Performance Of A Coconut Fiber-packed Down-flow Hanging Filter For Lower-strength Swine Wastewater Treatment

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Swine farming generates large volumes of wastewater requiring treatment before discharge. In small-scale Vietnamese farms, barn flushing dilutes biogas digester effluents, producing lower-strength wastewater that still exceeds discharge standards. This study evaluated a down-flow hanging filter (DHF) reactor packed with coconut fiber for the treatment of such lower-strength swine wastewater (chemical oxygen demand (COD): 741.90±25.98 mg/L; biochemical oxygen demand (BOD_5): 127.93±4.01 mg/L; total nitrogen (TN): 44.67±2.92 mg N/L; total phosphorus (TP): 35.77±2.21 mg P/L). Two parallel reactors were operated: a coconut fiber-packed reactor (DHF1) and an unpacked control (DHF0). During stable operation (days 15-44), DHF1 achieved removal efficiencies of 77.05±10.03% for COD, 79.30±7.06% for BOD_5, 56.05±8.38% for TN, and 63.82±7.44% for TP, significantly higher than those of DHF0 (54.45±7.11%, 39.83±13.16%, 35.07±7.76%, and 35.53±8.53%, respectively). The improved treatment performance of DHF1 was associated with enhanced biomass retention within the coconut fiber matrix. First-order kinetic analysis further confirmed that coconut fiber packing enhanced apparent first-order rate constants (k) by 1.9-3.1-fold across all parameters compared to the unpacked control, providing concentration-independent evidence of enhanced reactor performance applicable to system design and scale-up. These results indicate that coconut fiber is a sustainable and biodegradable alternative for decentralized post-treatment of lower-strength swine wastewater from small-scale farms with diluted effluents.

Keywords: Down-flow hanging filter; Coconut fiber; Lower-strength wastewater; Small-scale farms; Organic matter removal; Nutrient removal

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1. Introduction

Swine farming is a major component of Vietnam's agricultural sector. However, its rapid expansion has resulted in the generation of large volumes of wastewater characterized by high organic and nutrient loads, posing significant risks to soil and aquatic environments if inadequately treated [1–3]. Several physicochemical and biological technologies have been applied for swine wastewater treatment, including electrocoagulation, electrochemical processes, anaerobic digestion (AD), constructed wetlands (CWs), and membrane bioreactors (MBRs) [4, 5]. Despite their demonstrated effectiveness under controlled conditions, these technologies are often constrained by high capital and operational costs, complex operational requirements, and limited nutrient removal efficiency when treating compositionally variable wastewaters generated under different farm management conditions.

In Vietnam, anaerobic digestion remains the predominant treatment option due to its operational simplicity and potential for energy recovery. However, biogas effluents typically retain residual organic matter and nutrients that exceed permissible discharge limits, underscoring the need for effective post-treatment processes [6, 7]. It is important to recognize that swine wastewater strength varies considerably depending on farm scale, animal stocking density, management practices, and the extent of water use for barn cleaning. In small-scale swine farms, which are predominant in rural areas of Vietnam, routine flushing of swine houses for hygiene purposes introduces substantial volumes of cleaning water into the effluent stream, significantly diluting organic matter and nutrient concentrations relative to those reported for intensive large-scale operations [3, 4]. Although such lower-strength effluents are widespread at the community level and representative of a large fraction of small-farm wastewater in Vietnam, they remain comparatively understudied with respect to appropriate post-treatment technologies [8, 9]. The development of simple, low-cost, and decentralized treatment systems specifically suited to the lower-strength wastewater generated by small-scale farms, therefore, represents a relevant and practical research priority.

In attached-growth biological treatment systems, the characteristics of carrier media are fundamental to process efficiency, as they directly influence biofilm formation, biomass retention, and mass transfer processes [10]. The physicochemical properties of the media, such as surface area, porosity, and material composition, govern microbial attachment and biofilm stability, thereby determining treatment performance [11]. Conventional carriers, including polyurethane sponge and synthetic plastics, are widely applied due to their high durability and well-developed pore structures [10]. However, these materials present several limitations, including high cost, poor biodegradability, and environmental concerns associated with their long-term use and disposal. Recent studies have therefore emphasized the development of sustainable alternatives, particularly natural and waste-derived materials (e.g., biochar, lignocellulosic biomass, and mineral-based media), which offer comparable biofilm support while improving environmental compatibility and reducing operational costs [11]. Among these alternatives, lignocellulosic materials have attracted particular attention due to their porous structure and abundant surface functional groups, which facilitate microbial attachment and substrate retention. Nevertheless, the performance and functional role of specific natural fibers as carrier media under decentralized, lower-strength wastewater treatment conditions remain insufficiently characterized, and their application in engineered biofilm reactors requires further systematic investigation [10].

The down-flow hanging filter (DHF) reactor has attracted increasing attention as a decentralized biological treatment technology suited to resource-limited settings. The DHF concept is derived from the down-flow hanging sponge (DHS) process, which enables wastewater treatment through passive air diffusion without mechanical aeration [11, 12]. Similar to DHS, DHF reactors promote the development of stratified microbial microenvironments, with aerobic conditions near the carrier surface and anoxic or anaerobic zones within the carrier matrix, thereby facilitating simultaneous organic matter oxidation and nitrogen transformation [8, 13]. These characteristics make DHF a particularly suitable platform for evaluating the performance of different carrier materials under attached-growth conditions in decentralized applications. Nevertheless, most reported DHF and DHS configurations rely on synthetic polyurethane sponge as the primary packing material [14]. which is associated with relatively high cost, limited biodegradability, and increasing concerns regarding long-term environmental sustainability.

To address these limitations, the present study investigates the feasibility of using natural coconut fiber as a carrier in a DHF reactor for lower-strength swine wastewater treatment. Coconut fiber is an abundant agricultural by-product in Vietnam and possesses a highly porous structure, large specific surface area, and strong water-retention capacity, which are favorable for microbial attachment and biofilm development [15, 16]. In addition, its lignocellulosic composition and fibrous morphology may enhance the retention of particulate organic matter and provide a sustained carbon source through gradual hydrolysis, thereby potentially supporting biological nutrient removal processes. Among various natural materials, coconut fiber represents a promising yet underexplored candidate for use as an attached-growth medium in engineered wastewater treatment systems. Previous studies have explored coconut fiber in filtration systems and constructed wetlands. However, its role as a carrier medium in engineered biofilm reactors for decentralized swine wastewater post-treatment has not been systematically investigated [17].

