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Low-cost, reliable, and highly efficient removal of COD and total nitrogen from sewage using a sponge-filled trickling filter

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ABSTRACT

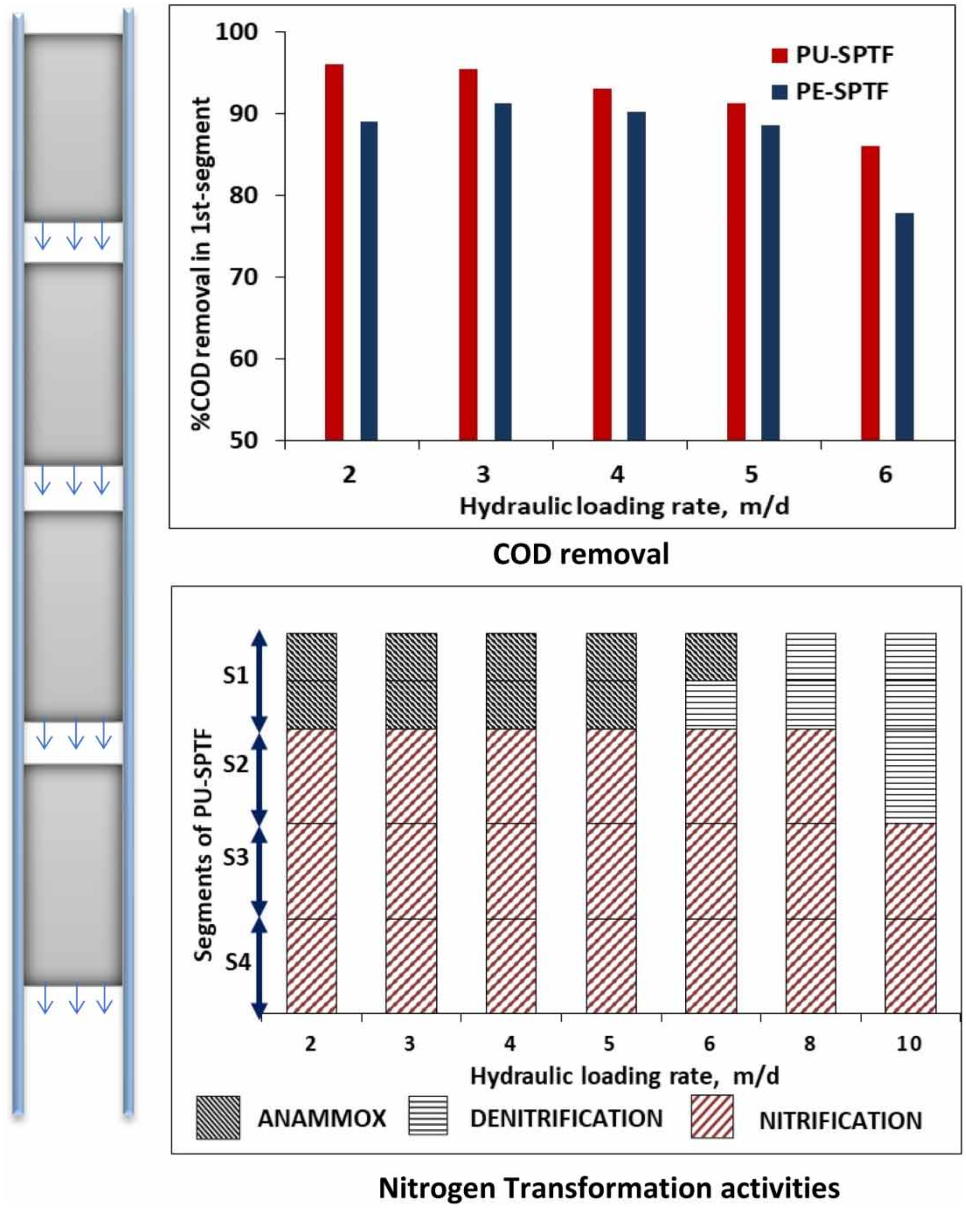
Development of low-cost and reliable reactors demanding minimal supervision is a need-of-the-hour for sewage treatment in rural areas. This study explores the performance of a multi-stage sponge-filled trickling filter (SPTF) for sewage treatment, employing polyethylene (PE) and polyurethane (PU) media. Chemical oxygen demand (COD) and nitrogen transformation were evaluated at hydraulic loading rates (HLRs) ranging from 2 to 6 m/d using synthetic sewage as influent. At influent COD of ~350 mg/L, PU-SPTF and PE-SPTF achieved a COD removal of 97% across all HLRs with most of the removal occurring in the first segments. Operation of PE-SPTF at an HLR of 6 m/d caused substantial washout of biomass, while PU-SPTF retained biomass and achieved effluent COD $<$ 10 mg/L even at HLR of 8–10 m/d. The maximum Total Nitrogen removal by PE-SPTF and PU-SPTF reactors was 93.56 ± 1.36 and 92.24 ± 0.66%, respectively, at an HLR of 6 m/d. Simultaneous removal of ammonia and nitrate was observed at all the HLRs in the first segment of both SPTFs indicating ANAMMOX activity. COD removal data, media depth, and HLRs were fitted ($R^2 > 0.99$) to a first-order kinetic relationship. For a comparable COD removal, CO_2 emission by PU-SPTF was 3.5% of that of an activated sludge system.

Key words: CO_2 emission, low-cost sewage treatment, polyethylene sponge media, polyurethane foam media, total nitrogen removal, trickling filter

HIGHLIGHTS

- A sponge-filled trickling filter (SPTF) system with random packing of sponge media is examined for sewage treatment.
- COD removal of 97% was achieved in both PE-SPTF and PU-SPTF at an HLR of 6 m/d and feed COD 350 mg/L.
- Total nitrogen removal was 93 and 92% by PE-SPTF and PU-SPTF reactors, respectively.
- Energy consumption in SPTF is ~25 times lower than that in a conventional activated sludge process.

