Experimental Investigation On Optimal Soil Column Depth For Efficient Soil Aquifer Treatment

Makhania M. P.[1*] and Popawala R. D.[2]

[1]Research Scholar, Department of Civil Engineering, Gujarat Technological University, Ahmedabad, Gujarat, INDIA, mitalimakhania@gmail.com

[2]Professor, Department of Civil Engineering, C. K. Pithawala College of Engineering and Technology, Surat, Gujarat, INDIA

ABSTRACT

Water scarcity and the rapid increase in wastewater generation associated with urbanization have intensified the need for sustainable and decentralized water reuse solutions. Soil Aquifer Treatment (SAT) is a nature-based technology that improves wastewater quality through integrated physical filtration, chemical adsorption, and biological degradation processes occurring within soil-aquifer systems. In this study, the performance of SAT systems was experimentally evaluated using laboratory-scale layered soil columns operated under different hydraulic retention times (HRTs). Experiments were conducted to evaluate the efficiency of different soil column depths. Raw sewage wastewater was applied to ten soil columns consisting of fine and coarse sand layers, operated under short (4 hrs) and long (24 hrs) HRTs over a continuous period of 45-100 days. Key water quality parameters, including biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), nitrogen species, phosphorus, total dissolved solids (TDS), and pH, were systematically monitored. The results demonstrate substantial improvements in effluent quality, with BOD and TSS removal efficiencies reaching up to 80% and 75-80%, respectively. Treatment performance was strongly influenced by soil depth and retention time, with longer HRTs and layered soil configurations enhancing organic matter degradation, nutrient removal, microbial activity, and system stability while reducing clogging risks. These findings confirm that SAT systems represent a low-energy, cost-effective, and environmentally sustainable solution for decentralized wastewater reuse and can play a significant role in achieving net-zero water cycles in rapidly urbanizing regions.

Keywords: Decentralized Wastewater Reuse, Hydraulic Retention Time, Layered Soil Columns, Net-Zero Water Cycle, Soil Aquifer Treatment (SAT).

Introduction

Global freshwater resources are under increasing stress due to population growth, climate change, and accelerating urbanization. The United Nations estimates that by 2030, global water demand may exceed sustainable supply by nearly 40%, making wastewater reuse an essential component of future water management strategies[15]. In developing countries such as India, rapid urban expansion and uneven water distribution further intensify water scarcity, particularly in semi-arid regions such as Gujarat. The inadequate expansion of centralized wastewater infrastructure has led to untreated discharges, groundwater degradation, and growing environmental and public health concerns.

Decentralized wastewater treatment and reuse systems offer an effective alternative by reducing reliance on centralized infrastructure, minimizing conveyance losses, and enabling localized water recycling[9]. Among various nature-based treatment technologies, Soil Aquifer Treatment (SAT) has emerged as a robust and sustainable solution due to its low energy requirements, minimal chemical inputs, and compatibility with natural hydrogeological processes. SAT involves the controlled infiltration of treated or partially treated wastewater through soil layers, where contaminants are attenuated through physical filtration, chemical adsorption, microbial degradation, and redox-driven transformations[14].

SAT systems have been successfully implemented in managed aquifer recharge (MAR) projects worldwide, most notably the wastewater reuse scheme in Israel, which supplies reclaimed water for agricultural irrigation. These large-scale systems demonstrate the long-term stability and effectiveness of SAT for organic matter and nutrient removal. Experimental investigations of decentralized SAT configurations under Indian wastewater characteristics remain limited, particularly with respect to layered soil profiles and the influence of short versus long hydraulic retention times (HRTs)[9].

Soil properties, layering, influent quality, and hydraulic loading conditions play a critical role in determining SAT performance, influencing organic matter degradation, nutrient transformation, and clogging behaviour. Despite this, comparative experimental studies evaluating raw, primary-treated, and secondary-treated wastewater under identical SAT operating conditions are infrequent. Addressing these gaps is essential for optimizing SAT design and promoting its adoption in decentralized urban water reuse systems.

This study experimentally evaluates the performance of layered SAT soil columns treating raw sewage wastewater under controlled laboratory conditions and variable hydraulic retention times. The outcomes aim to provide practical insights into system optimization for decentralized wastewater reuse and to support sustainable net-zero water cycle planning in rapidly urbanizing regions.

Literature Review

SAT is widely recognized as a nature-based solution within the broader framework of MAR, enabling the attenuation of physical, chemical, and biological contaminants through subsurface filtration, sorption, and biogeochemical transformation processes. Over the past decade, research has increasingly focused on understanding SAT performance mechanisms, system optimization, and its applicability for decentralized wastewater reuse.

Extensive studies confirm that SAT systems are highly effective in removing organic matter, primarily through aerobic and anaerobic biodegradation during soil passage. SAT columns as biogeochemical reactors, where redox zonation significantly enhances the removal of dissolved organic carbon (DOC) and biochemical oxygen demand (BOD)[14].

Organic matter removal efficiency is strongly influenced by HRT and soil texture. Finer soil media promote higher removal efficiencies due to increased surface area and extended residence time[1]. BOD removal exceeding 70% in sand-based SAT columns operated under longer HRTs[5]. However, several studies note that SAT favours the transformation of organic fractions rather than complete mineralization; recalcitrant compounds often persist, resulting in comparatively lower chemical oxygen demand (COD) removal[10].

TSS removal in SAT systems occurs mainly through physical straining and sedimentation, particularly in the upper soil layers. TSS removal efficiencies generally range between 70% and 90%, depending on influent quality and pretreatment level[7,14]. Clogging remains a major operational constraint, especially when treating raw or minimally treated wastewater. To address this challenge, layered soil configurations have been widely investigated. The graded soil profiles distribute particulate loading vertically, delaying surface clogging and extending system lifespan[15]. Alternating fine and coarse layers improves hydraulic conductivity while maintaining high solids removal efficiency, thereby enhancing long-term operational stability[11].

Nitrogen removal in SAT systems is governed by sequential microbial processes, including ammonification, nitrification, and denitrification. Longer HRTs facilitate the formation of aerobic–anoxic interfaces, enabling effective nitrogen transformation[9]. Ammonium removal efficiencies exceeding 60-70% have been reported in sand-based SAT systems under optimized hydraulic and oxygen conditions[6,9]. Phosphorus removal is primarily controlled by adsorption and precipitation mechanisms, which are highly dependent on soil mineralogy. Studies indicate that phosphorus removal efficiency declines over time due to saturation of sorption sites[8,9], underscoring the need for appropriate media selection and potential regeneration strategies.