Accordingly, this study aimed to evaluate the treatment performance of a coconut fiber-packed DHF reactor treating lower-strength swine wastewater under continuous operation. Reactor performance was assessed in terms of organic matter and nutrient removal (chemical oxygen demand, COD; biochemical oxygen demand, BOD_5; total nitrogen, TN; and total phosphorus, TP), and first-order kinetic analysis was applied to provide concentration-independent, quantitative comparisons of treatment performance. The findings are expected to provide practical insights into the development of cost-effective, low-energy, and sustainable post-treatment technologies for small-scale swine farms, with broader implications for decentralized wastewater management in Vietnam and similar developing country contexts.

2. Materials and methods

2.1. Reactor configuration and packing material

Two laboratory-scale down-flow hanging filter (DHF) reactors were constructed from transparent glass to allow visual observation of flow distribution and biofilm development. Each reactor had external dimensions of 150×150×1000 mm and an effective volume of 6 L. The reactor comprised two functional zones: (i) a biological treatment zone (600 mm height) containing the hanging packing material, and (ii) a sludge collection zone (200 mm height) with a 45° sloped bottom to facilitate solids settling and sludge withdrawal. Sampling ports were installed at the effluent outlet and at the bottom of the reactor. A schematic diagram of the reactor configuration is shown in Fig. 1.

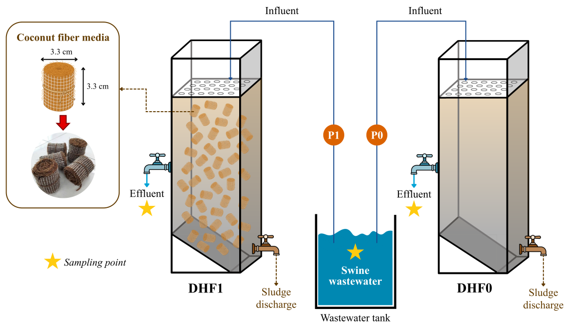

Fig. 1. Schematic diagram of two down-flow hanging filter (DHF) reactors in the laboratory.

Two identical reactors were operated in parallel. The experimental reactor (DHF1) was packed with coconut fiber media as a carrier, while the control reactor (DHF0) was operated without packing material. Coconut fiber was selected due to its low cost, high porosity, biodegradability, and wide availability in Vietnam.

A total of 88 cubic coconut fiber pieces (3.3×3.3×3.3 cm) were used in DHF1. Before installation, the coconut fiber media were pretreated to remove soluble impurities, residual pigments, and fine particles that could interfere with water quality analyses. The media were soaked in warm water (40-50°C) for 24 h, followed by repeated rinsing with clean tap water until the rinse water became completely colorless. After washing, the coconut fiber cubes were drained and air-dried in the shade at ambient temperature to maintain their physical structure and prevent thermal degradation. The pretreated media were then stored in clean sealed containers until use.

2.2. Operating conditions

To promote microbial attachment and initial biofilm formation, the pretreated coconut fiber media were immersed in activated sludge obtained from a swine biogas digester (Mo Cay commune, Vinh Long province, Vietnam) for 7 days. During this period, 100-200 mL of swine wastewater was added daily to sustain microbial activity.

Subsequently, both reactors were inoculated with a 1:1 (v/v) mixture of swine wastewater and activated sludge and operated in batch mode for 7 days as an acclimation phase. Effluent samples were collected daily to monitor COD removal. Acclimation was considered complete when COD removal efficiencies stabilized, defined as variations of less than 5% over consecutive days. Following acclimation, both reactors were operated continuously. Influent swine wastewater was collected from the same biogas digester and homogenized before use to minimize fluctuations in the actual wastewater. The influent characteristics during operation were as follows: COD 741.90±25.98 mg/L, BOD_5 127.93±4.01 mg/L, TN 44.67±2.92 mg N/L, and TP 35.77±2.21 mg P/L. The influent was supplied using a peristaltic pump and evenly distributed at the top of each reactor using a perforated distribution plate, allowing downward flow in a dripping mode through the reactor column. In DHF1, wastewater passed through the coconut fiber packing, whereas in DHF0, it flowed through the empty column. The observed TN and TP concentrations are representative of lower-strength effluents commonly generated at small-scale farms in Vietnam. At this farm, wastewater from the biogas digester undergoes further dilution by water routinely used for barn flushing and equipment cleaning, a practice that is widespread among smallholder pig farmers in the region. Consequently, the influent in this study characterizes a lower-strength swine wastewater, which nonetheless requires effective treatment to meet discharge standards. Despite their reduced pollutant loads, such effluents represent a prevalent and environmentally significant treatment challenge in rural agricultural contexts.

The influent flow rate was set to 0.75 L/h, with a hydraulic retention time (HRT) of 8 h. The organic loading rate (OLR) ranged from 2.15 to 2.31 kgCOD/m3.day, based on the influent COD concentration. The temperature was maintained at 28-32°C, and the pH was adjusted to 6.5-7.5 using NaHCO3 and HCl. The total experimental duration was 44 days, including reactor adaptation and stable operation. The performance evaluation was conducted using data collected during stable operation (days 15-44) to assess the removal of COD, BOD_5, TN, and TP. Kinetic behavior was analyzed employing an apparent first-order model. Process stability was appraised based on the temporal variations in removal efficiency observed during continuous operation.

2.3. Analytical methods

Water quality parameters, including COD, BOD_5, TN, and TP, were analyzed according to Standard Methods [18]. Effluent samples were collected once daily from each reactor, stored at 4°C, and analyzed within 24 h to minimize sample degradation. COD was determined using the closed reflux dichromate method, while BOD_5 was measured using the 5-day incubation method at 20°C. TN was analyzed using a high-temperature combustion chemiluminescence method with a TOC/TN analyzer, providing direct measurement of total nitrogen. TP was determined by the ascorbic acid colorimetric method, with absorbance measured at 880 nm using a UV-Vis spectrophotometer. All analyses were performed in triplicate to ensure accuracy and reproducibility.