GRAPHICAL ABSTRACT



1. INTRODUCTION

India being a country with the highest human population in the world generates a huge flow of domestic sewage. This voluminous sewage output poses two main challenges to administrative bodies: (1) providing sewerage system and centralized sewage treatment infrastructure and (2) operating sewage treatment facilities to achieve disposal norms. As reported by the Central Pollution Control Board (CPCB), the estimated daily sewage generation in India amounts to a staggering 72.368×10^6 m^3/d while the operational sewage treatment capacity stands at 26.869×10^6 m^3/d, accounting for merely 37% of the total sewage generation in India (CPCB 2021). One of the main reasons for this conspicuous disparity is the absence of economically viable infrastructure to convey sewage from individual houses to treatment plants. Furthermore, the sewage treatment plants in urban areas are already grappling with spatial constraints, limiting their capacity expansion prospect (Katam *et al.* 2021). Rural areas are not only challenged by the lack of sewage collection and treatment infrastructure but also by the scarcity of skilled personnel to operate treatment facilities. As a result, unrestrained disposal of untreated sewage causes air, soil, rivers, lakes, and groundwater degradation (Singh *et al.* 2012; Wear *et al.* 2021).

The challenges posed by sewage overload can be mitigated through the adoption of decentralized wastewater treatment (DWT) approaches. A spectrum of decentralized technologies has been employed for wastewater treatment, encompassing constructed wetland systems, septic tanks, vermifiltration, etc. However, drawbacks exist for each technology. The integrated constructed wetland system, studied by Behrends *et al.* (2007), demonstrated good chemical oxygen demand (COD) destruction (80–87%) and ammoniacal nitrogen removal (95%). However, key limitations of constructed wetland systems include a large space requirement, longer hydraulic retention time (HRT), lengthy maturity period, limited oxygen availability, and clogging due to recalcitrated sludge (Makopondo *et al.* 2020). Sabry (2010) reported DWT using upflow septic tanks/baffled reactors (USBRs) with a notable COD removal of 87% after 1 year of operation. USBR systems involve multiple components, such as baffles, plates, electrical controllers, and biogas escaping lines, and their fully efficient performance requires an extended operational period (Santiago-Díaz *et al.* 2019). Vermifiltration studied by Sinha *et al.* (2008) achieved 98% BOD_5 removal. Nonetheless, vermifiltration being a surface area-based technology, higher hydraulic loading rates (HLRs) can reduce HRT and subsequently impact system performance. Moreover, earthworms are very sensitive to higher hydraulic loads and/or adverse environmental conditions (Dey Chowdhury *et al.* 2022). Besides the above technologies, conventional suspended growth (e.g. activated sludge process (ASP)) and attached growth (e.g. trickling filter (TF)) processes offer excellent sewage treatment efficiency. However, the use of ASPs in rural areas is not feasible due to the need for skilled operators and high-energy consumption. On the other hand, attached growth processes are reported to offer superior treatment efficiencies, operational flexibility, microbial density, and lower biomass production and operational expenditure (Abyar & Nowrouzi 2023). Moreover, attached growth systems such as TFs are reported to remove emerging pollutants from domestic wastewater (Jong *et al.* 2018; Shukla & Ahammad 2023) and perform nitrification to transform ammonia into nitrate (Forbis-Stokes *et al.* 2018). Thus, a TF may be explored as an ideal DWT system that is of low-cost and easy to install and operate. However, a conventional TF packed with stones requires a strong structure. Furthermore, the stone medium provides a smaller surface area for the immobilization of microbes, leading to poor treatment efficiency. Although plastic media with a high surface area are commercially available, they are primarily manufactured by some select companies, making them costly. Recently, polyurethane (PU) sponge pieces of different shapes have gained the attraction of researchers as low-cost biomass carriers owing to their lightweight and high surface area and porosity. Various versions of downflow hanging sponge (DHS) reactors have been reported for sewage treatment to achieve >90% BOD and COD removal (Machdar *et al.* 2000; Tandukar *et al.* 2006; Ismail *et al.* 2020; Dacewicz & Grzybowska-Pietras 2021). However, DHS reactors involve hanging sponge pieces of different shapes through a string or a curtain (Machdar *et al.* 2000; Tandukar *et al.* 2007). Another version of DHS reactor employed randomly packed sponge pieces with each sponge piece covered by a polypropylene plastic net. Yet another DHS reactor used solid cubes made by copolymerization of PU with epoxy resin (Onodera *et al.* 2014; Nomoto *et al.* 2018). Modifications such as hanging the sponge media or covering the sponge media with a plastic net require skillful supervision and specialized manufacturing tools, which also limits its application in rural areas and increases the cost of TF systems.

Hence, this study is conducted to systematically investigate the potential of a TF system consisting of randomly packed sponge cubes as a standalone sewage treatment unit. Two types of sponge cubes, namely polyethylene (PE) and PU, were used as the packing media. Removal of COD and total nitrogen (TN) was investigated along the vertical segments of TF systems operated under varied HLRs. Also, COD removals achieved at various HLRs were fed to a simple first-order kinetic model to derive the kinetic parameters that can be used to design field-scale sponge-filled trickling filter (SPTF) systems.

2. MATERIALS AND METHODOLOGY

2.1. Reactor configuration

A schematic diagram of the experimental SPTFs is shown in Figure 1. Each SPTF was composed of four identical, vertically aligned cylindrical segments. Each segment was 350 mm in height and 100 mm in diameter, separated by a 100 mm spacing. These separation spaces facilitate the ingress of atmospheric air into the reactor making it a self-ventilated system. It is imperative to note that the packing media within each segment were randomly filled to a height of 300 mm, and at the bottom, the media were supported by an iron grid having 6–8 mm^2 openings.

A common feed tank was employed to supply sewage to both reactors. The sewage was introduced into the system through a single-point inlet pipe, positioned at the center of the uppermost segment of each reactor. To regulate the flow of sewage, peristaltic pumps were utilized. To facilitate the collection of treated effluent, dedicated effluent collection tanks were situated