Research has expanded beyond conventional pollutants to examine the fate of pathogens and emerging contaminants in SAT systems. Several studies report substantial removal of pharmaceuticals through a combination of biodegradation and sorption[14,16]. Pathogen attenuation in SAT systems is achieved through filtration, adsorption, and natural die-off mechanisms. Effective virus and bacteria removal, supporting the suitability of SAT for non-potable reuse applications. However, removal efficiency is sensitive to environmental conditions, including temperature, soil type, and HRT[3].

The application of SAT for decentralized wastewater reuse, particularly in developing and water-stressed regions, has gained increasing attention. The feasibility of SAT under arid and semi-arid conditions, highlighting its low energy demand and operational simplicity[12]. Studies emphasize the SAT's compatibility with variable wastewater quality and limited infrastructure availability[7].

Most research focuses on large-scale MAR systems or single influent types. Comparative studies evaluating raw wastewater under identical SAT conditions remain limited. Furthermore, the effects of short versus long HRTs in decentralized, laboratory-scale layered systems are insufficiently documented, particularly under Indian municipal wastewater characteristics.

Based on the reviewed literature, the following

Research gaps are identified: Limited experimental data on layered soil column SAT systems treating Indian municipal wastewater, and insufficient comparative evaluation of short and long hydraulic retention times under decentralized reuse scenarios, Lack of integrated assessment of organic matter, suspended solids, and nutrient removal across different pretreatment levels.

This study addresses these gaps by conducting a systematic experimental evaluation of layered SAT soil columns treating raw sewage wastewater under controlled HRT variations. The findings contribute original data to support the optimization and wider adoption of decentralized SAT systems.

Materials And Methods

Experimental Setup: The experimental study was conducted using ten vertical laboratory-scale soil columns fabricated from transparent PVC pipes to allow visual observation of clogging and biofilm development. Each column had an internal diameter of 40 cm and a total height ranging from 35-65 cm. The columns were packed with layered soil media designed to simulate infiltration basin conditions and minimize surface clogging. The configuration consisted of:

- Fine sand layer: 15-40 cm (effective size: 0.2-0.4 mm), serving as the primary treatment medium.
- Sandy Loam sand layer: 40-55 cm (effective size: 0.8-1.2 mm), placed at the bottom to facilitate drainage and prevent media washout.
- Head zone: 15 cm at the top to simulate surface water accumulation

All soil media were locally sourced, thoroughly washed, oven-dried, sieved, and characterized for grain size distribution and permeability prior to column packing. Table 1 presents the physical characteristics of the soil media used in the experimental SAT columns. The properties of fine and coarse sand layers were analyzed to evaluate their role in filtration and hydraulic performance. These parameters form the basis for assessing contaminant removal efficiency under varying HRTs.

Table 1: Physical characteristics of soil media

Parameter	Fine Sand	Sandy Loam Sand
Effective size (mm)	0.2-0.4	0.8-1.2
Uniformity coefficient	1.6-1.9	1.4-1.6
Porosity (%)	35-40	30-35

Hydraulic conductivity (m/day)	1.5-2.5	3-4.5

Hydraulic Retention Time and Operational Conditions: Two HRT scenarios were evaluated to assess treatment performance under varying contact durations. Influent flow rates were maintained using calibrated peristaltic pumps to ensure consistent hydraulic loading across all columns. The systems were operated continuously for periods ranging from 45 to 100 days to allow stabilization, biofilm development, and establishment of steady-state conditions.
Influent Wastewater Characteristics: Raw sewage influent wastewater was used to represent realistic decentralized wastewater treatment scenarios commonly encountered in urban contexts. Table 2 summarizes the average influent wastewater characteristics used in the SAT column experiments. Raw sewage effluents were analyzed to establish baseline water quality conditions. These values provide the reference framework for evaluating contaminant removal efficiencies under varying HRTs.

Table 2: Average influent wastewater characteristics

Parameter	Raw
pH	6.9-7
BOD (mg/L)	280-320
COD (mg/L)	480-520
TSS (mg/L)	700-760
NH_4-N (mg/L)	35-40

Monitoring Parameters and Analytical Methods: Water quality parameters monitored included pH, total dissolved solids (TDS), BOD, COD, total suspended solids (TSS), hardness, ammonical nitrogen, nitrite, nitrate, and total phosphorus. All analyses were conducted in accordance with Standard Methods for the Examination of Water and Wastewater[1]. Treatment performance was evaluated by calculating removal efficiency using the following expression:

$$\text{Removal efficiency (\%)} = \frac{C_i - C_e}{C_i} x100$$

where C_i and C_e represent influent and effluent concentrations, respectively.

Results And Discussion

pH and Total Dissolved Solids

The pH of raw sewage ranged from 6.94 to 7, and increased slightly to 7.3-7.6 following SAT treatment, indicating effective buffering during soil passage. This stabilization is attributed to carbonate mineral dissolution and microbial metabolic processes. The neutral to mildly alkaline effluent pH is favourable for downstream reuse applications. Figure 1 shows comparative removal efficiencies of SAT systems under short (4 hrs) and long (24 hrs) HRTs. Results highlight the operational advantage of extended retention in achieving higher pollutant removal and greater system stability.
Figure 2 shows a comparison of TDS concentrations in influent and SAT-treated effluent under short and long HRTs. Longer HRTs achieved higher TDS removal (up to ≈45%), while shorter HRTs showed moderate reductions (≈25-35%). Results highlight the partial salinity control of SAT systems through adsorption, ion exchange, and dilution within soil media. TDS concentrations decreased from approximately 500 mg/L to 369-376 mg/L, corresponding to a removal efficiency of 24-38%. Although the SAT is not specifically designed for salinity control, partial TDS reduction occurs through adsorption, ion exchange, and dilution within the soil matrix, as reported in studies[9].

Organic Matter Removal (BOD and COD)

SAT columns demonstrated substantial removal of organic matter, with BOD removal efficiencies ranging from 65% to 80%. The highest removals (76-80%) were achieved in columns with greater soil depth and a 24 hrs HRT, indicating enhanced aerobic biodegradation and biofilm development. Figure 3 shows the BOD removal efficiency under short and long HRTs for raw sewage wastewater. Results emphasize the role of hydraulic contact time in promoting microbial activity and stable organic matter degradation. Figure 4 shows the COD removal efficiency for raw sewage wastewater under short and long HRTs. Findings highlight the persistence of recalcitrant organic fractions and the importance of optimized HRT for enhanced biodegradation.
COD removal was comparatively lower, ranging from 35-45% across all configurations. This disparity reflects the persistence of recalcitrant organic fractions that are less amenable to biodegradation during soil passage. Table 3 summarizes average BOD and COD removal efficiencies for influent types and HRTs. Table 4 summarizes the column definitions referenced in the figures corresponding to layer thickness.

