Transitioning Toward a Circular Economy in Super-Intensive Shrimp Aquaculture: A Comprehensive Review of Resource Recovery From Wastewater and Waste Sludge

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ABSTRACT

Super-intensive shrimp farming activities in the Mekong Delta of Vietnam generate substantial waste loads that threaten coastal environments. This review paper systemizes eco-circular technologies aiming toward zero-discharge and resource recovery from aquaculture wastewater and sludge, drawing from reputable domestic and international scientific publications. For wastewater treatment and recirculation, consolidated data indicate that integrating biological settling ponds optimized for hydraulic retention time ~13.4 days, Biofloc technology, ultrafiltration membrane systems, and constructed wetlands efficiently removes 76–94% of organic and nutrient pollutants, cutting effluent discharge from 1,000 m^3/day down to 33 m^3/day. For waste sludge recovery, compiled empirical studies demonstrate that anaerobic co-digestion of shrimp sludge with sugarcane bagasse boosts methane yields by up to 53% at an optimal mixing frequency of 1 time/day. Additionally, aerobic co-composting of shrimp sludge with coconut coir pith (at a 7 : 3 ratio) inoculated with an EM consortium over 65 days produces a mature organic fertilizer with an ideal C/N ratio (~19.7), which strongly supports *Lactuca sativa* growth, though the residual electrical conductivity (EC ~12 mS/cm) requires careful monitoring. Systematized LCA and LCC analyses confirm the outstanding ecological sustainability and economic efficiency of this closed-loop configuration, yielding a net residual value of 32.22 VND/m^3 of recirculated water and 786.67 VND/kg of compost. Ultimately, linking smallholders through agricultural cooperative models is the key strategic recommendation to overcome capital expenditure and land availability barriers.

Keywords: life cycle assessment, resource recovery, shrimp pond waste sludge, super-intensive shrimp farming, water recirculation

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INTRODUCTION

The aquaculture sector, particularly brackish water shrimp farming, serves as one of the strategic pillars of Vietnam's agricultural economy. In 2025, Vietnam's total shrimp export turnover reached USD 4.6 billion, a 19% increase compared to 2024, marking an all-time high (VASEP, 2026). To meet export targets and optimize profit per unit area, the shrimp industry is undergoing a profound paradigm shift from extensive and semi-intensive methods to super-intensive shrimp farming (SISF) models, particularly for the white-leg shrimp (*Litopenaeus vannamei*) (Ngan et al., 2025; Thang, 2023).

In contrast to traditional models that yield only 0.8–1.5 tons/ha, the SISF model operates at ultra-high stocking densities ranging from 150 to over 300 individuals/m^3. This boosts productivity to 10–15 tons/ha, and even reaches 25–70 tons/ha per crop in greenhouse-enclosed farming systems (Nguyen et al., 2019; Nguyen, 2021). However, this extreme escalation in stocking density and yield poses a critical dilemma regarding the environmental carrying capacity of coastal ecosystems.

According to nutrient dynamics studies, shrimp assimilate only a fraction of the provided nutrients. Approximately 26.3% of total nitrogen (TN), 12.2% of total phosphorus (TP), and 17.5% of total organic carbon (TOC) are retained within the shrimp biomass; the remainder (over 73% of TN and 87% of TP) is discharged into the water column or accumulates as bottom sludge (Thao et al., 2024; Trang et al., 2022). Consequently, the SISF model generates massive volumes of two primary waste streams:

- Wastewater: To maintain water quality at high stocking densities, SISF farms must implement continuous water exchange regimes ranging from 10% to 30% of the total pond volume daily, combined with bottom siphoning (Tien et al., 2024). The discharged wastewater carries a heavy organic pollution load. Parameters such as chemical oxygen demand (COD), biochemical oxygen demand (BOD), total suspended solids (TSS), and nitrogenous compounds NH_4^+, NO_2^-) frequently exceed the National technical regulations by multiple folds (Ton et al., 2023; Tran et al., 2023).
- Waste sludge: It is estimated that the amount of sludge generated from super-intensive shrimp ponds can reach 123–151 tons/ha per crop (Tri et al., 2022). This consists of dense, low-to-moderately saline sludge (1.28–4.19‰) that is highly enriched with organic matter (11.1–23.2%) and harbors a massive microbial load (An et al., 2024; Thang, 2023).

The direct discharge of untreated wastewater and sludge into canals and rivers is the root cause of eutrophication, dissolved oxygen depletion, and proliferation of pathogenic microbial populations. The transmission of Early Mortality Syndrome (EMS) caused by *Vibrio parapaemolyticus* or White Spot Disease (WSD) has caused, and continues to cause, severe economic losses to the shrimp industry on a global scale (Hai et al., 2020). Furthermore, under the severe impacts of climate change (salinity intrusion, temperature fluctuations), the vulnerability of open-culture systems has become increasingly evident (Nguyen et al., 2019).

Driven by these practical constraints, this review article aims to systemize and comprehensively evaluate the application potential of the circular economy in super-intensive shrimp farming systems. Three core objectives are targeted: (i) To analyze nutrient dynamics and material flows in depth to elucidate the nature of pollutants in the SISF model; (ii) To synthesize and compare the performance of modern ecological technologies in treating

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and recycling shrimp pond wastewater and sludge; (iii) To provide a comprehensive insight into the feasibility of the circular model using standardized international assessment tools such as Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and energy efficiency analysis.

Through these objectives, this review is expected to provide solid scientific evidence for researchers, shrimp farmers, and policymakers to plan and develop the Mekong Delta (MD) shrimp industry sustainably, enhancing climate resilience and meeting the stringent standards of the global export market.

Nutrient Dynamics and Waste Characteristics in SISF Systems

Nutrient dynamics and mass balance

The key to evaluating the sustainability and environmental carrying capacity of super-intensive shrimp farming systems lies in the principle of mass balance. Escalating culture intensity demands massive feed inputs, resulting in a corresponding increase in nutrient loads within the effluent streams. In these systems, waste sludge and wastewater contain highly elevated nutrient concentrations, originating primarily from unconsumed feed biomass and shrimp feces (Nguyen, 2025).

Nutrient flow analyses reveal that white-leg shrimp exhibit explicit physiological limits regarding feed assimilation. Specifically, only approximately 23% to 30% of the nitrogen ingested via feed is converted into shrimp biomass (Nguyen, 2025). Further detailed analyses regarding the accumulation of other nutrients indicate that the retention rate of TP in shrimp is the lowest, reaching only about 12.2%, whereas the accumulation efficiencies for TN and TOC are 26.3% and 17.5%, respectively (Thao et al., 2024).

This substantial disparity in the mass balance implies that most nutrients - approximately 70–77% of nitrogen and nearly 88% of phosphorus - are not absorbed by the shrimp. Instead, they are excreted into the aquatic environment or accumulate as bottom sludge (Thao et al., 2024). If left unmanaged, this surplus nutrient load poses a severe risk of eutrophication and harmful algal blooms in the receiving water bodies (Nguyen, 2025).

From a kinetic perspective, nitrogen transformation pathways within shrimp ponds are heavily governed by stocking density, feeding regimes, siphoning frequency, and water exchange rates (Nguyen, 2025). Nitrogen derived from decomposing feed enters the water column as total ammonia nitrogen (TAN), dissolved nitrogen, and nitrites/nitrates (NO_x), while also accumulating in the bottom sludge (Nguyen, 2025). Throughout the culture cycle, the concentrations of TAN, NO_x, and dissolved nitrogen exhibit a continuous upward trend (Nguyen, 2025).

Controlling the volume and frequency of water exchange plays a decisive role in limiting the overall pollution load. Kinetic simulation scenarios for nitrogen demonstrate that implementing a daily water exchange rate of 50% doubles the TN load discharged into the environment compared to a 20% exchange regime (Nguyen, 2025). Consequently, minimizing water exchange, coupled with optimized feed management, represents an imperative technical solution to mitigate nutrient leakage into the surrounding ecosystem.

Physicochemical characteristics and pollution loads of SISF effluents

The SISF system requires continuous water exchange and bottom siphoning to maintain a viable habitat for

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shrimp stocked at high densities. This operational process generates two primary effluent streams: daily exchange wastewater and siphon wastewater. The volume of generated effluent is substantial, with an estimated average SISF discharging around 218 m^3/ha/day (Nam et al., 2022).

The organic and nutrient pollution profiles of SISF effluents far exceed those of traditional aquaculture models, exerting immense pressure on natural receiving water bodies (Figure 1).