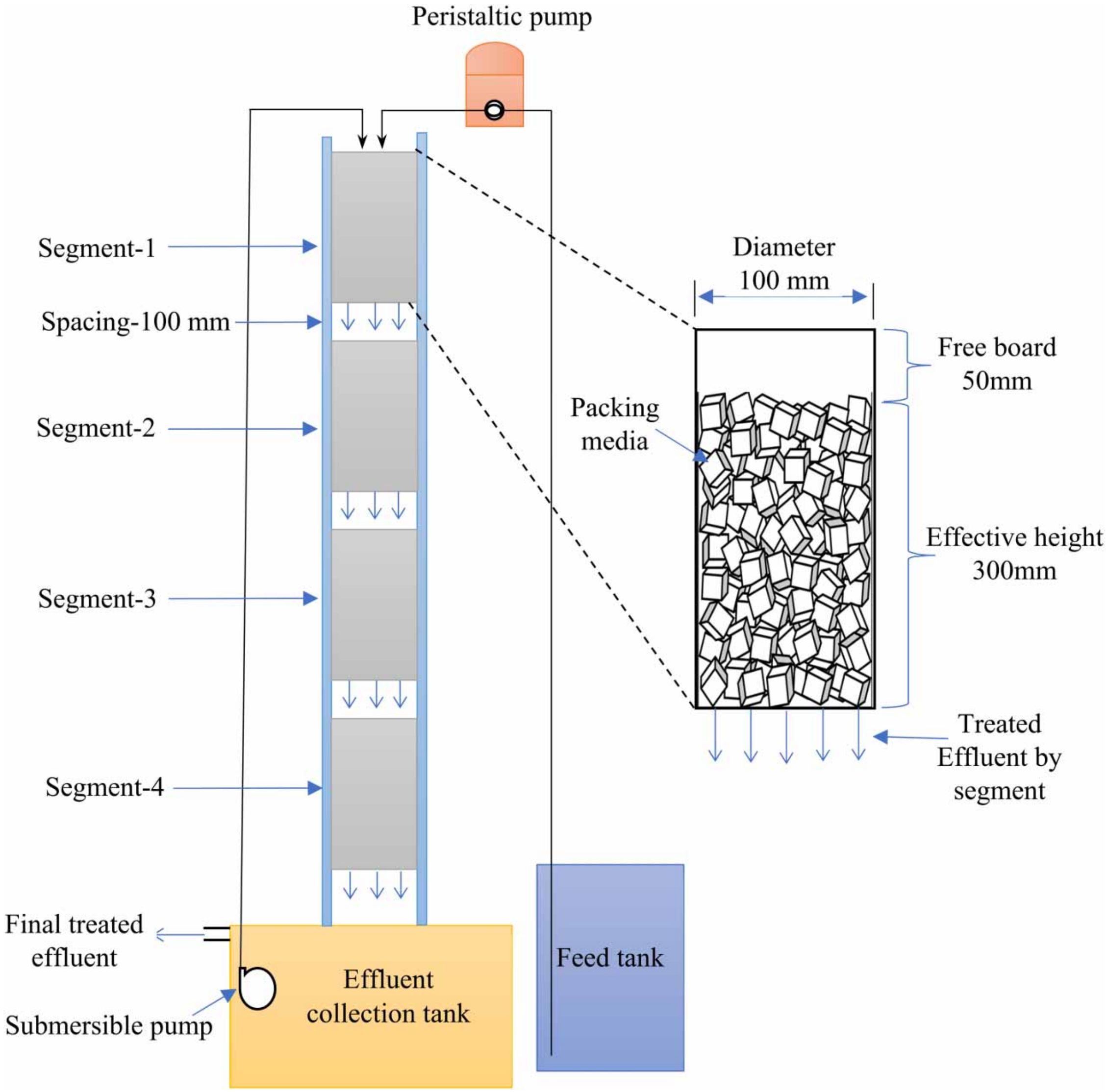


Figure 1 | Schematic diagram of SPTF system and packing media dimensions.

at the base of each reactor. Recirculation of treated sewage was carried out using submersible pumps placed in the effluent collection tanks.

2.2. Media material and properties

The performance of SPTFs was examined for two different packing media. One was a semi-rigid expanded PE foam, also known as hit-loan sponge foam, and the other was a soft PU foam. Both PE and PU foams are known to have a remarkable resistance to a range of weather conditions, exhibiting minimal signs of deterioration over time. Both PE and PU foams were uniformly cut into 12 mm square cubes and randomly packed in each segment of SPTFs.

The apparent density of media was determined in a laboratory by considering the ratio of the dry mass to the volume of the cube. The porosity of sponge media was determined by immersing a sponge cube in a known volume of distilled water under a vacuum for 5 h, with a reduced volume of water representing the percentage of porosity after removal of the immersed media (Beas *et al.* 2015; Dacewicz & Grzybowska-Pietras 2021). The apparent density value for PE and PU was 20 and 32 kg/m^3, respectively. The porosities of PE and PU foams were approximately 58.8 ± 0.2 and 95.9 ± 0.4%, respectively.

2.3. Synthetic sewage

The thorough examination of SPTF system's performance at different HLRs required consistency in the characteristics of raw sewage (Nguyen *et al.* 2010).

To maintain consistency in the experimental set-up, daily quantities of synthetic sewage were prepared to emulate the composition of real sewage, encompassing organic matter, nutrients, and trace elements. A synthetic sewage solution was prepared by adding 33.7 g sugar, 5 g NH_4Cl, 1 g NaCl, 2.6 g $NaH_2PO_4 \cdot 2H_2O$, 1.025 g $MgSO_4 \cdot 7H_2O$, 5 g peptone, 1 g $CaCl_2$, and 0.5 g $FeCl_3$ per 100 L of tap water (Rottlers *et al.* 1999; Nopens *et al.* 2001; O'Flaherty & Gray 2013). The characteristics of this synthetic sewage were: 375 ± 25 mg/L COD, 14.56 ± 0.62 mg/L ammonia (NH_4-N), 11.23 ± 0.55 mg/L nitrate (NO_3-N), 5.17 ± 1.25 mg/L PO_4-P, and a pH of 7 ± 0.4.

2.4. Start-up of the reactors

Activated sludge was collected from a secondary clarifier of an activated sludge plant treating domestic sewage, and diluted with sewage and tap water to the mixed liquor suspended solids (MLSS) concentration of 3,000–3,500 mg/L. First, all the packing media were submerged in the diluted activated sludge and then filled in all segments of the corresponding reactors. To achieve effective immobilization, the diluted activated sludge was continuously recirculated to the uppermost segment of each SPTF system using a submersible pump until the effluent from the bottom-most stage was almost free from turbidity. The initial amounts of biomass immobilized on media in segments 1, 2, 3, and 4 were 10.8, 11.5, 11.2, and 9.6 g-SS/L of media volume in PE-SPTF, and 14.52, 13.48, 14.96, and 11.7 g-suspended solids/L of media volume in PU-SPTF, respectively.

2.5. Operational conditions

Both reactors were operated continuously under ambient temperature conditions. To prevent microbial growth, the feed tank and the feed pipeline were cleaned daily using an acidic solution.