2.4. Statistical analysis

All results are reported as mean ± standard deviation (SD). Statistical differences between DHF1 and DHF0 were evaluated using a one-way analysis of variance (ANOVA) in RStudio. Differences were considered statistically significant at p-value <0.05.

2.5. Kinetic analysis

To further quantify treatment performance, removal kinetics of COD, BOD_5, TN, and TP were evaluated using an apparent first-order kinetic model, which is widely applied for attached-growth biofilm reactors. The model is expressed as:

$$C_e = C_0 e^{-kt} \tag{1}$$

where C_0 and $C_e(\mathrm{mg/L})$ are influent and effluent concentrations, respectively, $t(\mathrm{h})$ is the hydraulic retention time (HRT), and $k\left(\mathrm{h}^{-1}\right)$ is the apparent first-order removal rate constant. The value of k was calculated as:

$$k = -\frac{\ln\left(C_e/C_0\right)}{t} \tag{2}$$

Kinetic coefficients were calculated using average influent and effluent concentrations during the stable operational period (days 15-44). The calculated k values were compared between DHF1 and DHF0 to evaluate the effect of coconut fiber packing on removal rates [19].

3. Results and discussion

3.1. Organic matter removal characteristics of the DHF reactors

The organic matter removal performance of the two DHF reactors treating swine wastewater was evaluated under continuous operation at an HRT of 8 h. During the stable operational period (days 15-44), the influent exhibited relatively high and consistent organic strength, with average COD and BOD_5 concentrations of 741.90±25.98 mg/L and 127.93±4.01 mg/L, respectively (Fig. 2). The resulting BOD_5/COD ratio of 0.17±0.01 indicates that a substantial fraction of organic matter was slowly biodegradable or refractory, a characteristic commonly reported for swine wastewater following anaerobic digestion [9, 20]. This wastewater poses considerable challenges for biological post-treatment processes, as efficient removal requires effective biomass retention, prolonged substrate-microorganism contact, and the capacity to transform complex organic compounds [21]1].

In Fig. 2, both reactors reached stable performance after the acclimation phase; however, substantial differences in organic matter removal were observed between the two configurations. The DHF1 consistently outperformed the control DHF0 reactor in terms of both COD and BOD_5 removal throughout the monitoring period. The average COD removal efficiency in DHF1 was 77.05±10.03%, which was significantly higher than the 54.45±7.11% achieved by DHF0. One-way ANOVA confirmed that the difference in COD removal performance between the two reactors was statistically significant (p-value <0.0001). Similarly, DHF1 achieved a markedly higher average BOD_5 removal efficiency of 79.30±7.06%, compared to only 39.83±13.16% in DHF0, with the difference again being highly significant (p-value <0.0001). In addition to achieving higher average removal efficiencies, the effluent COD and BOD_5 of DHF1 were lower than those of DHF0, which were 170.50±75.08 and 337.90±53.57 mg/L, and 26.47±8.95 and 76.93±16.70 mg/L, respectively. Although the temporal variability of effluent COD in DHF1 was comparable to or slightly higher than that observed in DHF0, the substantially lower effluent concentrations indicate a higher effective organic loading tolerance in the packed DHF reactor. For BOD_5, DHF1 showed lower effluent concentrations and reduced variability, indicating improved process robustness.

The superior organic matter removal observed in DHF1 reflects the functional role of coconut fiber as a structured support medium, facilitating enhanced contact between wastewater constituents and active microbial sites. The observed organic matter removal in DHF1 can be attributed primarily to the combined physical retention and biological degradation mechanisms of the coconut fiber media [22]. The fibrous, highly porous structure of coconut fiber provides a large specific surface area, facilitating the interception and temporary retention of suspended solids and particulate organic matter. This retention promotes a more gradual release and conversion of complex substrates, thereby improving substrate accessibility for microbial degradation [23]. Besides, improvements in COD and BOD_5 removal have been reported for other porous bio-carriers employed in attached-growth systems treating high-strength agricultural wastewater [24]].

In addition, coconut fiber served as a structurally stable matrix supporting the accumulation of active microbial communities [25]]. Their rough surface morphology and heterogeneous microstructure enhanced the distribution and persistence of microbial populations within the reactor, thereby reducing the risk of biomass washout compared to the unfilled DHF0 reactor, which relied primarily on suspended biomass [26]. Within the coconut fiber matrix, oxygen transfer limitations and localized substrate gradients likely created functionally diverse zones for sequential organic matter degradation [25]. These stratified biofilm structures facilitate the oxidation of readily biodegradable organic matter in aerobic regions while enabling further transformation of slowly biodegradable and refractory compounds in deeper anoxic zones. These microenvironmental conditions are particularly advantageous under the low influent BOD_5/COD ratios observed and contribute to improved carbon utilization efficiency [26]. Therefore, the enhanced and stable organic matter removal achieved by the coconut fiber-based DHF reactor established favorable conditions for subsequent nutrient transformation processes. High biomass retention, well-developed biofilms, and the formation of aerobic-anoxic microenvironments provided a functional basis for coupled nitrogen and phosphorus removal, as discussed in the following sections.

Taken together, these findings highlight that coconut fiber functions not only as a physical filtration medium but also as an effective biofilm carrier that fundamentally alters reactor behavior. The combination of its high porosity, rough surface morphology, and lignocellulosic composition enables simultaneous enhancement of solids retention, microbial attachment, and internal carbon availability [25, 26]]. These properties collectively contribute to the development of stratified biofilm structures with coexisting aerobic and anoxic microenvironments, which are essential for efficient organic matter degradation, particularly under low BOD_5/COD conditions [27, 28]. Unlike conventional inert synthetic media, coconut fiber may also retain and gradually release organic substrates, thereby sustaining microbial activity when readily biodegradable carbon is limited. This multifunctional role provides a mechanistic basis for the enhanced COD and BOD_5 removal observed in the packed DHF reactor.