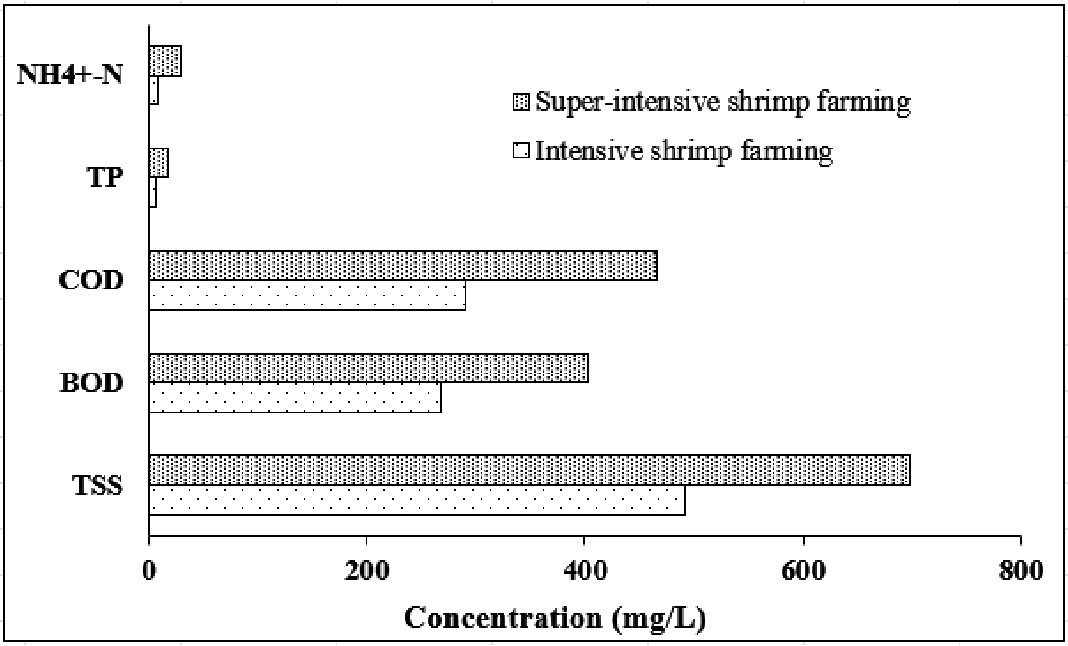

Figure 1. Comparison of pollutant loads in intensive and SISF pond effluents

A study by Nam et al. (2022) documented that the daily pollutant load discharged per hectare can reach up to 177.15 kg of TSS, 113.49 kg of COD, 9.86 kg of TN, and 4.19 kg of TP. The extreme concentration of these components - derived from unconsumed feed, shrimp feces, and molted exoskeletons - will lead to the eutrophication of surface waters, dissolved oxygen depletion, and the outbreak of dangerous epidemics across the entire farming region if discharged directly into the external environment without passing through a treatment system.

A synthesis of the physicochemical parameters of SISF effluents (Table 1) reveals the following:

- Organic matter and suspended solids: Siphon wastewater (SW) are characterized by peak pollution concentrations due to its high content of shrimp feces and uneaten feed. The TSS concentration in the SW stream can reach 3,422.9 mg/L, exceeding the 80 mg/L threshold of QCVN 40:2025/BTNMT by more than 42-fold. The COD concentration in the SW stream also reaches up to 1,853.7 mg/L, and has even been recorded at 2,054.6 mg/L in Ben Tre, far surpassing the permissible limit of 90 mg/L.
- Nitrogenous and phosphorous compounds: Although the updated regulations no longer mandate the control of NH_4^+ for aquaculture effluents, empirical data show that the NH_4^+ concentration in the SW stream remains at an alarming level (101.21 mg/L), posing direct toxicity to aquatic organisms. Regarding mandatory parameters, the TN content in siphon water ranges from 145 to 161.32 mg/L, which is 4 times higher than the 40 mg/L threshold. The TP content also reaches up to 91.68 mg/L in SW, far exceeding the discharge limit into rivers and streams (14 mg/L), making it the primary driver of algal blooms.

- Microbial pollution: Coliform densities in super-intensive effluents frequently exceed the threshold (5,000 MPN/100 mL) of the updated regulation, ranging from 7,850 to 27,585 MPN/100 mL. This indicates a high risk of cross-transmission of diseases between adjacent farming areas if the effluent is not thoroughly disinfected.

Table 1. Physicochemical parameters of SISF pond effluents compared with QCVN 40:2025/BTNMT discharge thresholds

Parameter	Unit	Daily water exchange (WE)	Siphon wastewater (SW)	Combined pond effluents	Threshold (QCVN 40:2025/BTNMT column B)
pH	-	7.53 ± 0.24	7.46 ± 0.27	7.4 - 7.87	6.0 - 9.0
BOD_5	mg/L	-	-	16.02 - 757.3	≤ 60
COD	mg/L	198.31 ± 62.46	1,853.7 ± 1,103.8	29.86 - 2,054.6	≤ 90
TSS	mg/L	238.61 ± 152.48	3,422.9 ± 2,820.3	36.6 - 698.6	≤ 80
TN	mg/L	19.48 ± 6.80	161.32 ± 163.93	2.02 - 145.0	≤ 40
TP	mg/L	4.68 ± 1.91	91.68 ± 133.50	0.78 - 17.32	≤ 14
Coliforms	MPN/100 mL	-	-	7.850 - 27.585	≤ 5,000

(Source: Compiled from Nam et al., 2022; Ton et al., 2023; Thang, 2023; Tri et al., 2022)

Characteristics and Quantities of Pond Bottom Waste Sludge

In contrast to wastewater, pond bottom sludge is a dense organic sediment collected through the siphon system. In the MD, it is estimated that the volume of waste sludge generated per hectare of SISF ponds ranges from 123 to 151 tons per crop (Tri et al., 2022). Poor management of this substantial sludge volume, such as direct discharge into canals and rivers, not only causes sedimentation and narrowing of waterways but also leads to organic pollution and salinization of surrounding agricultural lands.

From a circular economy perspective, shrimp pond bottom sludge is essentially a nutrient bank. An analysis by Thang (2023) documented that the physicochemical composition of SISF shrimp pond sludge has a pH ranging from neutral to slightly alkaline (6.57–8.0). Furthermore, the sludge contains an abundant TOC content, ranging from 5.14% to 9.79%. Due to unconsumed feed inputs, TN, and TP accumulation in SISF sludge reaches relatively high concentrations of 1.85 mg/g and 0.69 mg/g, respectively (Thang, 2023).

A critical characteristic that must be considered when reusing shrimp sludge is salinity. The salinity of SISF bottom sludge is recorded at a moderate level, ranging from 3.18 to 4.83‰ (occasionally reaching up to 5.4‰), which is significantly higher than that of semi-intensive models (Thang, 2023). This factor poses a major technical challenge when applying biological decomposition processes (such as aerobic or anaerobic digestion),

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as high salinity can inhibit microbial growth. However, a positive finding recorded from the study by Thang (2023) is that although the concentrations of highly toxic heavy metals in the sludge are higher than those in traditional models (As: 16.23 mg/kg; Zn: 81.81 mg/kg), they remain within safe limits, fully complying with the QCVN 43:2025/BTNMT National technical regulation on sediment quality. This characteristic confirms that SISF shrimp pond waste sludge fully satisfies ecological safety criteria for use as an input material for organic compost or biogas production.

Ecological Technologies for Wastewater Recirculation and Treatment

Biological settling pond systems: Optimization of hydraulic retention time and area planning

Sedimentation kinetics and optimization of hydraulic retention time

The core mechanism for the effective operation of biological settling pond systems lies in extending the hydraulic retention time (HRT). This extension ensures that suspended solid particles precipitate completely and provides the indigenous microbiota with adequate time to mineralize dissolved organic matter. Through non-linear regression models evaluating the correlation between effluent pollutant concentrations and HRT across 20 typical SISF farms, a study by Nam et al. (2022) demonstrated that COD and TSS removal efficiencies increase exponentially as HRT is prolonged.