HLR, HRT, and organic loading rate (OLR) are important operating parameters for TFs (Arthur *et al.* 2022). The PE-SPTF and PU-SPTF were operated at HLRs of 2, 3, 4, 5, and 6 m/d. The corresponding overall OLRs were 0.58, 0.88, 1.17, 1.46, and 1.75 kg-COD/$m^3 \cdot$d, respectively. At these HLRs, the corresponding overall HRTs were 0.6, 0.4, 0.3, 0.24, and 0.2 d, respectively. Owing to superior performance, the PU media reactor was subjected to further evaluation at two additional HLRs of 8 and 10 m/d.

2.6. Sampling and analytical methods

A sample of influent was obtained from the end of the pipeline feeding the raw sewage to the uppermost segment of the reactor. Effluent samples were collected from the bottom of each segment and analyzed for various parameters without filtration.

The pH of the samples was measured using an Analab digital pH meter (India). Analyses of parameters such as COD, ammonia (NH_4-N), and nitrate (NO_3-N) were performed according to methods 5220 C, 4500-NH_3 F, and 4500-NO_3 B, respectively, described in Standard Methods for the examination of water and wastewater (APHA 2017).

3. RESULTS AND DISCUSSION

3.1. COD removal in PE-SPTF and PU-SPTF at varying HLRs

The reduction in COD concentration along with the reactor height is shown in Figure 2(a) and 2(b), respectively for the PE- and PU-SPTF systems at different HLRs. The corresponding overall HLRs are also shown in Figure 2.

It may be noted from Figure 2 that both reactors achieved an excellent COD removal of up to 97%. Also, most of the COD removal occurred in the first segment of each SPTF reactor. In the PE-SPTF, as the HLR increased from 2 to 5 m/d, the COD concentrations in the effluent from the first segment increased from 30.5 ± 1.37 to 41.7 ± 2.12 mg/L. In contrast, the PU-SPTF consistently maintained effluent COD concentrations below 35 mg/L after the first segment at the HLRs of 2–5 m/d. However, at an HLR of 6 m/d, COD increased to 50.8 ± 2.28 mg/L after the first segment. On the other hand, in the PE-SPTF first segment effluent COD increased from 41.7 ± 2.12 to 80.74 ± 2.26 mg/L at an HLR of 6 m/d. Nevertheless, the final treated effluent from both reactors consistently recorded COD levels below 10 mg/L across all the examined HLRs, providing a remarkable COD removal efficiency of about 97%.

The consistent COD removal in SPTFs within the HLRs ranging from 2 to 5 m/d can be elucidated by considering the inherent characteristics of the randomly packed reactors. Notably, such reactors lack a defined flow path. At lower hydraulic rates, the influent sewage may not fully cover the entire media volume and surface. Subsequently, as the hydraulic rate is

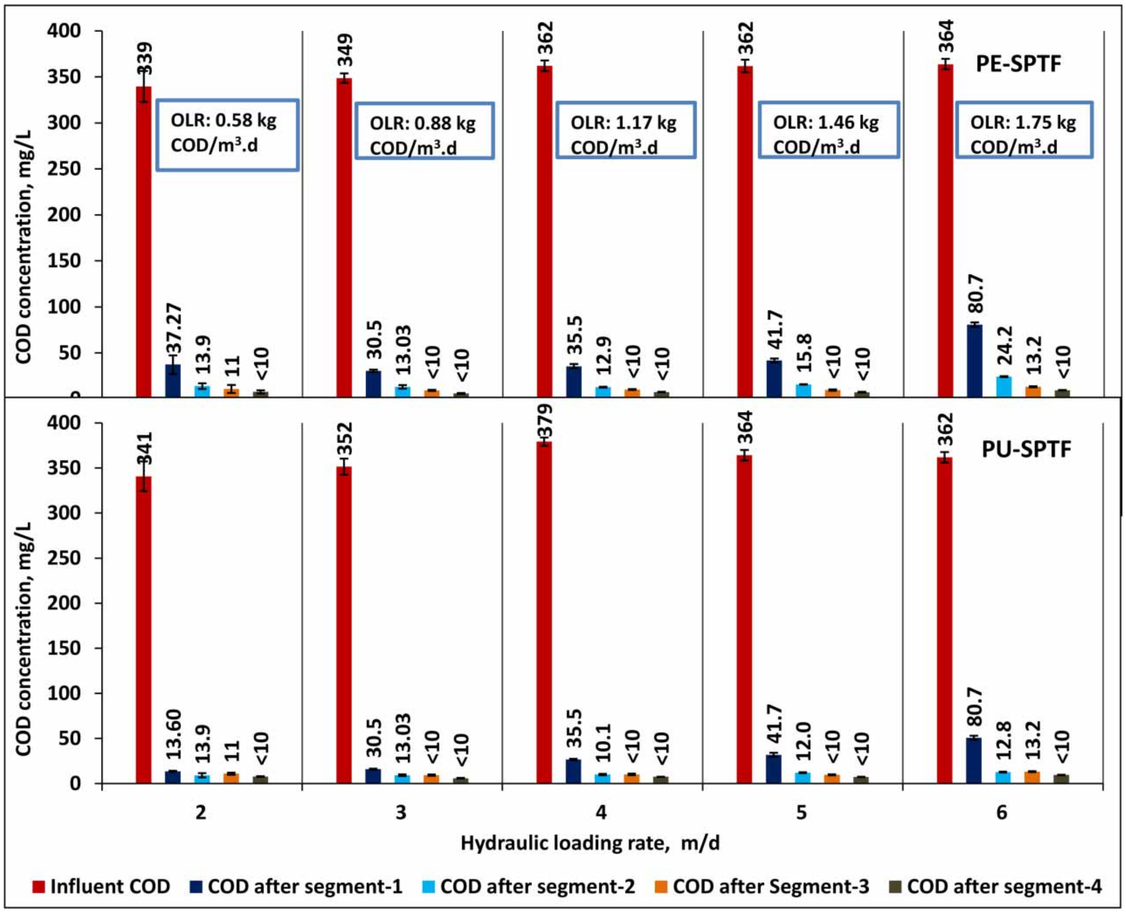


Figure 2 | COD concentration profiles in PE-SPTF and PU-SPTF at varying HLRs and OLRs.

increased, a more uniform distribution of the influent is achieved (Huamán *et al.* 2022), resulting in greater coverage of the media surface by the applied sewage. Furthermore, the biomass growth within the media can introduce delays and alterations in the flow pathways (Fleifle *et al.* 2013) leading to better contact opportunities between the biomass and sewage. Thus, the SPTFs could maintain excellent COD removal efficiencies at higher HLRs and OLRs due to the reasons mentioned above.

