	Pyrolysis or gasification (S3, S4)	Producer heat; biochar;	Thermochemical processes are best suited to low-moisture solids and can extend recovery beyond AD [15]

Table 2. Constraints Used to Bound Scenario Comparisons

Scenario	Included units	Expected energy contribution	Expected pollution-risk reduction	Integration complexity	Primary enabling requirement
S0	Baseline handling only	Very low	Low to moderate (dependent on existing practice)	Low	Compliance-focused waste handling
S1	AD + CHP	Moderate	Moderate to high	Moderate	Solids capture and thickening
S3	AD+CHP + thermochemical solids conversion	Moderate to high (site-dependent)	High	High	Dewatering and solids preparation; safe char handling
S2	AD + CHP + MFC polishing	Moderate (plus niche DC)	High	High	Robust effluent side-stream management and electrode maintenance

4 Conclusion

This study developed a hybrid bioenergy recovery framework for intensive aquaculture systems that links waste capture and partitioning to complementary conversion routes: anaerobic digestion as the primary pathway for wet residues, microbial fuel cells as a polishing and niche electricity recovery step for residual soluble organics, and thermochemical conversion of dewatered solids to extend energy recovery and generate carbon-rich coproducts. The framework is grounded in established anaerobic digestion modelling practice and bioelectrochemical and thermochemical evidence bases, and it is explicitly positioned for the decentralised electrification of aquaculture operations, where power reliability is a binding constraint. The conceptual results indicate that the strongest and most defensible contribution to on-farm electrified food production is achieved by prioritising robust solids capture and stable digestion, followed by adding hybrid components to solve operational problems: effluent quality compliance for polishing units and dispatchability or circular coproduct management for thermochemical units. In terms of a circular economy, the framework supports reduced pollution risk and improved resource recovery; however, it also emphasises safeguards, particularly for the handling of digestate and bio-waste. The principal limitation is that the study is conceptual and requires a minimal-data pilot protocol comprising routine waste characterisation (TS, VS, COD, nitrogen and phosphorus), BMP screening, and monitoring of inhibition and biogas quality, followed by bounded model parameterisation to compare pathway configurations under realistic operational constraints.

Future work should proceed through a measurable pilot protocol: i. Characterise daily and seasonal residue generation using TS, VS, COD, TKN, TP, moisture content, and C:N ratio. ii. Conduct BMP tests for raw sludge, thickened sludge, and co-digestion blends to establish site-specific methane yields. iii. Monitor AD stability through pH, alkalinity, volatile fatty acids, ammonia, hydrogen sulphide, methane fraction, and biogas flow rate and iv. Develop a techno-economic and life-cycle model comparing S0 to S4 under realistic farm loads, including pumps, aeration, water treatment, cold-chain demand, maintenance, and backup power displacement.

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Appendix

(A)

(B)