- Meeting domestic discharge standards: According to the kinetic simulations by Nam et al. (2022), for the effluent to comply with the permissible thresholds of QCVN 02-19:2014/BNNPTNT (COD ≤ 150 mg/L and TSS ≤ 100 mg/L), the minimum retention times required are 4.47 days for COD and 6.23 days for TSS.
- Meeting stringent international standards: To align with the Best Aquaculture Practices (BAP) standards (which strictly mandate an effluent TSS concentration below 50 mg/L), mathematical modeling indicates that the HRT must be extended and optimized to 13.4 days (Nam et al., 2022). At this specific HRT parameter, the TSS removal efficiency reaches 71.8% (reducing from an influent concentration of 177 mg/L to an effluent concentration of 50 mg/L). Concurrently, this timeframe represents an absolute safe threshold for the microbiota to thoroughly degrade COD and other nutrient compounds (Nam et al., 2022).

Planning the minimum settling pond area

Derived from optimized kinetic parameters, spatial planning for the settling pond system is calculated quantitatively using the flow balance equation. Given the optimal HRT of 13.4 days, an average effluent generation rate of 218 m^3/ha/day for SISF (Nam et al., 2022), and a standard design pond depth of 1.5 m which aligned with the technical recommendations of WWF-VN, the minimum settling pond area must be established at 1,947 m^2 per hectare of culture pond area (Nam et al., 2022).

Ecological efficiency accounting by Thao et al. (2024) confirms that when the discharge stream is routed through a scientifically planned settling pond system, the effluent pollutant load drops sharply: TN decreases to 30.9 mg/L, TP drops to 1.0 mg/L, and TSS achieves an ultra-clean level of just 20.2 mg/L. This significantly facilitates the subsequent water recirculation phase.

Ecological Zonation Structure of Settling Pond Systems

To maximize the operational capacity of the allocated 1,947 m^2/ha land asset, the ecological architecture of the settling pond system should be scientifically partitioned into a continuous three-tier series to optimize natural physicochemical and physiological processes:

- Anaerobic pond: Characterized by a short HRT (2–3 days), this unit directly receives the highly concentrated organic load from the bottom siphon wastewater stream to precipitate heavy sludge and initiate the preliminary anaerobic digestion of recalcitrant, long-chain organic compounds (Nam et al., 2022).
- Facultative pond: Operating with an HRT of 3–6 days, this unit integrates alternating aerobic and anaerobic processes to further degrade dissolved organic compounds distributed within the water column (Nam et al., 2022).
- Aerobic/polishing pond: Designed with an HRT of 3–5 days, this final stage integrates the stocking of biomass filtering fish species (such as Tilapia) to fully assimilate remaining shrimp feces and unconsumed feed (Hai et al., 2020). Additionally, salt-tolerant aquatic macrophytes are cultivated to thoroughly uptake diluted dissolved nitrogen and phosphorus before recirculating the biologically clean water back into the culture ponds (Thang et al., 2024).

Table 2 further quantifies this hydraulic optimization, reporting the modeled effluent BOD and TSS concentrations, the corresponding TSS removal efficiency, and the compliance status of the settling pond system across three representative HRT scenarios.

Table 2. Kinetic modeling of pollutant removal efficiency as a function of hydraulic retention time in biological settling pond system

HRT	The effluent BOD (mg/L)	Effluent TSS concentration (mg/L)	TSS removal efficiency (%)	Compliance assessment
< 4 days	> 160	> 140	< 45 %	Non-compliant with QCVN 40:2025/BTNMT
6,23 days	~110	~100	~55 %	Compliant with QCVN 40:2025 /BTNMT (Minimum threshold)
13,4 days	< 80	< 50	> 71,8 %	Compliant with QCVN and international BAP standard (Optimized scenario)

(Source: Data adapted from regression functions in Nam et al., 2022)

Biofloc Technology and Water Recirculation: Converting Waste into Biomass

Sedimentation Kinetics and Optimization of Hydraulic Retention Time

The operational principle of Biofloc technology (BFT) is based on manipulating the Carbon/Nitrogen (C/N) ratio in the water column by supplementing external organic carbon sources (such as molasses or cassava flour) in conjunction with continuous, high-intensity aeration. When the C/N ratio is elevated above 15/1, heterotrophic bacteria undergo an exponential growth phase, outcompeting autotrophic bacteria. This bacterial community is capable of directly assimilating toxic ammonia (NH_3/NH_4^+) and NO_2^- derived from shrimp waste to synthesize cellular protein (Iber & Kasan, 2021).

This biological process aggregates microorganisms, algae, fungi, and unconsumed feed particles into suspended flocs within the water column. The hallmark of this ecological technology is that these nutrient rich flocs (containing 30–45% crude protein) serve as an excellent natural food source for white-leg shrimp (Nguyen et al., 2019). Consequently, BFT delivers dual benefits: it thoroughly controls ambient ammonia concentrations within safe thresholds without requiring water exchange, and it substantially lowers the feed conversion ratio, resulting in up to a 20% reduction in commercial feed costs.

Recirculating Aquaculture Systems

Recirculating aquaculture systems (RAS) represents a fully closed-loop technological solution, wherein culture effluent is pumped through a sequential series of filtration modules (mechanical filtration for feces/sludge separation, nitrifying/denitrifying biofiltration, and UV/Ozone disinfection) before being 100% recirculated back into the culture ponds (Suantika et al., 2018).

A major contemporary advancement in RAS is the integration of ultrafiltration membranes, establishing the Membrane-RAS (M-RAS) configuration. The ultra-small pore size of UF membranes allows for the absolute removal of colloidal suspended particles (< 35 μm), pathogenic bacteria (specifically *Vibrio* spp. strains), and viral pathogens prior to the water entering the biofilter (Widiasa et al., 2024). The application of M-RAS maintains strict stability of physicochemical parameters (DO, pH, alkalinity), yielding a shrimp survival rate of up to 86.85% at an ultra-high stocking density of 400 individuals/m^3 (Widiasa et al., 2024).

Viewed through the lens of the water balance principle, the efficiency of recirculating systems is definitive. Mathematical models demonstrate that a traditional intensive system can consume and lose up to 1,000 m^3 of water per crop via discharge and leakage. However, by implementing a recirculating configuration integrated with sequential biological treatment ponds, water loss is mitigated to just 33 m^3/day (primarily driven by evaporation). This translates to a 97% reduction in wastewater discharge volumes and a 20% savings in freshwater intake requirements (Nguyen, 2023). The synergy between BFT and M-RAS represents the ideal archetype for operationalizing a zero-discharge ecological model within the shrimp aquaculture industry.

Constructed Wetlands: Optimizing Treatment Via Aquatic Macrophyte Diversity

Although biological settling pond systems and RAS can eliminate most suspended solids and organic matter, dissolved nutrient forms - particularly nitrates and phosphates - remain a major challenge. Within this context, constructed wetlands (CWs) emerge as a highly effective, terminal ecological engineering solution for polishing shrimp aquaculture effluents (Iber & Kasan, 2021). The core mechanism of CWs in purifying wastewater is the synergistic interaction of three primary pathways: (i) physicochemical adsorption; (ii) microbial degradation (nitrification and denitrification); and (iii) the direct assimilation of inorganic ions (NH_4^+, NO_3^-, PO_4^{3-}) into the biomass of aquatic macrophytes. The radial oxygen loss from the root systems of wetland plants significantly accelerates the oxidation of organic compounds, thereby enhancing the overall performance of the entire system

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(Pham et al., 2021).

Empirical research conducted in Ben Tre demonstrated that reed-planted CWs eliminated 70% of COD and removed 64.1–76.6% of ammonium (That & Hoang, 2024). Systems utilizing the bulrush (*Scirpus littoralis*) yielded a comparable COD removal efficiency of 76% (Pham et al., 2021). Notably, regarding NO_2^- toxicity, CW systems integrating reeds and cattails have been proven capable of thoroughly removing 83–94% through intensive nitrification within the rhizosphere (Lin et al., 2005; Shi et al., 2011).

Experiments conducted by Phuong et al. (2025) using CW models planted with Flamingo flower (*Anthurium andraeanum*) on a gravel substrate blended with coconut coir documented superior treatment outcomes. After a 15-day hydraulic retention time, this system achieved an organic matter removal efficiency of up to 87.5%, while successfully removing 76% of ammonium, 91.6% of nitrite, and 44.1% of phosphate. This success is attributed not only to the plant species itself but also to the optimization of the coconut coir substrate, which acts as a sustainable organic carbon source that drives the denitrification process (Phuong et al., 2025).