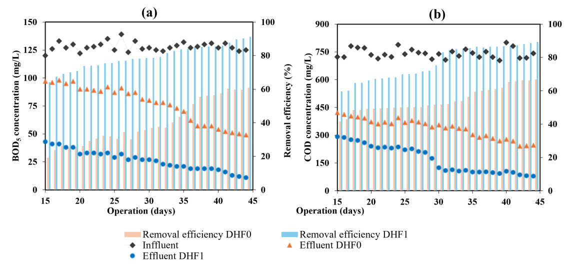

Fig. 2. Removal performance of (a) BOD_5 and (b) COD in the DHF0 and DHF1 reactors during stable operation (days 15-44).

3.2. Effect of coconut fiber media on total nitrogen removal

The incorporation of coconut fiber media resulted in a pronounced enhancement of TN removal in the DHF reactor. During the stable operational period (days 15-44), DHF1 consistently outperformed DHF0, achieving an average removal efficiency of 56.05±8.38% compared to 35.07±7.76% in DHF0 (Fig. 3). One-way ANOVA confirmed that the difference in TN removal efficiency between the two configurations was statistically significant (p-value <0.0001), indicating a robust and systematic effect of the coconut fiber packing on nitrogen transformation performance. This improvement highlights the functional role of coconut fiber as an effective attached-growth medium in the DHF reactor, particularly in enhancing biomass retention and promoting biofilm development.

Temporal profiles further revealed that DHF1 not only achieved higher average TN removal but also improved operational stability. As shown in Fig. 3, effluent TN concentrations in DHF1 decreased progressively over time and remained consistently lower than those in DHF0, with an average value of 19.60±3.72 mg N/L and 28.97±3.61 mg N/L, respectively. The difference between the two reactors could be attributed to operating under identical hydraulic conditions and receiving the same external influences; the observed performance enhancement can primarily be attributed to the coconut fiber media, which influenced biomass retention and the internal reactor microenvironment rather than external operational factors. The improved TN removal in DHF1 can be reasonably associated with the formation of attached biofilms on the coconut fiber media and the resulting development of heterogeneous redox conditions within the biofilm matrix [27, 28]. Under down-flow operation, dissolved oxygen penetration was likely restricted to the outer biofilm layers, while oxygen depletion toward the interior promoted the formation of oxygen-limited or anoxic microzones [29], which could be spatially separated from oxic zones. This spatial separation is widely recognized as conducive to coupled nitrification-denitrification pathways in biofilm-based treatment systems [12, 21].

Biomass retention and effective SRT were also likely key factors in enhancing nitrogen removal. Nitrifying microorganisms are slow-growing and particularly susceptible to washout under short SRT conditions [30, 31]. In the absence of attachment surfaces, as in DHF0, biomass retention depends largely on suspended solids, which limits the accumulation and persistence of nitrifying populations. In contrast, the coconut fiber matrix in DHF1 provided extensive attachment sites, effectively decoupling SRT from HRT and facilitating the enrichment and long-term stability of nitrogen-transforming microbial communities [27, 31]. The progressive improvement in TN removal observed in DHF1 over the operational period is consistent with the maturation of an attached biofilm capable of sustained nitrogen conversion.

Despite the relatively low influent BOD_5/COD ratio, DHF1 maintained stable TN removal performance. This indicates that TN removal was not solely dependent on readily biodegradable dissolved organic carbon. Instead, the physical retention of particulate and slowly biodegradable organic matter within the coconut fiber matrix likely supplied a sustained internal carbon source through gradual hydrolysis, thereby supporting nitrogen reduction processes in anoxic microzones [32–34]. In contrast, the limited retention of particulate organics in DHF0 reduced electron donor availability, constraining nitrogen removal efficiency under continuous-flow conditions. Therefore, the statistically significant enhancement of TN removal in DHF1 can be attributed to the combined effects of improved biomass retention, biofilm-associated redox heterogeneity, and sustained internal carbon availability. These features collectively underscore the suitability of coconut fiber-packed DHF reactors for stable nitrogen removal from lower-strength, compositionally variable swine wastewater representative of small-scale farms. Collectively, these results further highlight the role of coconut fiber as an effective biofilm carrier, facilitating nitrogen removal through integrated mechanisms of biomass retention, internal carbon supply, and the development of redox-stratified microenvironments.

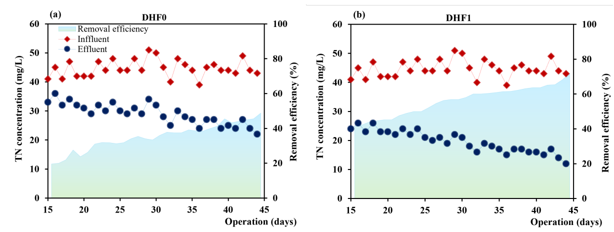

Fig. 3. Total nitrogen (TN) removal in (a) DHF0 and (b) DHF1 reactors during stable operation (days 15-44).

3.3. Phosphorus uptake and removal behavior of the DHF reactors

In addition to improving organic matter and nitrogen removal, the incorporation of coconut fiber media substantially enhanced TP removal in the DHF reactor. During the stable operational period (days 15-44), DHF1 achieved an average TP removal efficiency of 63.82±7.44%, which was markedly higher than that of DHF0 (35.53±8.53%) (Fig. 4). One-way ANOVA confirmed that the difference in TP removal performance between the two reactors was statistically significant (p-value <0.0001), indicating a systematic and reproducible effect of the coconut fiber media on phosphorus removal.

Influent TP concentrations remained relatively constant throughout the experiment period (35.77±2.21 mg P/L), reflecting the characteristic nutrient-rich nature of swine wastewater. As shown in Fig. 4, effluent TP concentrations in DHF1 gradually decreased with operational time and stabilized after approximately 35 days at 9.89±0.78 mg P/L. This stabilization indicates that the microbial community and biofilm structure in DHF1 had adapted effectively to the prevailing operational conditions and phosphorus loading [35]. In contrast, DHF0 exhibited substantially higher concentrations (20.00±1.32 mg P/L) and greater temporal fluctuations, reflecting limited phosphorus retention capacity and reduced operational robustness in the absence of carrier media [36].