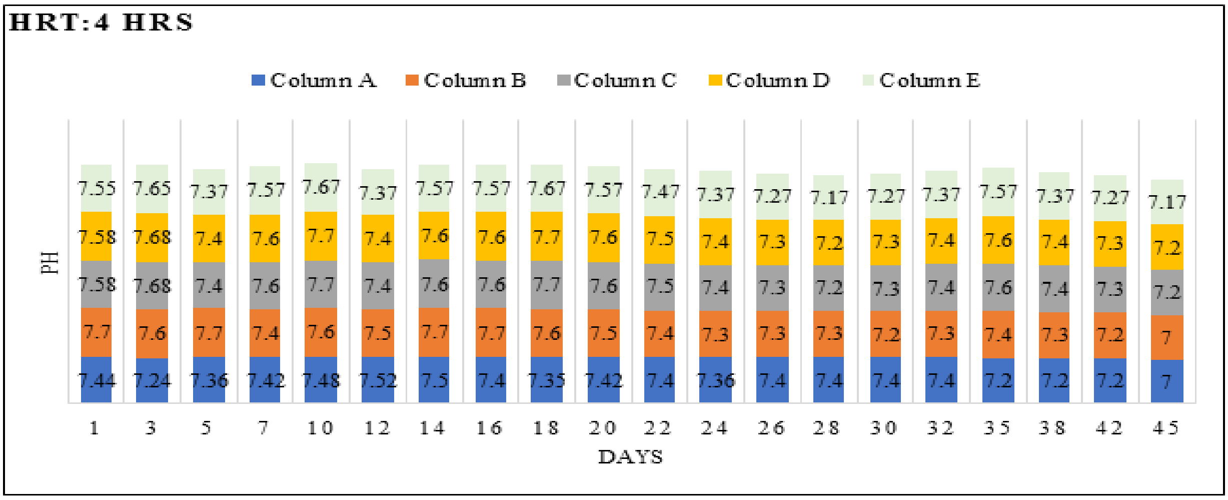
Table 3: Average BOD and COD removal efficiencies

Influent Type	HRT	BOD Removal (%)	COD Removal (%)
Raw	4 hrs	62-68	35-38
	24 hrs	74-80	42-45

Table 4: Indication of Each Column

Column	Soil Configuration	HRT	Influent Type
A	Fine sand (15 cm) + Sandy loam (15 cm)	4 hrs	Raw sewage
B	Fine sand (20 cm) + Sandy loam (15 cm)		
C	Fine sand (25 cm) + Sandy loam (15 cm)		

D	Fine sand (30 cm) + Sandy loam (15 cm)		
E	Fine sand (35 cm) + Sandy loam (15 cm)		
F	Fine sand (15 cm) + Sandy loam (15 cm)	24 hrs	Raw sewage
G	Fine sand (20 cm) + Sandy loam (15 cm)		
H	Fine sand (25 cm) + Sandy loam (15 cm)		
I	Fine sand (30 cm) + Sandy loam (15 cm)		
J	Fine sand (35 cm) + Sandy loam (15 cm)		



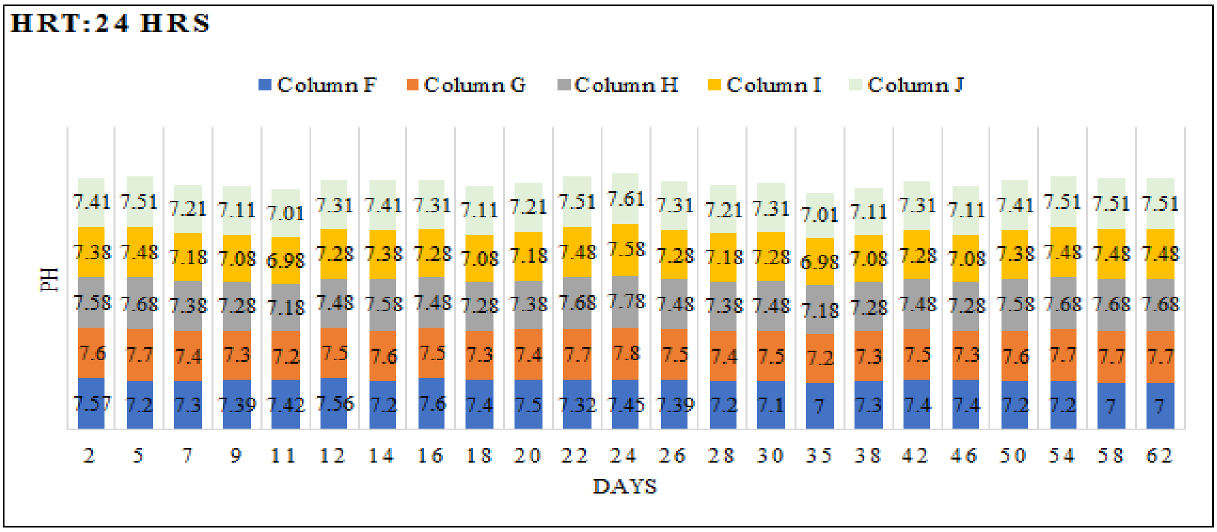
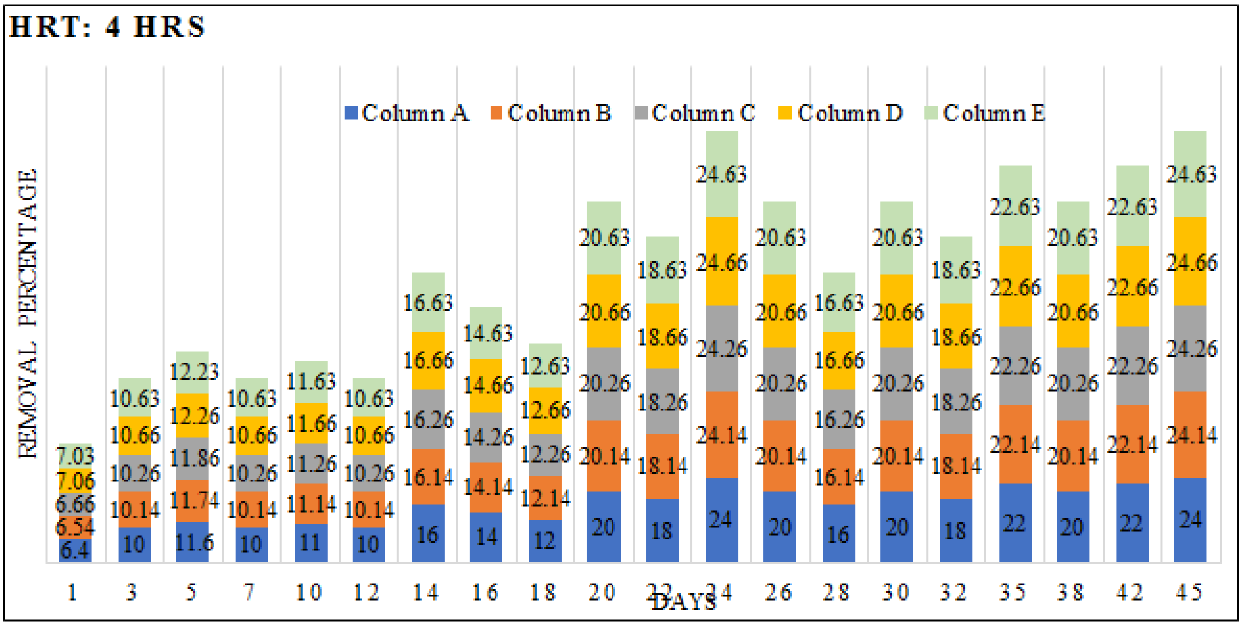