Water Recirculation Efficiency and Zero-Discharge Targets

Quantifying Resource Conservation Efficiency Via Water Mass Balance

To maintain water quality in high-density SISF ponds, periodic water exchange is an imperative technical requirement. The daily freshwater intake volume increments progressively with shrimp age, typically fluctuating between 10% and 30% of the total pond volume and can escalate to 50% under conventional farming scenarios. Applying a water mass balance analytical framework based on the conservation of mass equation provides the core scientific foundation to accurately quantify water consumption pathways and evaluate the efficiency of recirculating configurations:

- Effluent discharge in conventional open-culture models: Fieldwork conducted by Nguyen (2023) at a white-leg shrimp farm in Ca Mau revealed that the volume of wastewater discharged directly into the natural environment daily (encompassing pond exchange water, dense bottom siphon streams, evaporation, and seepage) reached up to 1,000 m^3/day (accounting for over 20% of the cumulative water footprint of the culture cycle). This massive discharge stream, laden with concentrated organic and nutrient loads, drives the degradation of natural receiving water bodies.
- Closed-loop recirculating water models: Upon transitioning to a closed-loop recirculation system - wherein effluents are routed through a sequential series of biological settling and polishing ponds for purification prior to being pumped back into the culture units - direct wastewater discharge into receiving rivers is eliminated. Data from Nguyen (2023) demonstrated that the actual water loss within the farm was confined solely to natural evaporation and embankment seepage, dropping to an ultra-low level of just 33 m^3/day. This recirculation process enables the farm to mitigate effluent discharge by 97% while directly conserving 20% of natural freshwater intake requirements.

This equivalent performance in water resource conservation was further validated by a detailed material flow cost accounting study conducted by Thang et al. (2024) on a 2.5-hectare closed-loop waste recovery model in Ca Mau province. The operational water accounting results indicated that the total daily exchange water (1,344 m^3/day), blended with the bottom siphon stream (134.4 m^3/day), yielded a recovered water volume of up to

1,465.7 m^3/day after passing through the biological settling pond system. The actual water loss escaping the system boundaries was exceptionally minor, restricted to a mere 12.7 m^3/day (Thang et al., 2024).

Dual Eco-Economic Benefits and Biosecurity Assurance

From a kinetic perspective, minimizing effluent discharge enables the system to sequester and isolate nutrients within its boundaries. Nitrogen kinetic simulations confirm that implementing a daily water exchange rate of 50% doubles the total nitrogen load discharged into the environment compared to a 20% exchange regime (Nguyen, 2025). Therefore, transitioning toward a fully closed-loop recirculating system represents the most effective technical measure to halt the eutrophication of receiving water bodies.

By applying the residual value method, a study by Nguyen (2023) quantified the economic value of water resources in SISF systems at 6,000 VND/m^3. Establishing recirculating configurations to retain this water volume within the system instead of discharging it minimizes operational input costs, directly offsetting the initial capital expenditure for infrastructure development.

Furthermore, reducing the continuous freshwater intake demand from natural canal systems eliminates the risks of cross-contamination by external pathogens. The integration of ultrafiltration technologies, such as M-RAS membranes combined with biological polishing ponds, provides the ideal framework to operationalize the Zero-discharge model, ensuring that the shrimp aquaculture industry satisfies the most stringent standards of international export markets (Nguyen et al., 2019; Widiasa et al., 2024).

Comparative assessment of wastewater technologies

The wastewater technologies reviewed above occupy markedly different points on the technology readiness spectrum. Biological settling ponds and constructed wetlands rest on comparatively simple, low-cost civil engineering and have been validated across multiple commercial SISF farms (Nam et al., 2022; That & Hoang, 2024), making them the most readily transferable options for smallholders once land is available.

BFT is likewise commercially proven but shifts the challenge from land to labor and energy since ammonia control depends on continuous aeration and close C/N monitoring. M-RAS, by contrast, remains supported by a single pilot scale dataset (Widiasa et al., 2024); its membrane costs, fouling behavior, and long-term operating economics are not yet documented well enough to justify treating it as commercially mature, and this distinction should temper expectations of near-term, farm level adoption.

A trade-off worth flagging explicitly is the tension between treatment efficiency and land footprint: achieving BAP-grade TSS removal (71.8%) via settling ponds demands an HRT of 13.4 days and 1,947 m^2/ha (Nam et al., 2022), an area unavailable to the majority of MD farmers who cultivate under 1 ha (Nguyen et al., 2019).

In practice, land constrained farms may only be able to meet the less stringent national compliance thresholds (4.47–6.23 days) rather than international BAP standards - a limitation not made explicit in the individual technology descriptions above.

Resource Recovery from Pond Waste Sludge

Biogas production from shrimp pond waste sludge

Biochemical challenges: High salinity and C/N ratio imbalance

Although SISF shrimp sludge contains a massive reservoir of nitrogen and phosphorus due to incomplete feed assimilation by the shrimp, its easily biodegradable organic carbon content is relatively limited. Elemental composition analysis indicates that siphon sludge exhibits a C/N ratio hovering around 18.46, which is significantly lower than the ideal threshold required for methanogenic bacterial activity (the optimal C/N ratio typically ranges from 25 to 30) (Thuan et al., 2023). This carbon deficiency stalls the metabolic pathways, thereby reducing biogas production efficiency.

In addition to nutrient imbalances, salinity acts as a severe inhibitory factor. In SISF systems, the salinity of the waste sludge is frequently recorded at highly elevated levels, reaching up to 20‰ (Thuan et al., 2023). High salt concentrations alter the osmotic pressure across microbial cell membranes, causing cellular dehydration and directly inhibiting the intracellular enzyme systems of anaerobic bacterial strains. Consequently, mono-digestion of SISF shrimp sludge to produce methane is generally inefficient, yielding low and unstable biogas outputs (Nam et al., 2022).

Anaerobic Co-Digestion Solutions Using Agricultural By-Products

Under single-source (mono-digestion) anaerobic conditions, treating SISF shrimp pond waste sludge encounters two major biochemical barriers that limit methane yield: an extremely low C/N ratio ranging from only 5.2 to 10 due to the accumulation of residual protein from shrimp feed (An et al., 2024), and highly elevated dissolved salt concentrations within the sludge (Zhang et al., 2019). Under the metabolic action of anaerobic microorganisms, this highly concentrated organic nitrogen is rapidly converted into free ammonium and un-ionized ammonia gas (NH_3), triggering ammonia toxicity accumulation, and directly inhibiting biomethane production pathways (Chen et al., 2007; Sirvichai & Chavalparit, 2020).

To overcome this kinetic limitation, anaerobic co-digestion currently represents the most breakthrough and sustainable engineering solution (Tran et al., 2022). By blending shrimp pond waste sludge with carbon-rich agricultural by-products readily available in the MD - such as sugarcane bagasse, rice straw, or lemongrass leaves post-essential oil distillation - operators can proactively adjust the C/N ratio of the influent feedstock mixture to an ideal level of 25 (Tran et al., 2022). The incorporation of these carbon-rich co-substrates plays a decisive role in balancing nutrient kinetics for the microbial community, while simultaneously diluting salt concentrations and enhancing the system's buffering capacity, thereby halting the risk of ammonia inhibition (Sirvichai & Chavalparit, 2020; Ye et al., 2013).

Empirical evaluations of digestion kinetics have demonstrated remarkable improvements in both biogas yield and production rates when applying anaerobic co-digestion:

- Superior efficiency of sugarcane bagasse: Experimental data from Tran et al. (2022) indicated that sugarcane bagasse is the most optimal carbon supplement due to its porous cellulose structure, which is readily biodegradable in brackish environments. Co-digestion of shrimp sludge with sugarcane bagasse boosted the specific CH_4 yield up to 126.8 L/kg of volatile solids (VS) fed, achieving a 53% increase compared to the mono-digestion of unblended waste sludge (82.48 L/kg VS) (Tran et al., 2022).

- Role of rice straw and lemongrass leaves: Other prevalent crop residues, such as rice straw and lemongrass leaves, also delivered distinct enhancements in biogas yields, ranging from 26% to 29% (Tran et al., 2022).

In parallel with the increased volume of recovered gas, the quality of the generated biogas was substantially improved. The CH_4 concentration in the gas mixture derived from the co-digestion treatments reached highly elevated levels, ranging from 41.77% to 44.36% (Tran et al., 2022), thereby significantly enhancing the heating value of the gas stream for practical utilization.

From the perspective of energy accounting and circular economy principles, converting this waste sludge into bioenergy satisfies the daily cooking energy demands of farm workers, curtails fossil fuel procurement costs, and minimizes the net carbon footprint of the entire SISF production cycle (Tien et al., 2024).