The enhanced TP removal in DHF1 can be attributed to the increased capacity for phosphorus capture and storage within the coconut fiber matrix. The high specific surface area and porous, fibrous structure provided favorable conditions for the formation of thick, well-developed biofilms, thereby supporting the enrichment of phosphorus-accumulating microorganisms [37, 38]. The extended SRT in DHF1 further facilitated intracellular polyphosphate storage, thereby sustaining biological phosphorus uptake. In contrast, biomass washout in DHF0 constrained microbial phosphorus assimilation and limited long-term phosphorus retention [39]. In addition to biological uptake, the coconut fiber matrix likely enhanced the retention and recycling of phosphorus within the reactor system. Aerobic regions near the biofilm surface likely favored phosphorus uptake, while deeper anoxic zones may have supported transient phosphorus release followed by re-uptake, a phenomenon commonly observed in biofilm-based systems [38, 40]. Although phosphorus speciation was not directly quantified in this study, the consistently high TP removal efficiency observed in DHF1 provides indirect evidence for the functional importance of such micro-scale redox heterogeneity [41].

Physical retention of particulate-associated phosphorus also contributed to TP removal in DHF1. The interwoven coconut fiber matrix acted as an effective biofiltration layer, capturing suspended solids and particulate phosphorus, which could subsequently be incorporated into the biofilm or removed with accumulated sludge [42]. This mechanism is particularly relevant under stable operation, when biofilm thickness and solids retention increase over time. In contrast, the lack of a filtration medium in DHF0 facilitated the washout of particulate phosphorus, thereby limiting overall TP removal efficiency [43]

The improved phosphorus removal performance of DHF1 is closely linked to the enhanced organic matter and nitrogen removal discussed. Efficient COD and BOD removal reduced competition for dissolved oxygen, while stable biomass retention supported coordinated organic degradation and phosphorus uptake processes [44–46]]. Collectively, these synergistic effects highlight the multifunctional role of coconut fiber media in strengthening nutrient removal pathways. The statistically significant and stable TP removal achieved by the coconut fiber-based DHF reactor underscores its potential as a robust treatment option for nutrient-rich swine wastewater under increasingly stringent discharge standards. Overall, these results reinforce the multifunctional role of coconut fiber as a biofilter medium, contributing to phosphorus removal through biofilm-mediated uptake, solids retention, and micro-scale redox interactions.

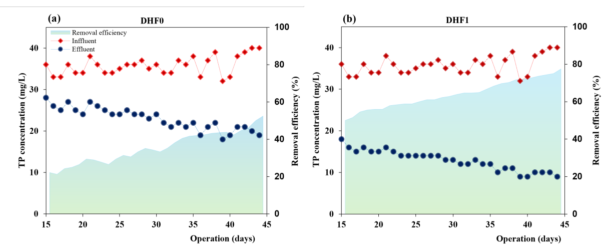

Fig. 4. Location of the KVMRT project

3.4. Kinetic evaluation of pollutant removal

Table 1. Apparent first-order kinetic coefficients (k) for pollutant removal in DHF reactors during the stable operational period (days 15-44).

Parameter	k ($\mathbf{h^{-1}}$) in DHF0	k ($\mathbf{h^{-1}}$) in DHF1
COD	0.100 ± 0.021	0.196 ± 0.057
BOD_5	0.067 ± 0.029	0.205 ± 0.046
TN	0.055 ± 0.015	0.105±0.024
TP	0.056 ± 0.017	0.130 ± 0.027

To more clearly quantify the improvement in treatment performance achieved by incorporating coconut fiber as a packing medium, apparent first-order kinetic coefficients (k) were determined for COD, BOD_5, TN, and TP during the stable operational period (days 15-44). Compared with evaluating treatment performance solely based on removal efficiency (%), the kinetic coefficient k reflects the reaction rate and therefore enables a more rigorous assessment of the intrinsic treatment capacity of the DHF system under a constant hydraulic retention time (HRT). The use of first-order kinetic models to describe the removal of organic matter and nutrients in biological treatment systems, including constructed wetlands, has been widely adopted and serves as an important basis for design and performance evaluation. The importance of this kinetic approach is further amplified in the context of lower-strength wastewater treatment, when influent pollutant concentrations are relatively low. Percentage removal efficiencies alone may underestimate differences in reactor performance, as small absolute differences in effluent concentrations can produce large relative differences in removal rates. The rate constant k, being concentration-independent, provides a more reliable measure of reaction intensity and biofilm activity, enabling direct performance comparison across studies treating wastewaters of varying strength. Furthermore, k values calculated under defined HRT conditions serve as fundamental design parameters for sizing DHF reactors to meet target effluent quality, which is critical for practical implementation at small-scale farms where engineering resources are limited [19, 47].

The results presented in Table 1 indicate that DHF1 consistently exhibited higher k values than DHF0 for all investigated parameters. Specifically, the COD removal kinetic coefficient in DHF1 was approximately 2 times higher than that in DHF0, while the BOD_5 kinetic coefficient increased by approximately 3 times. This finding suggests that coconut fiber significantly enhanced the biodegradation rate of organic compounds, likely by improving substrate–microorganism interactions and facilitating more efficient utilization of retained organic matter within the reactor matrix. For nutrient removal, kinetic enhancement was also evident. The k value for TN removal in DHF1 was approximately 1.9-fold higher than that in the unpacked system, whereas the TP kinetic coefficient increased by approximately 2.3-fold. These results indicate that coconut fiber packing improved nitrogen and phosphorus removal capacity in the DHF system, reflecting an overall intensification of biological conversion processes rather than solely an increase in removal efficiency. Similar improvements in first-order kinetic coefficients through optimization of system configuration and operational conditions have also been reported in wetland kinetic modeling studies for COD, BOD_5, and nitrogen removal [48]. Overall, the kinetic evaluation provides quantitative evidence that coconut fiber is an effective attached-growth medium that enhances pollutant removal rates in the DHF system by increasing the effective reaction efficiency under identical hydraulic conditions, supporting its potential application as a low-cost, environmentally friendly solution for post-treatment of swine wastewater.

3.5. Limitations and future perspectives

The present study was conducted over a relatively short operational period at a single hydraulic retention time; therefore, long-term operation under varying hydraulic conditions is required to fully assess carrier durability and process stability. Regarding physicochemical characterization, this study did not perform SEM imaging and BET surface area analysis to elucidate surface properties relevant to biofilm attachment. In addition, nitrogen and phosphorus species were not differentiated, limiting the quantitative interpretation of specific nutrient transformation pathways. Microbial community structure and functional activity were also not examined. Future studies should integrate extended reactor operation with detailed analysis of physicochemical characterization, nutrient speciation, and microbial analyses to further elucidate removal processes and support reactor optimization.