Figure 1: Performance of SAT for pH



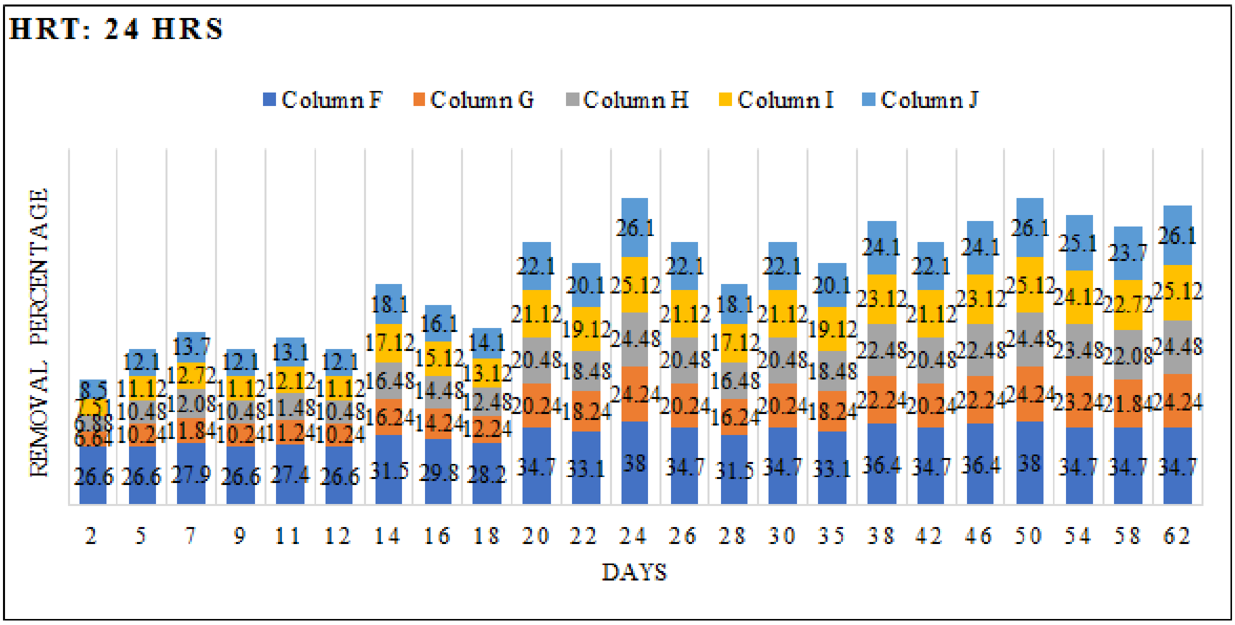


Figure 2: Performance of SAT for TDS

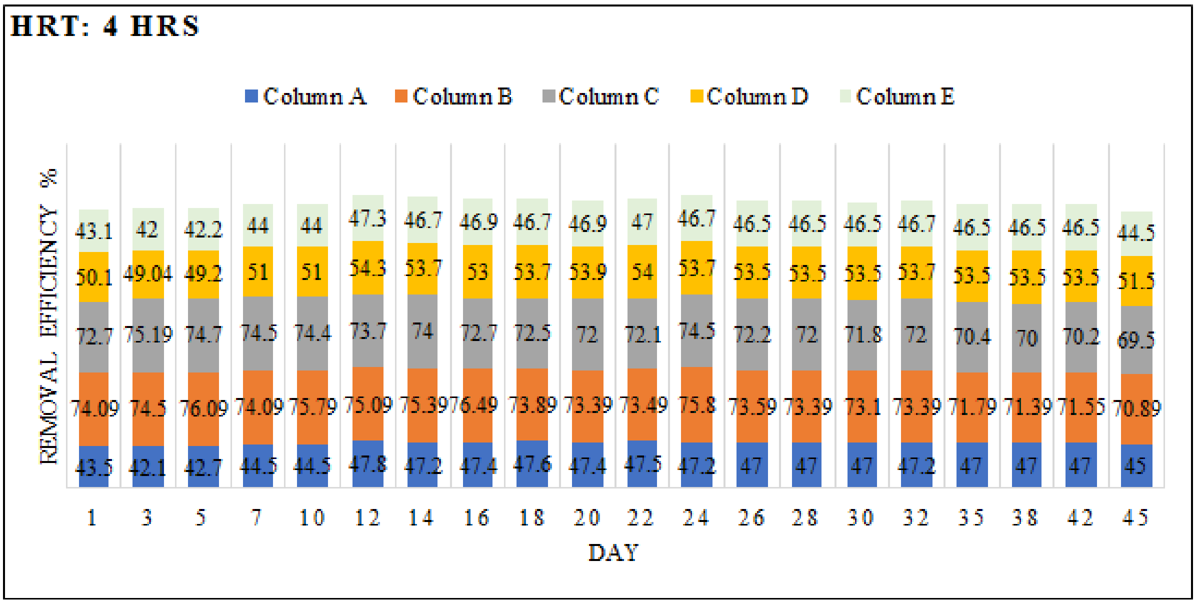
Suspended Solids Removal and Clogging Control

Figure 5 indicate TSS removal performance of layered SAT columns under short and long HRTs. Extended retention enhanced hydraulic stability, confirming the operational advantage of graded soil configurations for long-term SAT performance.