The results obtained from both PE and PU media reactors demonstrate notable efficient performance in comparison with prior studies. For instance, Mahmoud *et al.* (2010) investigated a DHS reactor containing PU sponge cubes wrapped in a plastic net. The authors reported the maximum COD removal of 89% from an initial concentration of 302 mg/L under an organic load of 1.2 kg-COD/m^3·d. In a study by Murata *et al.* (2021) employing a PU foam structural bed reactor with intermittent aeration, the maximum COD removal of 94 ± 5% was achieved at an organic load of 0.184 kg-COD/m^3·d. Uemura *et al.* (2012) studied the DHS system with three different media sizes. The applied organic load was 1.27 kg-COD/m^3·d on each media and achieved a COD removal ranging from 82 to 85%. These comparisons suggest that SPTFs with unmodified and randomly packed sponge media and receiving significantly higher COD load (overall OLR: 0.58–1.75 kg-COD/m^3·d) provide superior COD removal efficiencies as compared with the reactors involving modified and hanging sponge media.

It was observed that a significant amount of biomass was washed out from PE-SPTF and collected in the effluent collection tank when operated at an HLR of 6 m/d. This may be attributed to lower porosity and hence the lower biomass holding capacity of PE media. Hence, PE-SPTF was not subjected to HLRs greater than 6 m/d; however, PU-SPTF was tested further at HLRs of 8 and 10 m/d.

As shown in Figure 3, at HLRs of 8 and 10 m/d, the COD concentrations noted in the effluent of first segment of PU-SPTF were 128 ± 6.48 and 170.6 ± 5.41 mg/L, respectively. Nevertheless, the final treated effluent consistently exhibited COD concentration below 15 mg/L. These results indicate the capacity of PU-SPTF to maintain excellent COD removal efficiency even at a higher OLR and HLR. At the end of 106 d of continuous operation treating about 3,000 L of sewage, the first

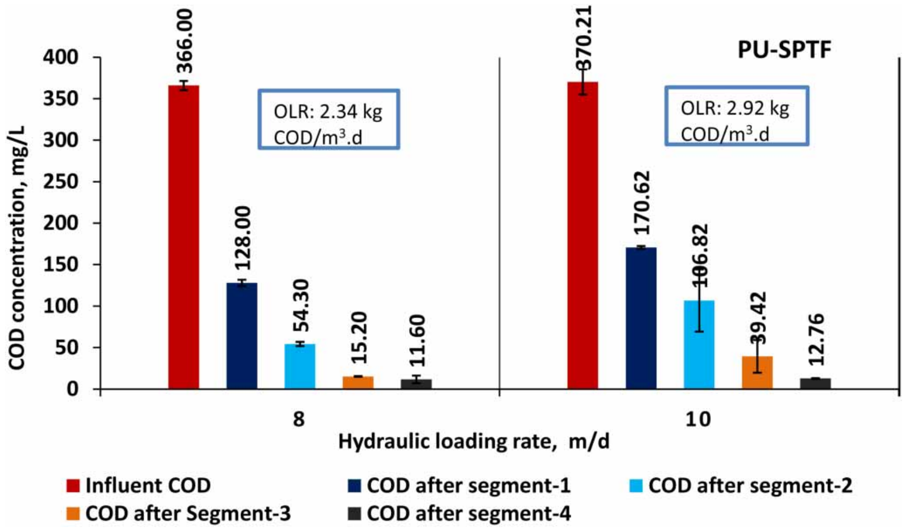


Figure 3 | COD concentration profiles in PU-SPTF reactor at HLRs of 8 and 10 m/d.

segment of PU-SPTF was choked due to excessive retention of biomass. Thus, the PU-SPTF system could deliver consistent COD removal for a long period although the sponge media were used without any physical or chemical modifications. After choking, the MLSS concentrations in segments 1–4 were found to be 75.25, 80.92, 64.67, and 41.92 g-SS/L media volume, respectively. As compared with the initial MLSS concentration, the MLSS concentration at the onset of choking increased about four- to six fold.

3.2. Nitrogen transformation in PE-SPTF and PU-SPTF at different HLRs

Figure 4(a) and 4(b) shows the results of NH_4-N and NO_3-N removal in PE-SPTF and PU-SPTF systems operated at HLRs of 2–6 m/d, respectively. It may be noted from Figure 4 that NH_4-N removal occurs predominantly in the first segment as noted in the previous studies (Machdar *et al.* 2000; Onodera *et al.* 2014).

In the PE-SPTF as shown in Figure 4(a), NH_4-N removal ranged from 68 to 79% within the first segment and reached near complete elimination at the end of the fourth segment for HLRs up to 5 m/d. However, at an HLR of 6 m/d, the removal efficiency slightly decreased to $92.52 \pm 2.31\%$. On the other hand, as illustrated in Figure 4(b), NH_4-N was completely removed at the end of the second segment and onward in the PU-SPTF, irrespective of the HLR.

A careful observation of Figure 4(a) reveals that for PE-SPTF, for the second segment and onward, the decrease in NH_4-N correlates well with the increase in NO_3-N concentration for HLRs of 2–5 m/d. A similar observation can also be made for PU-SPTF (Figure 4(b)) at HLRs of 2–5 m/d. This suggests that nitrification is the main mechanism contributing to ammonia removal in segments 2–4. Since most of the organic load is removed in the first segment, the lower segments will remain fully aerated, which is a prerequisite for nitrification (Onodera *et al.* 2014). However, it is interesting to note that at an HLR of 6 m/d, NO_3-N is almost completely removed, and NH_4-N is partially (~50%) removed in the first segment. Specifically, in the first segment of the PE-SPTF, NO_3-N removal increased from $47.29 \pm 4.24\%$ at an HLR of 2 m/d to $99.74 \pm 0.13\%$ at an HLR of 6 m/d. Similarly, in the PU-SPTF, NO_3-N removal in the first segment increased from $41.25 \pm 2.06\%$ at an HLR of 2 m/d to $96.36 \pm 3.01\%$ at an HLR of 6 m/d. The higher HLR will lead to a higher OLR (in this case, ~7.0 kg-COD/m^3·d on the first segment) which may trigger anoxic conditions leading to consumption of NO_3-N as an electron acceptor. Nevertheless, the NH_4-N concentration would remain unaffected under anoxic conditions. However, the simultaneous removal of NO_3-N and NH_4-N in the first segment in the current study indicates the possibility of anaerobic oxidation of NH_4-N (ANAMMOX) in the presence of NO_2-N by the ANAMMOX organisms (Mac Conell *et al.* 2015). No other plausible explanation exists for the simultaneous and significant removal of NO_3-N and NH_4-N. It is worth noting that no specific conditions were intentionally maintained or provided in SPTF systems for the simultaneous removal of NO_3-N and NH_4-N. It may be understood that the first segment receiving the highest organic load will be partially aerobic. Such conditions facilitate the partial oxidation of NH_4-N to NO_2-N in the first segment (Guo *et al.* 2010; Wang *et al.* 2010; Kumar *et al.* 2016; Bressani-Ribeiro *et al.* 2018)