Hydrodynamic Optimization: Theoretical Foundations and Mixing Frequency Control

In the operational practice of biogas systems in the MD, shrimp waste sludge exhibits cohesive properties and a high propensity for stratification, leading to the formation of scum layers. This scum layer forms a rigid crust on the liquid surface, impeding gas release and severely degrading the system's biogas production efficiency (Nam et al., 2022). To overcome this limitation, mechanical intervention via mixing is an imperative engineering technique. From a theoretical perspective, mixing disintegrates scum formations, ensures uniform distribution of nutrients, temperature, and pH, and maximizes the interfacial contact area between the microbial community and the substrate (El-Bakhshwan et al., 2015; Stroot et al., 2001).

However, the relationship between mixing intensity and biomethane yield is non-linear, involving a fundamental microbiological trade-off. International studies have demonstrated a paradox: excessive or continuous high-frequency daily mixing fails to enhance efficiency and instead reduces CH_4 yields (Monyluak et al., 2021). Extreme mixing regimes generate shear stresses that disrupt the structural integrity of biological sludge flocs, directly inhibiting the methanogenic pathways of the bacterial community (Muftah et al., 2009).

Applying this theoretical framework to SISF shrimp sludge, an empirical study conducted by Thuan et al. (2023) evaluating the mixing frequency of shrimp sludge slurry (with a fixed duration of 2 minutes per mixing event) documented the following (Figure 2):

- Optimal zone (Low frequency): Implementing an intermittent, low-frequency mixing regime (1, 2, or 4 times/day) yielded a substantial increase in CH_4 productivity. Among these, a mixing frequency of 1 time/day represented the absolute optimum, boosting CH_4 yield by 10.01% compared to the unmixed control. Mixing frequencies of 2 and 4 times/day also provided corresponding increases of 5.99% and 4.2%, respectively.
- Inhibitory zone (High frequency): Confirming the negative correlation theory of microbial kinetics, when the mixing frequency was escalated to a high level (8 times/day), the CH_4 yield dropped abruptly, performing no better than the unmixed control.

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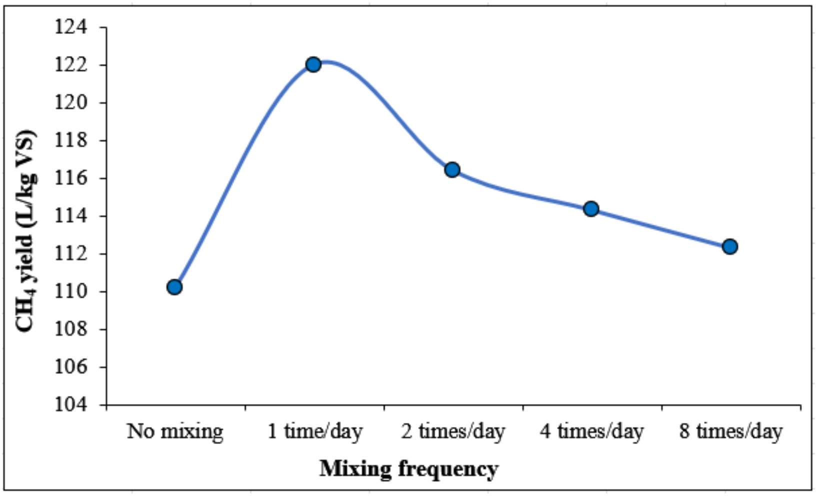

Figure 2. Optimization of mixing frequency for CH_4 recovery from SISF shrimp pond sludge

(Source: Derived from data in Thuan et al., 2023)

Composting: Reclaiming nutrients from pond bottom sludge

Composting Kinetics: Blending Ratio Optimization and Parameter Control

The primary obstacle in direct composting of super-intensive shrimp pond bottom sludge is its highly dense structure, high moisture content (typically > 72%), and an extremely low C/N ratio hovering around 5.2 (An et al., 2024). If composted without amendments, the matrix collapses into localized anaerobic states, generating offensive odors (due to the release of NH_3 and H_2S) and causing substantial nitrogen loss.

To resolve this issue, agricultural engineers have implemented a co-composting technique blending shrimp sludge with coconut coir pith - an abundant agricultural by-product in the MD. Coconut coir pith possesses a highly porous structure, excellent water-retention capacity, and inherently high carbon content (up to 40%). Quantitative experiments have established the optimal blending ratio at 7 : 3 (70% shrimp pond sludge : 30% coconut coir pith) on a wet weight basis (An et al., 2024). This specific ratio immediately adjusts the initial moisture content of the compost matrix to the ideal range of 60–70%, providing the essential porosity required for oxygen diffusion.

Concurrently, to accelerate mineralization, a secondary Effective Microorganisms (EM) consortium (comprising photosynthetic bacteria, lactic acid bacteria, and yeasts) is inoculated into the compost pile. The synergy between the coconut coir pith and the EM inoculum drives excellent physicochemical kinetic transformations over a 65-day aerated, manually turned composting cycle:

- Temperature kinetics: The system rapidly enters the thermophilic phase. The core temperature of the compost matrix increases sharply, peaking at 44.6°C on day 36. This thermal level functions as a biological pasteurization mechanism, effectively eliminating most pathogenic bacteria (*Vibrio*, *Salmonella*) and helminth eggs harboring in the bottom sludge (An et al., 2024).
- pH fluctuations and nutrient transformation: The pH of the compost matrix undergoes an initial slight decline driven by the formation of volatile organic acids (such as lactic acid), followed by a gradual increase into a

slightly alkaline range, stabilizing at pH = 8.19 (An et al., 2024). Intensive mineralization takes place, with available potassium increasing from 4,300 mg/kg to 7,200 mg/kg, and available phosphorus escalating from 136.4 mg/100 g to 1,030 mg/100 g.

- Optimization of the C/N ratio: This represents the most critical success of the model. Enabled by the abundant carbon source from the coir pith, the TOC of the compost pile increases to 10.9%, while TN is retained at 7.51 g/kg. Consequently, the C/N ratio of the final compost product reaches 19.7 (An et al., 2024). According to international agronomic standards, a C/N ratio within the 15–20 range confirms that the compost is fully mature, highly humified, and ready to immediately deliver nutrients to crops without inducing nitrogen immobilization in the soil.

Table 3 summarizes the complete physicochemical transformation of the sludge-to-compost matrix over the 65-day cycle, benchmarking the raw-sludge and finished-compost values of each parameter against their agronomic significance

Table 3. Physicochemical profile transformations of shrimp pond sludge after a 65-day aerobic composting cycle

Parameter	**Unit**	**Raw sludge (un-composted)**	**Compost product (after 65 days)**	**Agronomic quality evaluation**
Humidity	%	72.0	63.0	Porous texture, complies with storage standards
pH (KCl)	-	5.29	8.19	Slightly alkaline, ideal for soil microbiota
EC	mS/cm	15.23	12.00	Relatively high (saline); caution required during application
TN	g/kg	9.20	7.51	Abundant nitrogen source
Available Potassium	mg/kg	4,300	7,200	Sharp increase driven by mineralization
Available Phosphorus	mg/ 100 g	136.4	1,030	Highly assimilable form for root systems
TOC	%	4.8	10.9	Enhances soil humus content
C/N ratio	-	5.2	19.7	Achieves the perfect ideal threshold (15–20)

(Source: Compiled from an et al., 2024)

Agronomic Efficiency and Salinity Control Challenges

From a practical standpoint, the ultimate objective of the circular economy is for recycled products to generate distinct residual value. Biological assessments utilizing shrimp-sludge-derived compost for cultivation trials on Looseleaf lettuce (*Lactuca sativa*) have yielded highly promising results.

In a bioassay conducted by an et al. (2024) across different soil compost blending treatments, biometric measurements after 45 days indicated that the treatment consisting of 80% baseline soil and 20% shrimp sludge compost promoted the most superior growth. Under this treatment, lettuce shoot length reached 12.8 ± 0.2 cm and leaf length reached 6.1 ± 0.3 cm, which were approximately 30% to 40% higher than the 100% baseline soil control (An et al., 2024). This vigorous growth is attributed to the superior moisture-retention characteristics of the organic fertilizer (enabled by the coconut coir matrix) alongside a continuous supply of macro-nutrients (N, P, K) in highly available forms, which enhances root proliferation and maximizes nutrient uptake.