TSS concentrations decreased significantly from an average influent value of ≈733 mg/L to approximately 172 mg/L, achieving 75-80% removal. Removal was dominated by physical filtration and sedimentation, particularly within the upper soil layers. The incorporation of layered soil media effectively distributed particulate matter across multiple depths, reducing localized accumulation and minimizing surface clogging.

Nutrient Removal

Figure 6 Ammonical nitrogen and nitrate removal efficiencies in SAT systems under short and long HRTs. Ammonical nitrogen removal exceeded 60% under long HRT conditions, driven by sequential nitrification in aerobic zones followed by denitrification in anoxic microenvironments within deeper soil layers. The establishment of redox gradients under longer retention times was critical for effective nitrogen transformation. Phosphorus removal was moderate (30-45%) and primarily governed by adsorption and precipitation onto soil mineral surfaces. The results suggest that while SAT can provide partial phosphorus attenuation, long-term performance may be limited by sorption site saturation.



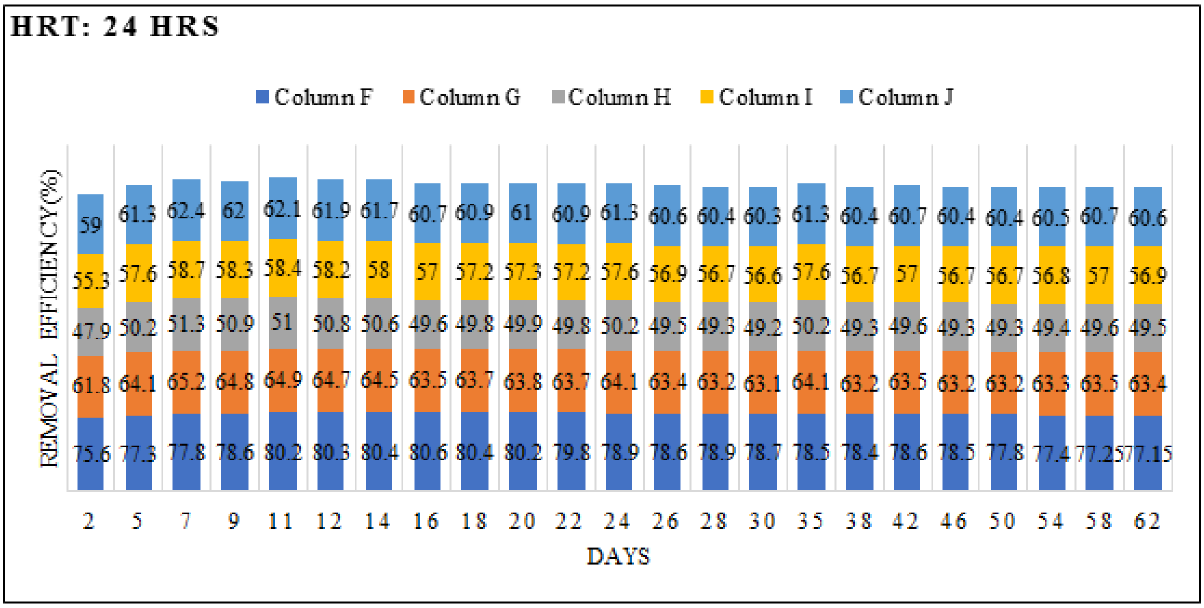
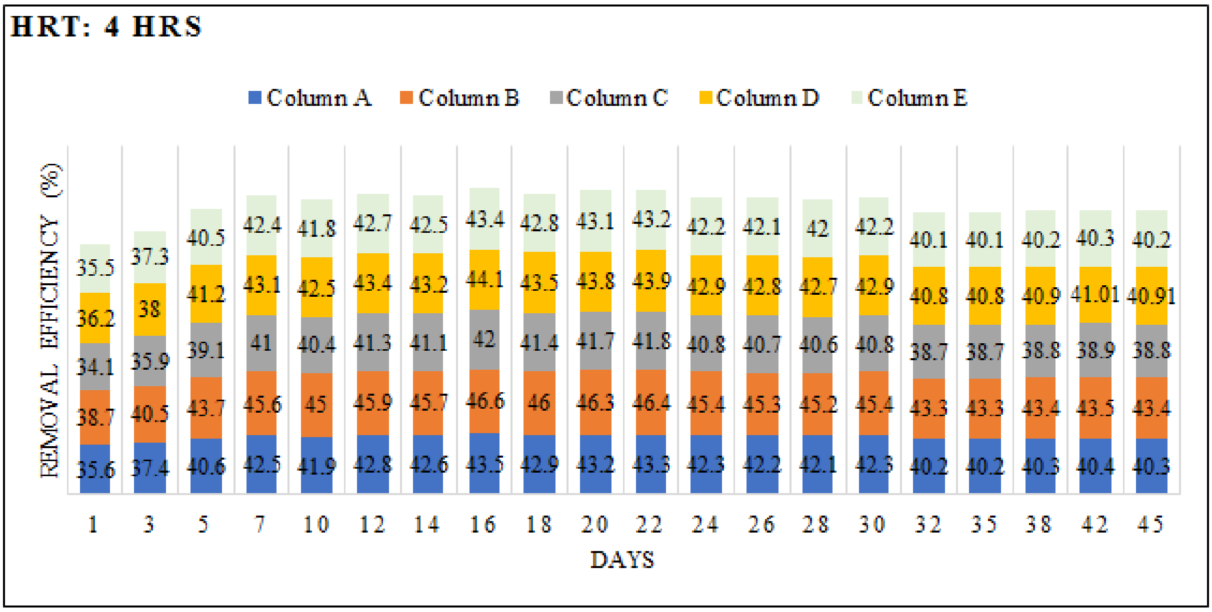