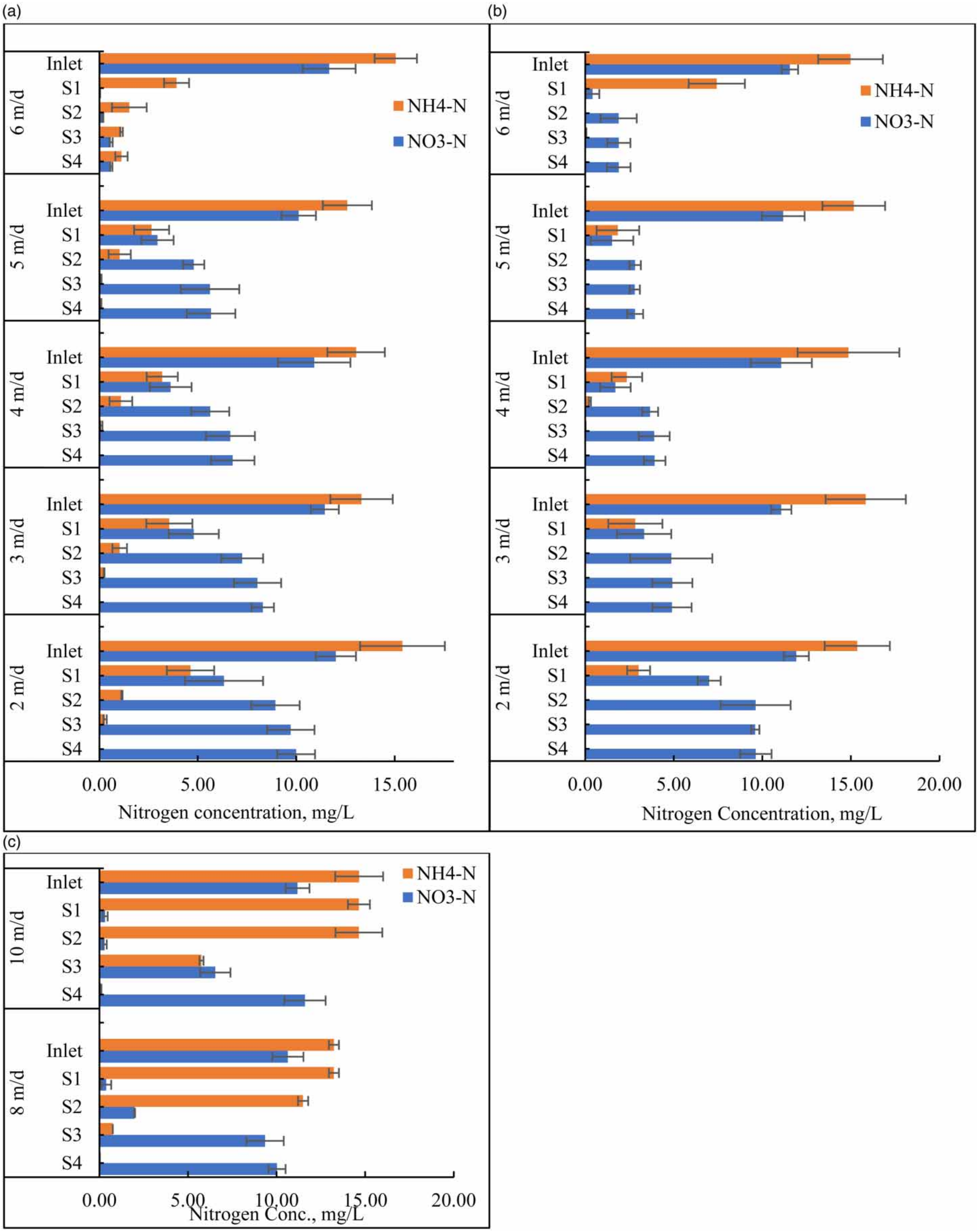


Figure 4 | Transformation of ammonia nitrogen (NH_4-N) and nitrate nitrogen (NO_3-N) (a) in PE-SPTF at HLRs 2–6 m/d, (b) in PU-SPTF at HLRs 2–6 m/d, and (c) in PU-SPTF at HLRs 8 and 10 m/d. (*S*1, *S*2, *S*3, and *S*4 represent the nitrogen concentrations measured in the effluent of segments 1, 2, 3, and 4, respectively.)

which in the presence of remaining NH_4-N will be oxidized by ANAMMOX organisms to N_2. The presence of ANAMMOX organisms in wastewater treatment plants and aerobic, anaerobic, and anoxic sludge is already reported (Ding *et al.* 2017; Mirza *et al.* 2021). Since the biomass used for the start-up was collected from a sewage treatment plant, the presence of ANAMMOX organisms in both SPTF systems is plausible. Consistent with the results of NO_3-N and NH_4-N removal discussed above, the TN (TN = NO_3-N + NH_4-N) removal increased with an increase in the HLR. The maximum TN removals observed in the PE-SPTF and PU-SPTF were 93.56 ± 1.36 and 92.24 ± 0.66%, respectively, at an HLR of 6 m/d. Since, almost the entire TN removal occurred in the first segments of PE- and PU-SPTFs, we calculated the volumetric TN removal rate based on the volume of media in the first stage. The volumetric TN removal rates in the PE-SPTF at HLRs 2, 3, 4, 5, and 6 m/d were 0.1, 0.16, 0.23, 0.28, and 0.45 kg-TN/m^3·d. The corresponding volumetric TN removal rates in the PU-SPTF were 0.11, 0.21, 0.29, 0.38, and 0.37 kg-TN/m^3·d. These results reveal that the volumetric TN removal rates in the PU-SPTF at HLRs 2–5 m/d are significantly higher than that in the PE-SPTF. The smaller volumetric TN removal rate in the PU-SPTF at 6 m/d may be attributed to a greater anaerobicity at a higher COD load which will adversely affect oxidation of ammonia to nitrite.