4. Conclusions

This study demonstrated that incorporating coconut fiber as a packing material significantly enhanced the performance of a down-flow hanging filter (DHF) reactor treating swine wastewater. Compared with the unpacked control reactor, the coconut fiber-packed DHF achieved higher and more stable removal efficiencies for COD (77.05±10.03%), BOD_5 (79.30±7.06%), TN (56.05±8.38%), and TP (63.82±7.44%) under continuous operation.

This enhancement was further corroborated by increased apparent first-order kinetic coefficients (k), affirming an improved reaction rate in coconut fiber-packed DHF. The superior treatment performance was chiefly attributable to improved biomass and solids retention within the reactor. Overall, these results indicate that coconut fiber represents a low-cost and biodegradable alternative to synthetic carriers, offering a practical and sustainable option for decentralized post-treatment of lower-strength swine wastewater generated by small-scale farms in resource-limited agricultural settings.

Acknowledgements

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References

[1] R. Rajagopal, P. Rousseau, N. Bernet, and F. Béline, (2011) *"Combined anaerobic and activated sludge anoxic/oxic treatment for piggery wastewater"* **Bioresource Technology *102***(3): 2185–2192. DOI: 10.1016/j.biortech.2010.09.112.

[2] C. Bailey, A. Spielmeyer, G. Hamscher, H. Schüttrumpf, and R. M. Frings, (2016) *"The veterinary antibiotic journey: comparing the behaviour of sulfadiazine, sulfamethazine, sulfamethoxazole and tetracycline in cow excrement and two soils"* **Journal of Soils and Sediments *16***(6): 1690–1704. DOI: 10.1007/s11368-016-1370-0.

[3] L. Huong and L. Duy, (2023) *"Environmental Efficiency of Pig Production in Chuong My District, Hanoi"* **Vietnam Journal of Agricultural Sciences *6***(4): 1992–2003. DOI: 10.31817/vjas.2023.6.4.09.

[4] N. H. Dan, E. R. Rene, and T. Le Luu, (2020) *"Removal of Nutrients from Anaerobically Digested Swine Wastewater Using an Intermittent Cycle Extended Aeration System"* **Frontiers in Microbiology *11***: 576438. DOI: 10.3389/fmicb.2020.576438.

[5] N. Chen, X. Zhang, Q. Du, J. Huo, H. Wang, Z. Wang, W. Guo, and H. H. Ngo, (2023) *"Advancements in swine wastewater treatment: Removal mechanisms, influential factors, and optimization strategies"* **Journal of Water Process Engineering *54***: 103986. DOI: 10.1016/j.jwpe.2023.103986.

[6] T. Okubo, K. Kubota, T. Yamaguchi, S. Uemura, and H. Harada, (2016) *"Development of a new non-aeration-based sewage treatment technology: performance evaluation of a full-scale down-flow hanging sponge reactor employing third-generation sponge carriers"* **Water Research *102***: 138–146. DOI: 10.1016/j.watres.2016.06.035.

[7] M. Hatamoto, T. Okubo, K. Kubota, and T. Yamaguchi, (2018) *"Characterization of downflow hanging sponge reactors with regard to structure, process function, and microbial community compositions"* **Applied Microbiology and Biotechnology *102***(24): 10345–10352. DOI: 10.1007/s00253-018-9406-6.

[8] H. V. Dang and L. M. Nguyen, (2025) *"Combining hybrid constructed wetlands with an alum-based slow sand filter for swine wastewater treatment: Effect of different hydraulic loading rates and alum dosages"* **Sustainable Water Resources Management *11***(5): 100. DOI: 10.1007/s40899-025-01270-z.

[9] N. N. Phan, Y. H. Duong, K. T. Tran, H. M. Bui, and T. T. Ngo. "Evaluation of the optimum conditions of an anaerobic Down-flow Stationary Fixed Film reactor for swine wastewater treatment". In: *IOP Conference Series: Earth and Environmental Science*. ***1349***. 1. 2024, 012017. DOI: 10.1088/1755-1315/1349/1/012017.

[10] P. Vydehi, G. Shyamala, G. Ravindran, and R. Gokulan, (2026) *"Biocarrier-driven enhancement of microbial reactor performance in wastewater treatment: A review"* **Bioprocess and Biosystems Engineering *49***: 473–488. DOI: 10.1007/s00449-025-03258-7.

[11] H. Wu, Y. Huo, F. Qi, Y. Zhang, R. Li, and M. Qiao, (2025) *"Biochar-supported microbial systems: A strategy for remediation of persistent organic pollutants"* **Biochar 7**: 113. DOI: 10.1007/s42773-025-00506-7.

[12] T. Watari, C. L. Vazquez, M. Hatamoto, T. Yamaguchi, and J. B. van Lier, (2021) *"Development of a single-stage mainstream anammox process using a sponge-bed trickling filter"* **Environmental Technology *42***(19): 3036–3047. DOI: 10.1080/09593330.2020.1720309.

[13] T. Watari, T. C. Mai, D. Tanikawa, Y. Hirakata, M. Hatamoto, K. Syutsubo, M. Fukuda, N. B. Nguyen, and T. Yamaguchi, (2017) *"Development of downflow hanging sponge (DHS) reactor as post treatment of existing combined anaerobic tank treating natural rubber processing wastewater"* **Water Science and Technology *75***(1): 57–68. DOI: 10.2166/wst.2016.487.

[14] Y. Miyaoka, W. Yoochatchaval, H. Sumino, P. Banjongproo, T. Yamaguchi, T. Onodera, T. Okadera, and K. Syutsubo, (2017) *"Evaluation of the process performance of a down-flow hanging sponge reactor for direct treatment of domestic wastewater in Bangkok, Thailand"* **Journal of Environmental Science and Health, Part A *52***(10): 956–970. DOI: 10.1080/10934529.2017.1324708.