Figure 3: Performance of SAT for BOD



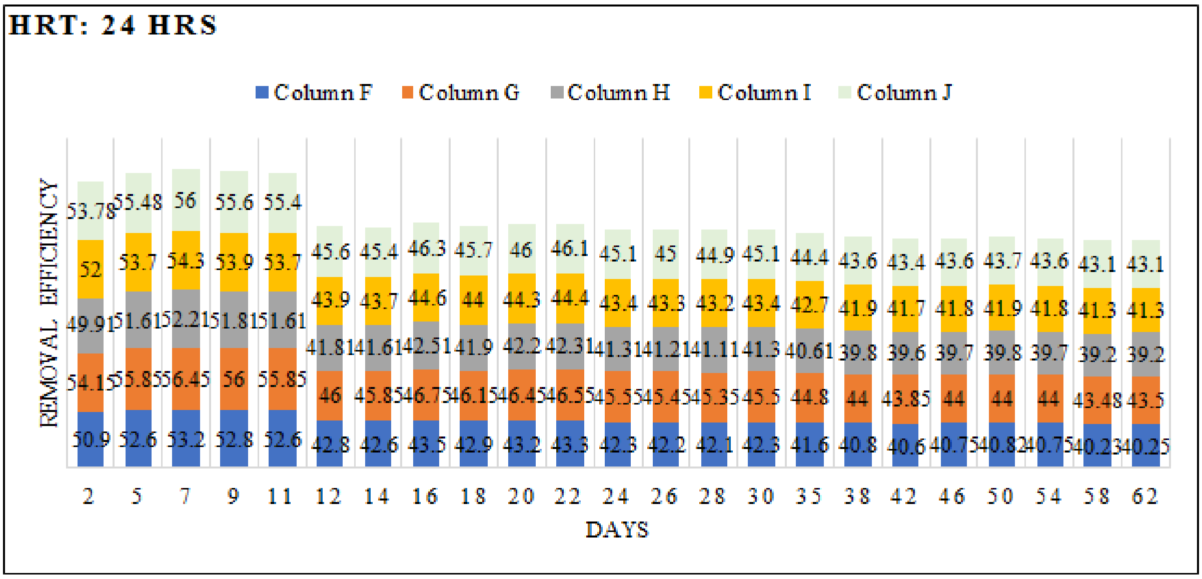


Figure 4: Performance of SAT for COD

Effect of Hydraulic Retention Time

Hydraulic retention time emerged as a key operational parameter influencing SAT performance. Longer HRTs consistently enhanced removal efficiencies across all measured parameters by increasing contact time, promoting microbial adaptation and biofilm maturation, and facilitating the development of aerobic-anoxic stratification. These findings underscore the importance of optimized HRT selection for achieving stable and efficient decentralized SAT operation.

The results indicate that HRT had a statistically significant effect ($p < 0.05$) on the removal of BOD, COD, and ammonical nitrogen, confirming that extended retention time substantially enhances biological degradation and nitrogen transformation processes. In contrast, TSS removal did not show a statistically significant difference ($p > 0.05$) between HRTs, suggesting that suspended solids removal is predominantly governed by physical filtration mechanisms rather than contact time.

Similarly, pH stabilization and TDS reduction exhibited limited statistical sensitivity to HRT variations, reflecting the buffering capacity of soil media and the non-selective nature of salt attenuation in SAT systems. Overall, longer HRTs significantly improve biologically driven processes, while physically controlled parameters remain comparatively insensitive to retention time. These results highlight HRT as a critical design and operational parameter for optimizing SAT systems intended for decentralized wastewater reuse.