However, physicochemical analysis revealed that despite undergoing a 65-day composting and blending cycle, the EC value of the compost only decreased from 15.23 mS/cm to 12.00 mS/cm (An et al., 2024; Thao et al., 2024). In agronomy, an EC threshold exceeding 4 mS/cm initiates salinity stress in salt-sensitive crops. Applying excessive quantities of this compost (such as treatments exceeding 20% compost by volume) can induce root scorching, disrupt osmotic pressure, and inhibit water uptake, thereby restricting plant growth (An et al., 2024).

To overcome this salinity challenge, two strategies must be implemented when managing shrimp-sludge derived compost (Thao et al., 2024):

- Application dosage control: The compost should strictly be used as a micronutrient supplement and a soil conditioner to improve soil porosity at a low blending ratio (< 20% of soil volume), and it must never be utilized as the primary growth medium.
- Pre-treatment desalination (Leaching): For industrial-scale operations, a mechanism utilizing harvested rainwater can be deployed to leach salts from the pond bottom sludge (via 3 to 5 cycles of flooding and draining) over approximately 1.5 months prior to entering the composting system. This method has been proven to thoroughly mitigate salinity, lowering the EC to an absolute safe threshold for all crop species.

Co-composting waste sludge from SISF ponds with coconut coir pith represents not only an ecological solution that eliminates tons of solid waste per crop, but also an economic avenue that generates direct financial value. LCC calculations indicate that farmers can capture a net benefit exceeding 780 VND for each kilogram of compost produced (Thang et al., 2024). Nevertheless, the success of this model depends entirely on precise control over physicochemical parameters, particularly the C/N ratio and salinity risk management.

Comparative assessment of sludge recovery pathways

Comparing the two principal sludge recovery pathways reveals a similar maturity gap. Anaerobic co-digestion delivers a well quantified 53% CH_4 yield increase (Tran et al., 2022), but this figure derives from a single farm scale trial; multi-site replication and standardized reporting of digester CAPEX/OPEX under MD conditions are still lacking.

Aerobic co-composting is further along in terms of agronomic validation (An et al., 2024), but is constrained by a residual EC of approximately 12 mS/cm even after 65 days of composting, meaning it can only serve as a soil conditioner rather than a stand-alone growth medium (Section 4.2.2). Neither technology has yet been documented beyond a single demonstration farm, so the reported economic returns of the closed-loop configuration should be read as pilot-scale evidence rather than confirmed commercial scale performance.

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Comprehensive Sustainability Assessment: Environmental, Energetic, and Economic Perspectives

Comparative synthesis of technology maturity, performance, and cost

While Sections 3 and 4 detail the performance of each technology individually, Table 4 consolidates these findings into a single comparative view - juxtaposing technology-readiness level, quantitative performance, indicative cost, environmental co-benefit, and principal scale-up barrier - to clarify which options are commercially transferable to MD smallholders today and which remain at the pilot or demonstration stage.

Table 4. Physicochemical profile transformations of shrimp pond sludge after a 65-day aerobic composting cycle

Technology	TRL / adoption stage	Key performance metric	Estimate cost (CAPEX/ OPEX)	Environmental co-benefit	Principal limitation / scale-up barrier
Biological settling ponds (3-tier)	Commercially validated across 20 SISF farms (Nam et al., 2022)	TSS removal 71.8% at HRT 13.4 days	~30 million VND per pond unit (Thao et al., 2024)	Enables compliance with QCVN 40:2025/ BTNMT and BAP; supports recirculation	Requires 1,947 m^2/ha - unattainable for most < 1 ha smallholder farms
Biofloc technology (BFT)	Commercially applied on ASC /BAP certified farms	20% reduction in feed cost; in-situ NH_3 control	Energy cost of continuous aeration (not separately quantified)	Converts waste N into protein biomass, cuts feed footprint	Needs continuous high-intensity aeration and precise C/N dosing - labor/ energy intensive
Membrane-RAS (M-RAS)	Pilot/ demonstration scale - single study (Widiasa et al., 2024)	86.85% shrimp survival at 400 individual/m^3	Not reported; membranes are typically the costliest component	Near-total water reuse; strong biosecurity barrier	Fouling behavior and full-scale cost data not yet documented
Constructed wetlands	Field-validated at multiple sites; transferable as a polishing stage	COD 70–76%; NH_4^+ 64–76%; NO_2^- 83–94% (species dependent)	Low OPEX (passive); added land area not separately costed	Passive, low energy polishing of dissolved nutrients	Performance is plant/substrate specific; adds further land requirement
Anaerobic co-digestion (biogas)	Lab/pilot scale - single farm-level trial (Tran et al., 2022)	CH_4 yield +53% with sugarcane bagasse	Digester ~90 million VND CAPEX; 6–8 million VND/	Displaces LPG, cuts fossil-fuel use and GHG footprint	High sludge salinity (up to 20‰) and low native C/N (5.2–

			crop LPG savings (Thao et al., 2024)		18.46) require reliable co-substrate supply
Aerobic co-composting	Lab/pilot scale - single bioassay (An et al., 2024)	C/N optimized to 19.7; net profit 786.67 VND/kg compost	Drying beds ~15 million VND (Thao et al., 2024)	Converts sludge to fertilizer, displaces synthetic inputs	Residual EC ~12 mS/cm limits use to < 20% blending; needs pre-desalination for broader crop use

Life Cycle Assessment and Carbon Footprint

Emission Hotspots in SISF Systems

The transition toward the SISF model effectively resolves productivity constraints but introduces profound ecological challenges. Insights from Nguyen et al. (2019) regarding the sustainability of shrimp exports highlighted that high-density intensive model carry severe environmental risks due to their absolute dependence on energy subsidies and material inputs.

To elucidate this issue, an energy sustainability model analysis for the MD shrimp industry conducted by Tien et al. (2019) confirmed that the primary barrier facing SISF is its high energy consumption intensity. Inventory analysis indicated that to produce 1 kg of commercial shrimp, the system consumes 78–97 MJ of energy, which translates to a massive greenhouse gas (GHG) emission load of 5.7–7.7 kg of carbon dioxide equivalent (CO_{2eq}) (Thang et al., 2024).

Deconstructing the emission hotspots through the lens of material mass balance, Trang et al. (2022) and Thao et al. (2024) demonstrated that the primary drivers directly influencing the global warming potential originate from two sources: commercial feed manufacturing and electrical energy consumption. To maintain DO levels and continuous hydrodynamic circulation for ultra-high stocking densities, mechanical aeration systems must operate 24/7, accounting for up to 80% of the cumulative energy demand, followed by water pumping systems at approximately 10% (Tien et al., 2024). Utilizing the national electricity grid (which is characterized by a high carbon emission factor) causes operational electricity consumption to contribute approximately 30% of the total carbon footprint across the entire shrimp farming life cycle (Thang et al., 2024).

Carbon Footprint of The Waste Recovery Model

When implementing circular technologies (such as biological settling pond systems, composting, and biogas digesters), an academic skepticism often arises: Does the construction and operation of these ancillary components introduce an additional emission burden that negates the overall ecological benefits? A LCA conducted by Nguyen et al. (2024) on a wastewater and waste sludge recirculation system at a representative farm (2.5 ha) in Ca Mau quantified the total GHGs for the treatment stage at 4,823.54 kg CO_2/crop (Figure 3).

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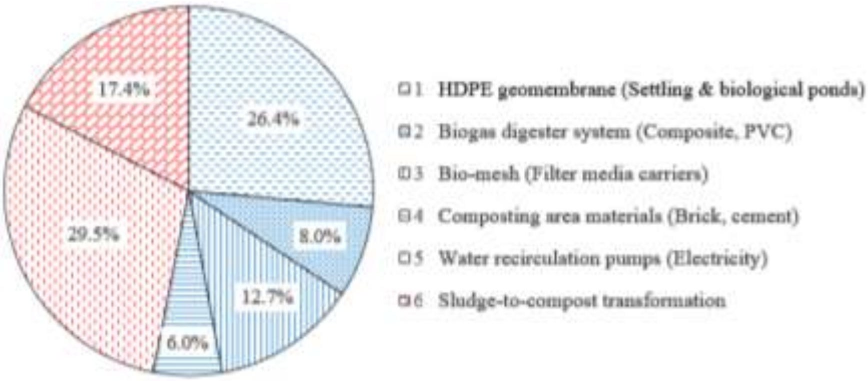

Figure 3. CO_2 emission inventory analysis of the water and waste sludge recovery system for super-intensive shrimp ponds per culture cycle

(Source: Extracted and compiled from LCA data in Thang et al., 2024)

- Construction phase (Material sources): The utilization of HDPE geomembrane liners (accounting for 26.4% of the generated CO_2), PVC piping, composite materials for the biogas digesters, and cement generates a notable emission load. However, in accordance with LCA amortization principles, these emissions are allocated exclusively to the initial culture cycle. As the system transitions into steady-state operation during subsequent years, the annualized CO_2 contributions from this category approach zero (Thang et al., 2024).
- Operational phase (Electricity consumption): The primary emission hotspot within the resource recovery system is the energy required to drive the recirculating hydrodynamics. Continuously operating the pumping system to recirculate a flow rate of 1,465.7 m^3/day from the secondary biological pond back into the culture system generates an emission load of 1,420.62 kg CO_2/crop, representing the highest share at 29.5% of the total treatment-stage emissions (Thang et al., 2024).