Figure 4(c) illustrates ammonia and nitrate removal in the PU-SPTF at HLRs of 8 and 10 m/d. It is interesting to note that while NO_3-N removal in the first segment was >96%, NH_4-N removal was negligible. This is opposite to what was observed in the PU-SPTF at HLRs of 2–6 m/d. It was observed that at HLRs of 8 and 10 m/d, the first segment was completely anaerobic, which is evident from the black color of biomass and foul odor. Such conditions favor the removal of NO_3-N by denitrification. On the other hand, the presence of fully anaerobic conditions will not allow nitrification of NH_4-N, resulting in a negligible removal of NH_4-N. However, in the lower segments (segments 3 and 4) where aerobic conditions prevail, NH_4-N is oxidized almost stoichiometrically to NO_3-N resulting in effluent nitrate concentrations of 10–12 mg-N/L. Based on the above discussion, a pictorial presentation of the predominance of ANAMMOX, nitrification, and denitrification activities in segments of the PU-SPTF at different HLRs is shown in Figure 5.

In the previous studies employing TFs containing hanging or covered sponge media, NH_4-N removal was found to be adversely affected due to the increase in organic load (Tawfik *et al.* 2011; Nomoto *et al.* 2018; Ismail *et al.* 2020; Murata *et al.* 2021). In contrast to these observations, the data from our study reveal that NH_4-N removal increased with the increase in the OLR from 0.58 to 1.46 kg-COD/m^3·d (HLR: 2–5 m/d), mainly due to ANAMMOX activity in the first segments of both the reactors. The residual NH_4-N in the effluent of the first segments was removed by nitrification in the subsequent segments of both reactors. Thus, the NH_4-N removal in PE- and PU-SPTFs was unaffected by organic loading. As explained in the above paragraphs and shown in Figure 5, more than one mechanism of NH_4-N and TN removal is possible in PE- and PU-SPTF systems containing randomly packed unmodified sponge media, leading to a greater removal of TN.

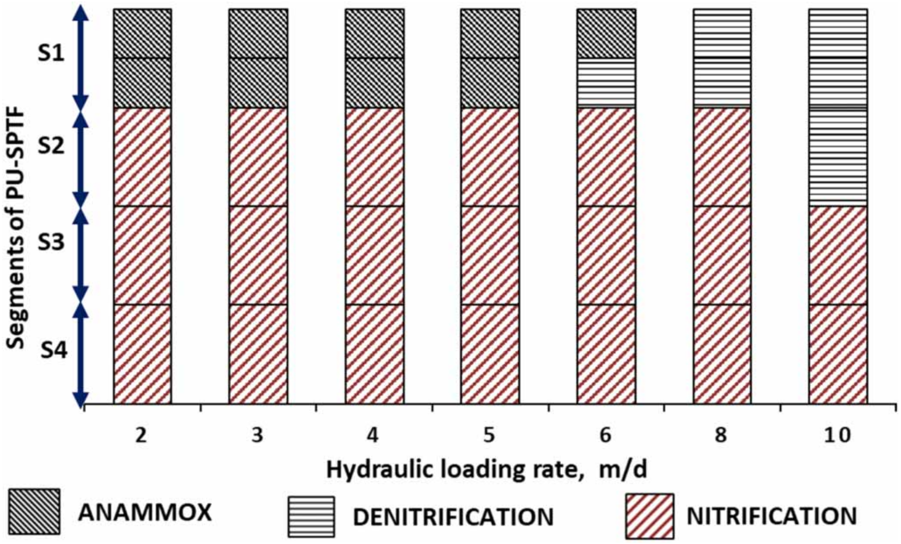


Figure 5 | Nitrogen transformation activities in segments of PU-SPTF at different HLRs.

The TN removal obtained in our study is comparable to or better than that reported in the published literature. Murata *et al.* (2021) found the highest TN removal of 74 ± 7% in a PU foam structural bed reactor with periodic mechanical aeration (Murata *et al.* 2021). Using a third-generation DHS reactor, Mahmoud *et al.* (2010) reported 72, 90, and 99% removal of ammonia at different HRTs of 2, 4, and 6 h, respectively. The authors also noted that out of the above removals, about 41, 31, and 19% of the initial ammonia remained unaccounted, i.e. could not be related to the generation of nitrate, indicating ammonia removal by the ANAMMOX process. Using TFs with rigid sponge media, Onodera *et al.* noted 30 and 28% TN removal (Onodera *et al.* 2013, 2014). Bundy *et al.* (2017) used a partially submerged DHS reactor operated at an OLR of 0.4 kg-COD/m^3·d, HRT of 0.6 d, and influent TN concentration of 42 mg/L, and reported 78% TN removal. A detailed comparison of COD and TN removal obtained in this study with the published reports is given in Table 1.

3.3. Kinetics of COD degradation in PE- and PU-SPTFs

A kinetic model for COD degradation would help predict the performance of the reactor and design a reactor for different organic and hydraulic parameters. Removal of organic matter by biodegradation normally follows the first-order kinetics (Metcalf *et al.* 2014). Fleifle *et al.* (2013) reported that the substrate utilization in a DHS system followed the first-order reaction kinetics. Similarly, Nomoto *et al.* (2018) observed that the first segment of a DHS exhibited first-order COD removal and the remaining segments exhibited a linear rate of substrate degradation. The first-order BOD removal rate with respect to the depth of the packed bed (d_{BOD}/dD) in TFs with plastic packing has been related to the HLR and the HRT (Velz 1948; Howland 1958; Schulze 1960). The integrated form of this formulation is delineated below (Metcalf *et al.* 2014):

$$\frac{S_e}{S_0} = e^{-kD/Q^n} \tag{1}$$

In the above equation, S_0 and S_e represent the influent and effluent BOD concentrations in mg/L, respectively, k denotes the experimentally determined rate constant, D is the depth of the packing media, Q is the hydraulic application rate in m^3/m^2·d (i.e. HLR), and n is a constant value associated with the characteristics of the packing media. We used Equation (1) with little modification, using COD instead of BOD concentrations to represent S_e and S_0. The linearized form of Equation (1) is shown as Equation (2). Different values of (D/Q^n) on the x-axis vs. ln (S_e/S_0) on the y-axis can be plotted to derive the constants for PE-SPTF and PU-SPTF media.