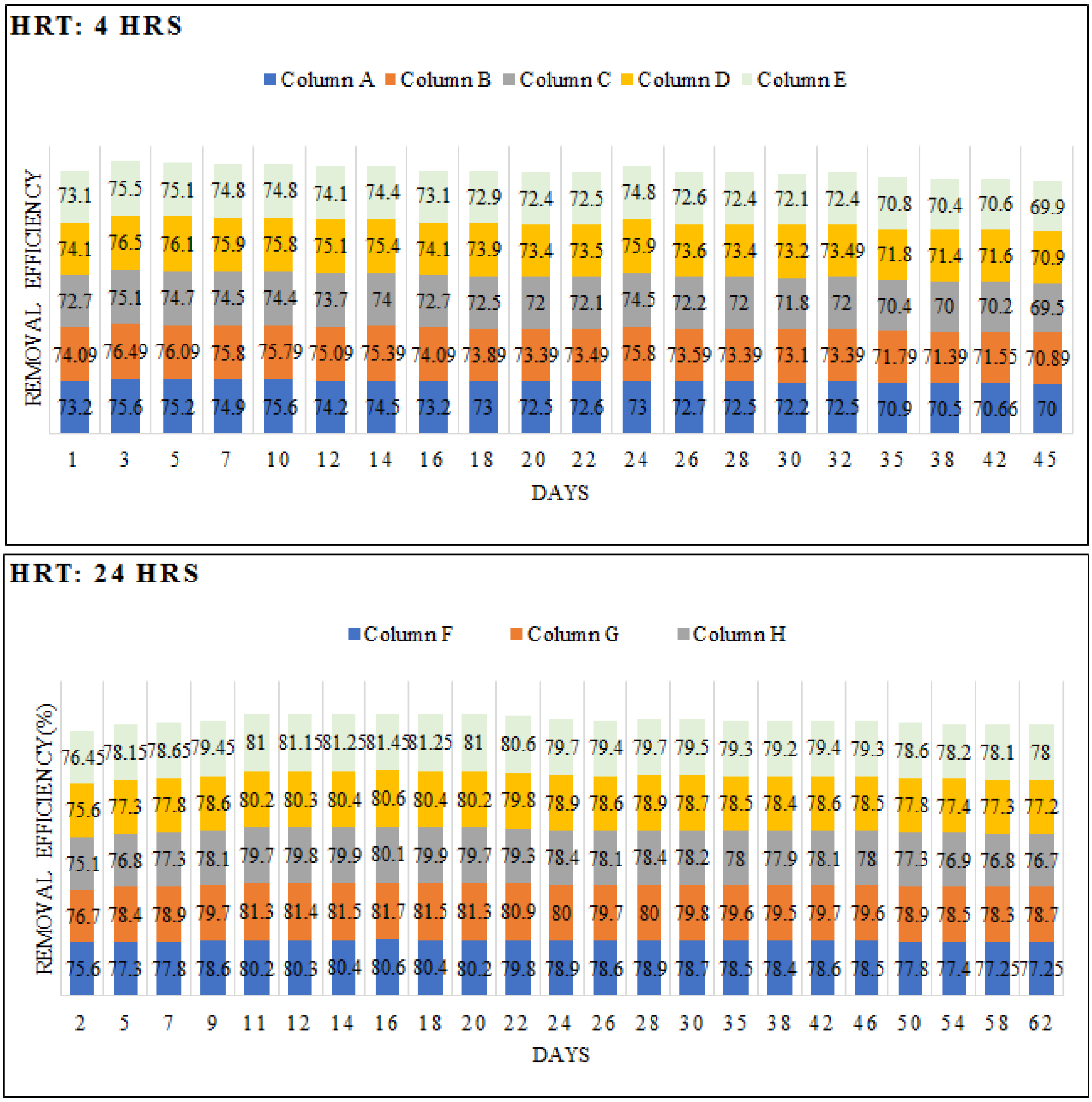
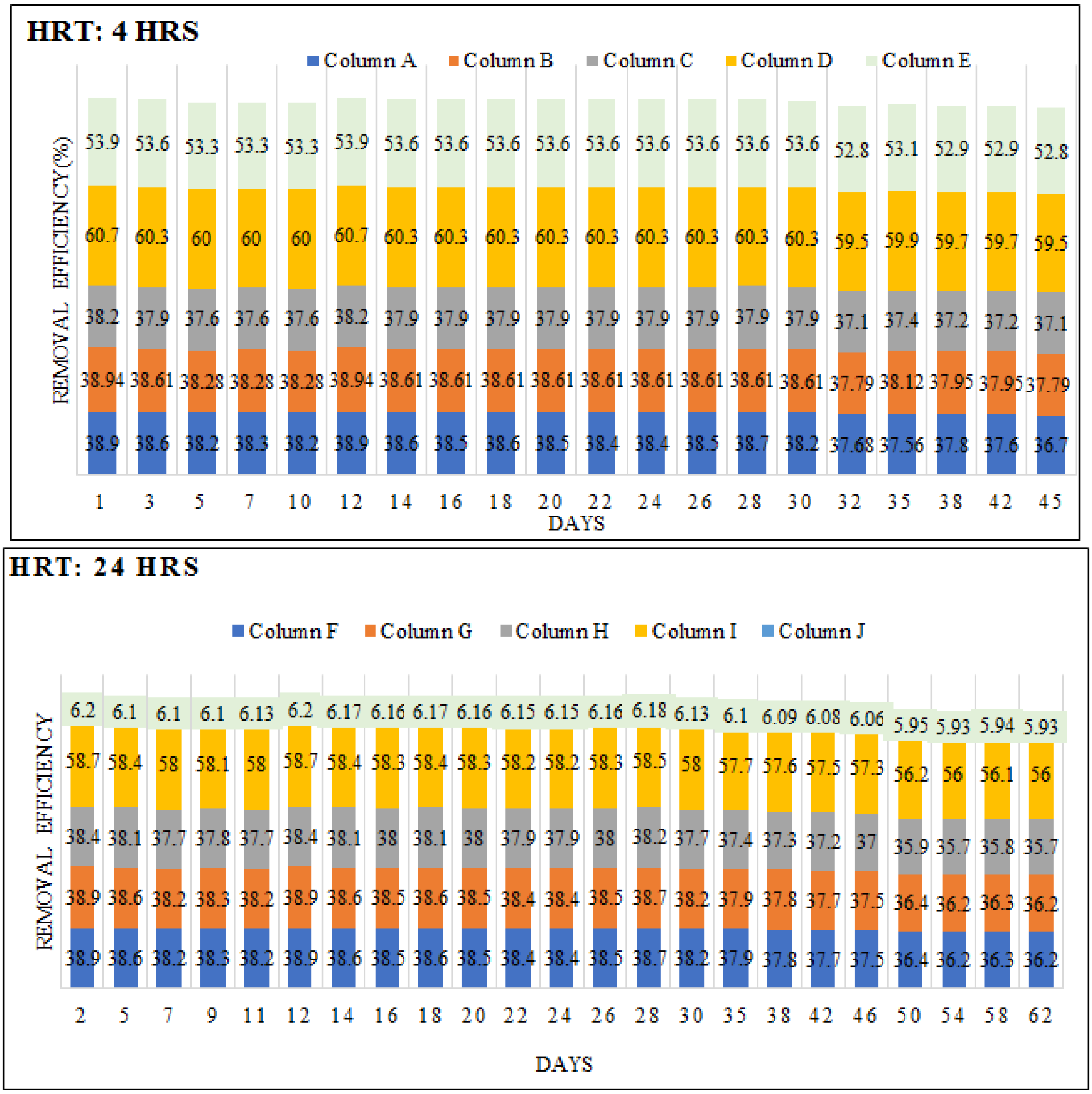


Figure 5: Performance of SAT for TSS



Figuere 6: Performance of SAT for Ammonical nitrogen

Implications for Decentralized Net-Zero Water Systems
The findings of this study highlight the potential of SAT systems as a cornerstone technology for achieving net-zero water cycles in decentralized urban contexts. Several key implications emerge:

Enhanced Resource Recovery and Water Security: SAT systems achieved 74-80% BOD removal, 75-80% TSS removal, and >60% ammonical nitrogen removal under long HRT, demonstrating their ability to produce effluent suitable for non-potable reuse applications such as Landscape irrigation, Industrial cooling, and MAR.
By recycling wastewater locally, SAT reduces dependence on centralized infrastructure and mitigates groundwater depletion in water-stressed regions.

Operational Efficiency and Sustainability: Short HRTs provided moderate treatment (BOD removal ≈62-68%), but longer HRT consistently improved performance across all parameters, underscoring the importance of retention time in system design. Layered soil configurations distribute solids vertically, reducing clogging risks and ensuring long-term operational stability. The low-energy demand and reliance on natural filtration and microbial processes make SAT systems particularly suitable for developing regions where energy and chemical inputs are limited.
Alignment with Net-Zero Urban Planning: SAT contributes to net-zero water cycles by:

- Closing the loop between wastewater generation and reuse.
- Reducing conveyance losses by treating water at the point of generation.
- Supporting localized resilience against climate variability and urban water stress.

Integration into decentralized infrastructure allows cities to minimize environmental footprints while maximizing water reuse efficiency.

Scalability and Adaptability: SAT systems can be scaled from small community-level installations to district-scale reuse schemes, offering flexibility in rapidly urbanizing regions. Their simplicity and modularity make them adaptable to diverse wastewater characteristics, soil types, and climatic conditions.

Policy and Planning Implications: Incorporating SAT into urban water management frameworks supports national and regional goals for sustainable resource management. Decision-making tools such as Multi-Attribute Decision-Making (MADM) frameworks can guide technology selection, balancing cost, efficiency, and environmental impact. SAT systems are not merely treatment units; they represent a strategic enabler of net-zero water cycles. By combining high pollutant removal efficiencies (up to 80%), low operational costs, and nature-based resilience, SAT offers a pathway toward sustainable, decentralized water reuse in urban societies.