Despite the recorded GHGs originating from the recirculation pumps, experts affirm that the cumulative emissions of this process remain substantially lower than the ecosystem damages inflicted by direct effluent discharge (Trang et al., 2022). More importantly, by applying a carbon offsetting mechanism derived from utilizing the captured biogas to replace commercial liquefied petroleum gas (LPG) and reusing the compost product to substitute synthetic chemical fertilizers, the net carbon footprint of the entire circular configuration drops sharply, substantiating the superiority of the zero-discharge paradigm (Thao et al., 2024; Thang et al., 2024).

Energetic and environmental efficiency of circular models

Eco-Energetic Assessment and Inventory Across Models

Eco-energetic inventory analyses have clearly deconstructed the substantial disparity in performance between the conventional linear model and the closed-loop circular model:

- Linear SISF model (Conventional): To sustain growth rates under ultra-high stocking densities, the system demands massive feed inputs and continuous 24/7 mechanical aeration. According to a baseline assessment by Tien et al. (2024) across representative farms in the MD, the average energy use efficiency (the ratio of Energy Output / Energy Input) reached only 9.47. In this model, energy productivity was limited to a low level of 0.19 kg/MJ, the specific energy consumed to produce 1 kg of commercial shrimp was 5.58 MJ/kg, and the net surplus energy value generated by the system stood at 1,206,133 MJ/ha.

- Integrated circular SISF model: When the system transitions toward a closed-loop eco-circular framework (integrating biological treatment settling ponds for water recirculation and anaerobic digestion for waste sludge recycling), the performance profile exhibits a systemic breakthrough. Reclaiming biomethane to substitute heating fuels or grid electricity for cooking, coupled with reusing the recirculated water, profoundly optimizes the input energy flows. Experimental calculations by Tien et al. (2024) indicated that the energy use efficiency of this closed-loop ecosystem surged to 26.54 (approximately 2.8 times higher than the conventional model). Notably, energy productivity escalated sharply to 26.45 kg/MJ, specific energy intensity dropped drastically to an ultra-efficient level of just 0.04 MJ/kg, and the net energy surplus reached a massive 11,294,813 MJ/ha.

Table 5 consolidates these four energy indices side by side, highlighting the magnitude of improvement achieved by the eco-circular configuration relative to the conventional linear model.

Table 5. Comparison of energy efficiency indices between the conventional SISF model and the closed-loop eco-circular SISF model

Energy assessment index	**Unit**	**Conventional SISF model**	**Eco-circular SISF model**	**Improvement assessment**
Energy use efficiency	fold	9,47	26,54	Increased by ~2.8-fold
Energy productivity	kg/MJ	0,19	26,45	Breakthrough increase driven by by-product recovery
Specific energy	MJ/kg	5,58	0,04	Drastic reduction in energy consumption intensity per kg of shrimp
Net energy	MJ/ha	1.206.133	11.294.813	Energy surplus (biogas) reinvested back into the system

(Source: Extracted and compiled from Tien et al., 2024)

Environmental efficiency through the lens of material mass balance

From the perspective of macro-environmental efficiency management, quantifying the surplus nutrient flows discharged into the environment is performed based on the principle of mass balance. By applying Data Envelopment Analysis mathematical modeling integrated with the mass balance principle across 230 farms in the MD, a study by Trang et al. (2022) revealed that the baseline environmental efficiency of the farms averaged only 19.52%, generating a surplus nutrient load of up to 1,216 kg/ha discharged directly into natural water bodies.

However, empirical analysis established a paradox of the SISF model exhibited an environmental efficiency index of up to 40%, which is significantly higher than the 23.27% of semi-intensive models and the 17.08% of conventional intensive models (Trang et al., 2022). This optimization is attributed to the deployment of hightech solutions, such as Biofloc and closed-loop recirculating filtration systems, which enable proactive water quality control and improve shrimp feed utilization efficiency.

Nevertheless, the predictive model by Trang et al. (2022) also warned that stocking density exhibits a distinct negative correlation with environmental efficiency - meaning that higher densities accelerate the risk of nutrient leakage. Consequently, incentivizing synchronized investment in ancillary anaerobic waste recovery facilities and achieving international certifications (VietGAP, ASC, BAP) represent vital solutions for sustainable development, preventing SISF from transforming into concentrated point sources of pollution.

Life Cycle Costing and economic benefit analysis: Substantiating the feasibility of the circular economy

Analysis of Capital Expenditure and Operational Expenditure

To realize the Zero-discharge objective, the system requires the establishment of peripheral components. The required investment scale depends heavily on the integration capacity and construction materials. According to an analysis by Thao (2023) in Ca Mau, upgrading to a basic water recirculation system (encompassing geomembrane liners and two aerators for the biological pond) demands a cost of approximately 100 million VND.

For a comprehensive recovery system (reclaiming both water and waste sludge), estimates by Thao et al. (2024) indicate a substantial installation cost: settling ponds (30 million VND), biological ponds (30 million VND), sludge drying beds (15 million VND), and a biogas digester system (90 million VND).

In contrast, a LCC analysis conducted by Thang et al. (2024) optimized material cost flows and documented that the initial Capital Expenditure (CAPEX) for a similar engineering cluster was only 78.71 million VND, with an Operational Expenditure (OPEX) of approximately 5 million VND per crop. The variations across these reports demonstrate that farmers can flexibly customize the scale of their circular infrastructure investments to align with their financial capacities.

Regenerative Revenue Streams and Cost Reductions

The core value of the circular economy lies in converting waste into residual value. Extant studies have quantified three primary benefit streams:

- Alternative energy: Utilizing biomethane derived from waste sludge replaces commercial LPG for cooking. The resulting cost savings range from 6 million VND/crop (Thang et al., 2024) to 8 million VND/crop (equivalent to 2.025 million VND/month) (Thao et al., 2024).
- Fertilizer production: Compost generated from the sludge yields a significant secondary revenue stream, fluctuating from 6.8 million VND/crop (Thao et al., 2024) to 31.5 million VND/crop (Thang et al., 2024), depending on production volumes and market accessibility.
- Nutrient procurement cost reductions: This represents the largest hidden economic benefit. Upon implementing the circular configuration, the input costs per kilogram of nitrogen, phosphorus, and TOC decrease by 53.6%, 62.8%, and 40%, respectively. This enables farmers to directly recover a value equivalent to 0.44 million VND per kg of nitrogen and 1.86 million VND per kg of phosphorus (Thao et al., 2024).

Quantifying Value Per Functional Unit and Net Profit

To provide compelling evidence for farmers, macro-economic indices have been micro-scaled into environmental functional units. Regarding water resources, using the residual value method, Thao (2023) determined the economic value of water in shrimp aquaculture to be 6,000 VND/m^3. The establishment of a recirculating system does not significantly degrade this value, while successfully conserving 20% of natural freshwater intake requirements. In a more detailed accounting, each cubic meter of treated and recirculated wastewater yields a net value of 32.22 VND, and each kilogram of compost generates a profit of 786.67 VND (Thang et al., 2024).

Synthesizing the overall financial balance sheet, Tien et al. (2024) provided definitive evidence regarding the capacity of the closed-loop ecosystem: the net income of the SISF model integrating material and energy recirculation reached over 5 billion VND/ha, which is more than 8-fold higher than the 603 million VND/ha generated by the conventional model. Concurrently, the initial investment ratio also dropped sharply due to efficient capital amortization (Tien et al., 2024).