[15] P. N. Nguyet, T. Watari, Y. Hirakata, M. Hatamoto, and T. Yamaguchi, (2019) *"Adsorption and biodegradation removal of methylene blue in a down-flow hanging filter reactor incorporating natural adsorbent"* **Environmental Technology *42***(3): 410–418. DOI: 10.1080/09593330.2019.1629636.

[16] Y. Zharkenov, T. Mkilima, A. Abduova, L. Zhaksylykova, A. Turashev, R. Imambayeva, N. Imambaev, M. Jaxymbetova, A. Smagulova, and E. Beysenbaeva, (2024) *"Utilizing biofilm-enhanced coconut coir for microplastic removal in wastewater"* **Case Studies in Chemical and Environmental Engineering *9***: 100726. DOI: 10.1016/j.cscee.2024.100726.

[17] Z. Z. Loh, A. Syafiuddin, N. S. Zaidi, E. L. Yong, M. B. Bahrodin, A. Aris, and R. Boopathy, (2025) *"Accelerated Start-Up and Microbial Community Using Novel Plant-Based Waste Biofilter Media for Treatment of Real Domestic Wastewater via Simultaneous Nitrification and Denitrification"* **ACS ES&T Water *5***(7): 3929–3938. DOI: 10.1021/acsestwater.5c00230.

[18] American Public Health Association (APHA), American Water Works Association (AWWA), and Water Environment Federation (WEF). *Standard Methods for the Examination of Water and Wastewater*. 22nd. Washington, DC, USA: American Public Health Association, 2012.

[19] H. Abyar, H. Younesi, N. Bahramifar, A. A. Zinatizadeh, and M. Amini, (2017) *"Kinetic evaluation and process analysis of COD and nitrogen removal in UAASB bioreactor"* **Journal of the Taiwan Institute of Chemical Engineers *78***: 272–281. DOI: 10.1016/j.jtice.2017.06.014.

[20] M. Ng, S. Dalhatou, J. Wilson, B. P. Kamdem, M. B. Temitope, H. K. Paumo, H. Djelal, A. A. Assadi, P. Nguyen-Tri, and A. Kane, (2022) *"Characterization of Slaughterhouse Wastewater and Development of Treatment Techniques: A Review"* **Processes *10***(7): 1300. DOI: 10.3390/pr10071300.

[21] A. Singh, Y. Soga, V. K. Tyagi, R. Singh, K. Chhoden, T. Watari, T. Okubo, C. S. P. Ojha, A. A. Kazmi, and S. K. Chauhan, (2025) *"Unlocking the potential of down-flow hanging sponge reactors for integrated nutrient management"* **Journal of Environmental Chemical Engineering *13***(5): 117591. DOI: 10.1016/j.jece.2025.117591.

[22] M. Z.-U. Zaman, N. Anjum, S. Dey, and H. M. Zakir, (2023) *"An Investigation of the Effectiveness of Recycled Coconut Fiber and Rice Husk as Filter Media for Wastewater Treatment"* **Journal of Global Ecology and Environment *17***(3): 30–39. DOI: 10.56557/jogee/2023/v17i38189.

[23] J. Liao, C. Fang, J. Yu, A. Sathyagal, E. Willman, and W.-T. Liu, (2017) *"Direct treatment of high-strength soft drink wastewater using a down-flow hanging sponge reactor: performance and microbial community dynamics"* **Applied Microbiology and Biotechnology *101***(14): 5925–5936. DOI: 10.1007/s00253-017-8326-1.

[24] T. Watari, Y. Hata, Y. Hirakata, N. N. Phan, T. H. Nguyen, S. Maki, M. Hatamoto, D. Sutani, T. Setia, and T. Yamaguchi, (2021) *"Performance evaluation of down-flow hanging sponge reactor for direct treatment of actual textile wastewater; Effect of effluent recirculation to performance and microbial community"* **Journal of Water Process Engineering *39***: 101724. DOI: 10.1016/j.jwpe.2020.101724.

[25] N. Sato, T. Saito, H. Satoh, N. Tanaka, and K. Kawamoto, (2017) *"Coconut-fibre biofilm wastewater treatment system in Sri Lanka: Microcosm experiments for evaluating wastewater treatment efficiencies and oxygen consumption"* **International Journal of Environmental Science and Development *8***(10): 691–695. DOI: 10.18178/ijesd.2017.8.10.1040.

[26] J. A. De Silva, A. K. Karunaratne, and V. A. Sumanasinghe, (2019) *"Wastewater treatment using attached growth microbial biofilms on coconut fiber: A short review"* **Journal of Agriculture and Value Addition** **2**(1): 61–70. DOI: 10.4038/java.v2i1.110.

[27] A. Tawfik, R. A. Wahab, A. Al-Asmer, and F. Matary, (2011) *"Effect of hydraulic retention time on the performance of down-flow hanging sponge system treating grey wastewater"* **Bioprocess and Biosystems Engineering** ***34***(6): 767–776. DOI: 10.1007/s00449-011-0528-9.

[28] L. Wu, W. Wei, J. Xu, X. Chen, Y. Liu, L. Peng, D. Wang, and B.-J. Ni, (2021) *"Denitrifying biofilm processes for wastewater treatment: Developments and perspectives"* **Environmental Science: Water Research & Technology *7***(1): 40–67. DOI: 10.1039/D0EW00576B.

[29] H. L. Ngo, N. N. Phan, T. T. Ngo, L. D. K. Tran, X.-T. Bui, H.-V. Nguyen, V.-T. Tra, M. Hatamoto, T. Watari, and T. Yamaguchi, (2026) *"Enhanced nitrogen removal in sponge membrane bioreactor coupled with iron scraps for municipal wastewater treatment: Performance and microbial community shifts"* **Case Studies in Chemical and Environmental Engineering *13***: 101318. DOI: 10.1016/j.cscee.2025.101318.

[30] T. Onodera, T. Okubo, S. Uemura, T. Yamaguchi, A. Ohashi, and H. Harada, (2016) *"Long-term performance evaluation of down-flow hanging sponge reactor regarding nitrification in a full-scale experiment in India"* **Bioresource Technology *204***: 177–184. DOI: 10.1016/j.biortech.2016.01.005.