Conclusions

The experimental evaluation demonstrates that Soil Aquifer Treatment (SAT) is an effective and sustainable option for decentralized wastewater reuse. Treatment performance was strongly influenced by hydraulic retention time (HRT) and soil configuration. Under short HRT conditions (4 hrs), biochemical oxygen demand (BOD) removal ranged from 62-68%, whereas longer retention (24 hr) consistently achieved 74-80% removal. Chemical oxygen demand (COD) removal similarly improved from 35-38% at 4 hrs to 40-45% at 24 hrs. Ammonical nitrogen removal exceeded 60% under long (24 hrs) HRT, compared to substantially lower efficiencies at shorter retention times. Total suspended solids (TSS) removal remained high (75-80%) across both scenarios; however, layered soil configurations combined with longer HRTs provided greater operational stability and reduced clogging risk. These results confirm that extended retention times and increased soil depth significantly enhance treatment efficiency, microbial activity, and redox stratification, thereby improving system resilience and performance. The use of layered media further contributes to stable long-term operation by promoting sequential physical, biological, and biochemical processes. SAT systems represent a low-cost and low-energy treatment alternative that aligns with nature-based solutions and supports the development of net-zero urban water cycles, particularly in water-stressed and developing regions. Their scalability, simplicity, and minimal operational requirements make layered SAT systems well-suited for decentralized urban applications.

Future research should focus on the development of long-term performance curves, a detailed investigation of clogging dynamics in multimedia filter layers, and a comprehensive evaluation of pathogen and micropollutant removal. In addition, the application of multi-attribute decision-making (MADM) frameworks is recommended to support systematic planning and implementation. Overall, this study confirms that layered SAT configurations are a sustainable, cost-effective, and robust solution for decentralized wastewater reuse, achieving up to 80% organic matter removal under optimized long-HRT conditions, compared to approximately 65% under short-HRT scenarios.

References

1. Alayu E. and Leta S., Effectiveness of two-stage horizontal subsurface flow constructed wetland planted with Cyperus alternifolius and Typha latifolia in treating anaerobic reactor brewery effluent at different hydraulic residence times, Environmental Systems Research, 9(25), 1–13, https://doi.org/10.1186/s40068-020-00183-4 (2020)

2. APHA, Standard Methods for the Examination of Water and Wastewater, 23rd ed., American Public Health Association, Washington, DC (2018) 3. Betancourt W. Q., Schijven J., Regnery J., Wing A., Morrison C. M., Drewes J. E., and Gerba C. P., Variable non linear removal of viruses during transport through a saturated soil column, Journal of Contaminant Hydrology, 223, 103479, https://doi.org/10.1016/j.jconhyd.2019.04.002 (2019)

4. Compaoré C. O. T., Maiga Y., Ouili A. S., Nikiema M., and Ouattara A. S., Purification potential of local media in the pre-treatment of greywater using vertical biofilters under Sahelian conditions, Journal of Agricultural Chemistry and Environment, 11(2), 117–131, https://doi.org/10.4236/jacen.2022.112008 (2022)

5. Drewes J. E., Heberer T., Rauch W., and Khan S. J., A four year simulation of soil aquifer treatment using columns filled with San Gabriel Valley sand, Water Research, 144, 26–35, https://doi.org/10.1016/j.watres.2018.07.012 (2018)

6. Idelovitch E., Icekson Tal N., Avraham O., and Michail M., The long-term performance of Soil Aquifer Treatment (SAT) for effluent reuse, Water Supply, 3(4), 239–246, https://doi.org/10.2166/ws.2003.0068 (2003)

7. Khaki Q. Z., Kumar B. T., and Kumar P., Recent trends in decentralized wastewater treatment system in developing countries: A critical review of case studies and future perspectives, Journal of Environmental Management, 398, 128467, https://doi.org/10.1016/j.jenvman.2025.128467 (2026)

8. Li T., Sun T., Chen Z., et al., Experimental study on phosphorus removal performance from water by SW ceramsite in a fixed bed column, Scientific Reports, 15, 42503, https://doi.org/10.1038/s41598-025-26636-3 (2025)

9. Loganathan P., Vigneswaran S., Kandasamy J., and Bolan N. S., Removal and Recovery of Phosphate From Water Using Sorption, Critical Reviews in Environmental Science and Technology, 44(8), 847–907, https://doi.org/10.1080/10643389.2012.741311 (2014)

9. Mienis O. and Arye G., Long-term nitrogen behavior under treated wastewater infiltration basins in a soil-aquifer treatment (SAT) system, Water Research, 134, 192-199, https://doi.org/10.1016/j.watres.2018.01.069 (2018)

10. Pang L., Farkas K., Lin S., Hewitt J., Premaratne A., and Close M., Attenuation and transport of human enteric viruses and bacteriophage MS2 in alluvial sand and gravel aquifer media laboratory studies, Water Research, 196, 117051, https://doi.org/10.1016/j.watres.2021.117051 (2021)

11. Perujo N., Romaní A. M., and Sanchez Vila X., A bilayer coarse-fine infiltration system minimizes bioclogging: The relevance of depth-dynamics, Science of the Total Environment, 669, 559–569, https://doi.org/10.1016/j.scitotenv.2019.03.126 (2019)
12. Sharma S. K., Kennedy M. D., Soil aquifer treatment for wastewater treatment and reuse, International Biodeterioration & Biodegradation, 119, 671–677, https://doi.org/10.1016/j.ibiod.2016.09.013 (2017)
13. Suresh Kumar P., Ejerssa W. W., Wegener C. C., Korving L., Dugulan A. I., Temmink H., van Loosdrecht M. C. M., and Witkamp G. J., Understanding and improving the reusability of phosphate adsorbents for wastewater effluent polishing, Water Research, 145, 365–374, https://doi.org/10.1016/j.watres.2018.08.040 (2018)
14. Turkeltaub T., Furman A., Mannheim R., and Weisbrod N., Continuous monitoring of a soil aquifer treatment system's physico-chemical conditions to optimize operational performance, Hydrology and Earth System Sciences, 26, 1565–1578, https://doi.org/10.5194/hess-26-1565-2022 (2022)
15. UNESCO, United Nations World Water Development Report 2023: Partnerships and Cooperation for Water, UNESCO Publishing, Paris (2023)
16. Valhondo C., Carrera J., Martínez Landa L., Wang J., Amalfitano S., Levantesi C., and Diaz Cruz M. S., Reactive Barriers for Renaturalization of Reclaimed Water during Soil Aquifer Treatment, Water, 12(4), 1012, https://doi.org/10.3390/w12041012 (2020)