CHALLENGES AND POLICY RECOMMENDATIONS

Barriers and challenges in circular system implementation

The transition from a direct-discharge paradigm to a closed-loop recirculating model necessitates a comprehensive restructuring of farm infrastructure. The core challenges currently facing shrimp farmers include:

- CAPEX barriers: Establishing a synchronized material and energy recirculation system requires an initial capital investment that is 2 to 3 times higher than that of conventional open-culture shrimp farming models (Tien et al., 2024). This abrupt cost escalation stems from the mandatory requirement to construct a complex series of peripheral facilities and components. Specifically, investors must allocate substantial capital for HDPE geomembrane liners to seal settling ponds, construct secondary biological treatment ponds, invest in composite biogas digester systems, zone compost processing areas, and install a network of high-capacity recirculation pumps and mechanical aerators (Tien et al., 2024). For most farmers in the MD, this constitutes a financial burden that far exceeds their self-accumulation capacity.
- Spatial and land availability constraints: To thoroughly treat the massive volumes of wastewater and waste sludge characterized by high organic loads, circular SISF systems require a substantial surface area to arrange sequential settling and biological ponds in strict accordance with the required HRT (Tien et al., 2024). These structural zoning requirements (encompassing sludge storage ponds, wastewater settling units, and recirculated water storage basins) present an insurmountable challenge for smallholder farmers, who typically own cultivating areas under 1.0 hectare (Nguyen et al., 2019). This land fragmentation represents the most critical bottleneck hindering the scaling of these eco-technologies.
- Shortage of highly technical human resources: Operating a closed-loop ecosystem (such as RAS or Biofloc technologies) or controlling the kinetics of anaerobic digestion (biogas production) and aerobic composting cannot rely merely on intuitive, traditional farming experience. It demands a workforce of operators and technicians possessing deep knowledge of water quality management, proficiency in controlling sensitive biochemical indices (such as C/N ratios, dissolved oxygen levels, and toxic gas concentrations including NH_3 and H_2S), and the capability to maintain microbial community balance under ultra-high stocking

densities (Tien et al., 2024). The current deficit of this high-quality human capital within the rural labor market significantly retards the effective adoption and operation of these systems.

- Regulatory and certification barriers: Beyond capital, land, and labor constraints, the current national technical regulation (QCVN 40:2025/BTNMT) no longer mandates NH_4^+ control for aquaculture effluent, even though empirical siphon-wastewater concentrations remain toxicologically significant (101.21 mg/L; Table 1), creating a gap between regulatory compliance and ecological protection. Aligning domestic thresholds with international BAP/ASC criteria - which are stricter on TSS (< 50 mg/L) than the national standard - would give farmers a single, clearer design target rather than the two-tier compliance landscape (national vs. export market) described in Section 3.1.1.

Policy recommendations: Prioritizing the development of cooperative models

To thoroughly address the systemic barriers regarding capital scarcity, land fragmentation, and the limited management capacity of individual farmers, the most strategic macro-level solution currently available is to restructure production configurations through the development and consolidation of agricultural cooperative models.

Horizontal integration via the cooperative model enables smallholder farmers to tightly interlink their operations, thereby overcoming the inherent disadvantages associated with diseconomies of scale (Nguyen et al., 2019). By participating in cooperatives, individual farmers can pool adjacent land resources to construct centralized, collective wastewater and waste sludge treatment facilities. This configuration allows them to share the initial capital expenditures for expensive machinery and collectively utilize community-based biogas distribution networks to optimize the bioenergy generated from waste sludge (Thao et al., 2022). Crucially, backed by a communal fund, the cooperative possesses the financial capacity required to jointly hire highly qualified technical experts to operate the system safely and optimally, thereby mitigating the critical human resource bottleneck (Tien et al., 2024).

Furthermore, in the context of escalating technical barriers within the global seafood market, compliance with stringent export standards regarding sustainability and eco-biosecurity constitutes a mandatory passport for Vietnamese shrimp to penetrate high-premium markets like the EU, the United States, and Japan (Nguyen et al., 2019). However, the auditing costs, complex record-keeping protocols, and technical infrastructure criteria mandated by these certification frameworks generally exceed the capacities of small-scale producers. In this scenario, the cooperative acts as a representative legal entity to facilitate group certification (Nguyen et al., 2019). This mechanism not only substantially curtails assessment expenses for individual members and simplifies the supply chain structure, but also supports smallholders in retaining their farm ownership rather than being driven out of the shrimp industry by the pressures of international integration (Nguyen et al., 2019).

Ultimately, establishing robust cooperatives creates the fundamental prerequisite for executing vertical integration with upstream seafood enterprises and conglomerates. Through off-take contracts and technology transfer agreements, large corporations can supply specific pathogen-free high-quality post larvae, standardized feed, and recirculating treatment technologies while guaranteeing stable market outputs. In return, the cooperative manages and monitors its members to ensure strict compliance with Zero-discharge regulations (Nguyen et al., 2019). This symbiosis between organized smallholders within cooperatives and large-scale enterprises represents the definitive pathway for the super-intensive shrimp aquaculture industry in the MD to simultaneously achieve national production targets and secure long-term sustainable development aligned with circular economy principles.

CONCLUSION

The booming development of SISF in the MD has contributed tremendously to national export turnover. However, the nutrient kinetic imbalance - where shrimp only assimilate approximately 23–30% of nitrogen and phosphorus from the feed - has generated a massive ecological footprint in the form of wastewater and pond bottom sludge. This review paper has systematized scientific evidence to affirm that transitioning from a 'Linear production - Direct discharge' paradigm to a 'Circular economy' framework is not merely a temporary fix, but a vital imperative for the long-term sustainable development of the shrimp industry.

Through a comprehensive deconstruction of these biogeochemical cycles, this study draws three core conclusions:

- First, regarding treatment and recovery technologies: The synchronized integration of internal ecological technologies (BFT, RAS) and external configurations (biological settling ponds, constructed wetlands) has established a robust biosecurity barrier. These systems not only thoroughly control organic and nutrient pollution parameters to comply with current national technical regulations (QCVN 40:2025/BTNMT) but also realize the Zero-discharge objective by minimizing seepage and water exchange requirements to the absolute maximum. Concurrently, shrimp pond waste sludge has been proven to be a high-value resource bank. Applying optimized hydrodynamic mixing regimes coupled with anaerobic co-digestion using agricultural by-products (such as sugarcane bagasse) boosts biomethane yields by up to 53%. Similarly, aerobic co-composting of shrimp sludge with coconut coir pith optimizes the C/N ratio to an ideal level of 19.7, generating a mineral-rich organic fertilizer source for agriculture.
- Second, regarding comprehensive sustainability assessments: Through the lenses of LCA and LCC, the circular shrimp farming model has demonstrated absolute superiority. Although it demands electrical energy for the water recirculation phase (accounting for 29.5% of the total treatment-stage emissions), the net surplus energy generated by this eco-system is dozens of times higher than that of the open conventional model. Recycling waste into bioenergy and agricultural inputs yields direct profits per functional unit, fully transforming environmental remediation costs into residual revenue streams.
- Third, regarding barriers and policy planning: The primary bottleneck of this ecological transition lies in the extremely high CAPEX and the land footprint constraints faced by individual smallholders. Consequently, establishing agricultural cooperative models to leverage economies of scale - enabling group certifications (such as ASC, BAP) and attracting green credit from upstream lead enterprises - represents the decisive macro level solution.

To further advance the circular economy in aquaculture, future research should focus on two primary fronts: (i) decoding the microbial metagenomics within the rhizosphere of halophytic plants in constructed wetlands to optimize denitrification pathways; and (ii) developing low-cost, natural desalination models to thoroughly eliminate the EC load in bottom sludge, thereby broadening the application scope of the derived compost on salt-sensitive crops.

Beyond these, three concrete gaps merit attention: (i) multi-farm, multi-year replication of anaerobic co-digestion and composting trials to establish standardized CAPEX/OPEX benchmarks under MD conditions, since the current economic figures rest on single demonstration sites; (ii) independent techno-economic and fouling studies of M-RAS at commercial scale, given that its promising survival rate results are not yet matched by cost data; and (iii) harmonization of national effluent regulations with export market certification thresholds (e.g., BAP TSS limits) to remove the two-tier compliance burden currently faced by exporting farms.

The synergy between eco-technological innovation and value chain management will serve as the driving force to position the MD as a global paradigm for sustainable, low emission super intensive shrimp aquaculture.

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