[31] D. Tanikawa, S. Yamashita, T. Kataoka, H. Sonaka, Y. Hirakata, M. Hatamoto, and T. Yamaguchi, (2019) *"Non-aerated single-stage nitrogen removal using a down-flow hanging sponge reactor as post-treatment for nitrogen-rich wastewater treatment"* **Chemosphere *233***: 645–651. DOI: 10.1016/j.chemosphere.2019.06.012.

[32] Y. Jia, M. Zhou, Y. Chen, Y. Hu, and J. Luo, (2020) *"Insight into short-cut of simultaneous nitrification and denitrification process in moving bed biofilm reactor: Effects of carbon to nitrogen ratio"* **Chemical Engineering Journal *400***: 125905. DOI: 10.1016/j.cej.2020.125905.

[33] A. Alvarado, S. West, G. Abbt-Braun, and H. Horn, (2021) *"Hydrolysis of particulate organic matter from municipal wastewater under aerobic treatment"* **Chemosphere *263***: 128329. DOI: 10.1016/j.chemosphere.2020.128329.

[34] L. Shi, X. Li, Q. Zhang, and Y. Peng, (2021) *"Effectively stimulating partial denitrification to utilize dissolved slowly-biodegradable organic matter by introducing in-situ biosorption and hydrolytic acidification"* **Bioresource Technology *333***: 125175. DOI: 10.1016/j.biortech.2021.125175.

[35] X. Xin, S. Liu, J. Qin, Z. Ye, W. Liu, S. Fang, and J. Yang, (2021) *"Performances of simultaneous enhanced removal of nitrogen and phosphorus via biological aerated filter with biochar as fillers under low dissolved oxygen for digested swine wastewater treatment"* **Bioprocess and Biosystems Engineering *44***(8): 1741–1753. DOI: 10.1007/s00449-021-02557-z.

[36] Y. Yang, Y. Zhu, D. Gan, X. Cai, X. Li, X. Liu, and S. Xia, (2024) *"Enhancing biofilm formation with powder carriers for efficient nitrogen and phosphorus removal"* **Science of The Total Environment *951***: 175812. DOI: 10.1016/j.scitotenv.2024.175812.

[37] Z. Bi, Y. Liu, W. C. Rutoh, and Y. Huang, (2024) *"Influence of operation sequences on phosphorus recovery by polyphosphate-accumulating organisms biofilm: Performance, kinetics and metabolic response"* **Journal of Water Process Engineering *61***: 105356. DOI: 10.1016/j.jwpe.2024.105356.

[38] R. Sandeep, J. F. Muscolino, W. V. Macêdo, M. Piculell, M. Christensson, J. S. Poulsen, J. L. Nielsen, and L. Vergeynst, (2023) *"Effect of biofilm thickness on the activity and community composition of phosphorus accumulating bacteria in a moving bed biofilm reactor"* **Water Research *245***: 120599. DOI: 10.1016/j.watres.2023.120599.

[39] X.-Y. Long, W. Dai, R. Tang, H.-W. Zhou, M. Xue, and T. Zhong, (2025) *"Influence of solid residence time on the phosphorus adsorption of extracellular polymer substances"* **Environmental Engineering Research *30***(2): 240394. DOI: 10.4491/eer.2024.394.

[40] H. Zhang, S.-S. Zhang, L. Zhu, Y.-P. Li, and L. Chen, (2022) *"Phosphorus recovery in the alternating aerobic/anaerobic biofilm system: Performance and mechanism"* **Science of The Total Environment *810***: 152297. DOI: 10.1016/j.scitotenv.2021.152297.

[41] H. Zhang, S.-S. Zhang, W. Zhang, W.-C. Ma, Y. Pan, L. Chen, L. Zhu, Y.-P. Li, and J.-R. Li, (2023) *"Clarification of the phosphorus release mechanism for recovering phosphorus from biofilm sludge in alternating aerobic/anaerobic biofilm system"* **Science of The Total Environment *904***: 166811. DOI: 10.1016/j.scitotenv.2023.166811.

[42] H. Zhang, Z. Bi, Y. Pan, Y. Huang, D.-P. Li, and J. Shan, (2020) *"Enhanced phosphorus storage in suspended biofilm by increasing dissolved oxygen"* **Science of The Total Environment *722***: 137876. DOI: 10.1016/j.scitotenv.2020.137876.

[43] A. B. Fanta, A. M. Nair, S. Sægrov, and S. W. Østerhus, (2021) *"Phosphorus removal from industrial discharge impacted municipal wastewater using sequencing batch moving bed biofilm reactor"* **Journal of Water Process Engineering *41***: 102034. DOI: 10.1016/j.jwpe.2021.102034.

[44] C. Chao, Y. Zhao, J. Keskar, M. Ji, Z. Wang, and X. Li, (2020) *"Simultaneous removal of COD, nitrogen and phosphorus and the tridimensional microbial response in a sequencing batch biofilm reactor: With varying C/N/P ratios"* **Biochemical Engineering Journal *154***: 107215. DOI: 10.1016/j.bej.2019.04.017.

[45] A. Tsitouras, N. Al-Ghussain, and R. Delatolla, (2021) *"Two moving bed biofilm reactors in series for carbon, nitrogen, and phosphorous removal from high organic wastewaters"* **Journal of Water Process Engineering *41***: 102088. DOI: 10.1016/j.jwpe.2021.102088.

[46] Y. Wang, T. Tang, J. Wu, S. Yang, X. Zhao, R. Zhu, Z. Zhao, M. He, and X. Huangfu, (2024) *"Succession of nitrogen and phosphorus removal functions of sludge and biofilm in low-temperature sewage treatment"* **Journal of Water Process Engineering *58***: 104836. DOI: 10.1016/j.jwpe.2024.104836.

[47] R. H. Kadlec and S. D. Wallace. *Treatment Wetlands*. 2nd. CRC Press, 2009. DOI: 10.1201/9781420012514.

[48] D. Ventura, R. Rapisarda, L. Sciuto, M. Milani, S. Consoli, G. L. Cirelli, and F. Licciardello, (2022) *"Application of first-order kinetic removal models on constructed wetlands under Mediterranean climatic conditions"* **Ecological Engineering *175***: 106500. DOI: 10.1016/j.ecoleng.2021.106500.