$$\ln\left(\frac{S_e}{S_0}\right) = -k\left(\frac{D}{Q^n}\right) \tag{2}$$

Since COD removal in segments other than the first segment was very small, the depth of media in Equation (2) was taken as 0.3 m being the packed depth of the first segment. The value of 'n' for randomly packed sponge cubes is not reported in the published literature to the best of our knowledge. Since the values of (D/Q^n) cannot be calculated without knowing 'n', we used various values of 'n' to calculate (D/Q^n) and reported the one that provided the best fit for the plotted data offering the R^2 value closest to 1.

As shown in Figure 6, the values of $n = 0.35$ and 0.5 gave the best fit for the plotted data, and the corresponding 'k' values were 11.45 (m/d)$^{0.35}$/m and 17.06 (m/d)$^{0.5}$/m for PE-SPTF and PU-SPTF reactors, respectively. The corresponding 'k' values normalized to 20 °C were 8.7 (m/d)$^{0.35}$/m and 12.96 (m/d)$^{0.5}$/m for PE-SPTF and PU-SPTF reactors, respectively. It may be noted that 'k' is a measure of substrate degradability or 'removability' in a given reactor system, and hence, a higher 'k' value indicates a greater removal efficiency. On the other hand, 'n' indicates the suitability of the packing media (Fleifle *et al.* 2013). The notably higher 'k' and 'n' values observed for the PU-SPTF than for the PE-SPTF may be attributed to the greater porosity of the PU sponge media, which allows for enhanced biomass accumulation and thereby superior biodegradation. We conducted some experiments at HLRs other than those used for the development of plots shown in Figure 6 to validate the substrate removal model (Equation (1)). At the end of the first segment, the actual effluent COD concentrations and COD concentrations predicted using Equation (1) substituted with 'k' and 'n' values determined as above were closely matching with $R^2 > 0.97$ for both the reactors. This suggests the robustness of the first-order COD removal model and kinetic parameters derived in this study.

Table 1 | Detailed comparison of COD and TN removal obtained in the SPTF with the published reports

Sl no.	Media type	Sewage type	COD influent, mg/L	COD effluent, mg/L	Organic loading, kg-COD/ m^3·d	%COD reduction	NH_4-N influent, mg/L	NH_4-N effluent, mg/L	NO_3-N influent, mg/L	NO_3-N effluent, mg/L	%TN removal	Reference
1	DHS-PU – covered by plastic net	Gray water	878 ± 260	53 ± 17	6.8	94 ± 3	14 ± 6	10 ± 5	–	1.7 ± 1.2	13 ± 7	Tawfik *et al.* (2011)
2	DHS – sixth generation	UASB treated	169 ± 80	48 ± 19	2.03	68 ± 17	25 ± 6	4 ± 3	N.D.	17.3 ± 4.9	28 ± 20	Onodera *et al.* (2014)
3	Cylindrical PU foam	Raw sewage	464 ± 121	45 ± 24	1.38	90 ± 5	37 ± 10[a]	4.7 ± 5.1[a]	–	2.5 ± 2.2	69 ± 15	Moura *et al.* (2018)
4	DHS-PU – adhering on rectangular sheet	UASB treated	167 ± 62	60 ± 28	2.03	64	40 ± 7	12 ± 7	–	17 ± 4	27	Tandukar *et al.* (2006)
5	DHS-PU – wrapped with perforated plastic	Pre-settled sewage	300 ± 37	60 ± 12	1.8	80 ± 4	25 ± 4	2.5 ± 2	–	13.9 ± 2.3	13	Mahmoud *et al.* (2010)
6	PU with inoculated microalgae	Primary effluent	210 ± 46	30 ± 3	0.42	86	50 ± 11[b]	17 ± 0.5[b]			62	Katam *et al.* (2021)
7	DHS-PU – covered by plastic net	UASB treated	355 ± 67	97 ± 20	7.89	71 ± 11	42 ± 2	30.2 ± 2.1	–	–	–	Nomoto *et al.* (2018)
8	PU – vertically fixed inside the reactor	Pre-settled sewage	451 ± 75	58 ± 18	0.46	87	35 ± 8[a]	19 ± 7[a]	–	1 ± 3	43	Murata *et al.* (2021)
9	DHS-PU – in cylindrical plastic net	Screened sewage	152	14	2.01	91	21.2	N.D.	N.D.	15.2	28	Miyaoka *et al.* (2017)
10	Rubber	Raw sewage	1,016 ± 29	69 ± 16	0.85	93	N.R.	N.R.	N.R.	N.R.	N.R.	Naz *et al.* (2015)
	Polystyrene		360 ± 32	38 ± 14	0.30	89	N.R.	N.R.	N.R.	N.R.	N.R.	
	Plastic		1,351 ± 117	69 ± 23	1.13	95	N.R.	N.R.	N.R.	N.R.	N.R.	
	Stone		821 ± 23	32 ± 17	0.68	96	N.R.	N.R.	N.R.	N.R.	N.R.	
11	Sponge	Effluent of anaerobic membrane bioreactor	129 ± 65	48 ± 21	1.29	63	26.5 ± 5	4.0 ± 3.5	0.9 ± 1	18.6 ± 7.3	32	Zhang *et al.* (2016)
	Zeolite			70 ± 43		46		9.2 ± 4.4		17.8 ± 7.9	35	
	Ceramsite			62 ± 41		52		9.6 ± 5.4		15.5 ± 7.1	43	
12	PE-SPTF	Synthetic sewage	364 ± 6	10 ± 0.2	1.8	97 ± 0.2	15 ± 1	1.1 ± 0.31	12 ± 1.3	0.6 ± 0.1	94	This study
	PU--SPTF		362 ± 4	8 ± 0.15	1.8	98 ± 0.7	15 ± 2	N.D.	11.5 ± 0.5	1.9 ± 0.7	93	

N.D. = not detected, N.R. = not reported, TN = total nitrogen concentration.

[a] TKN-nitrogen concentration.

[b] Total nitrogen concentration.

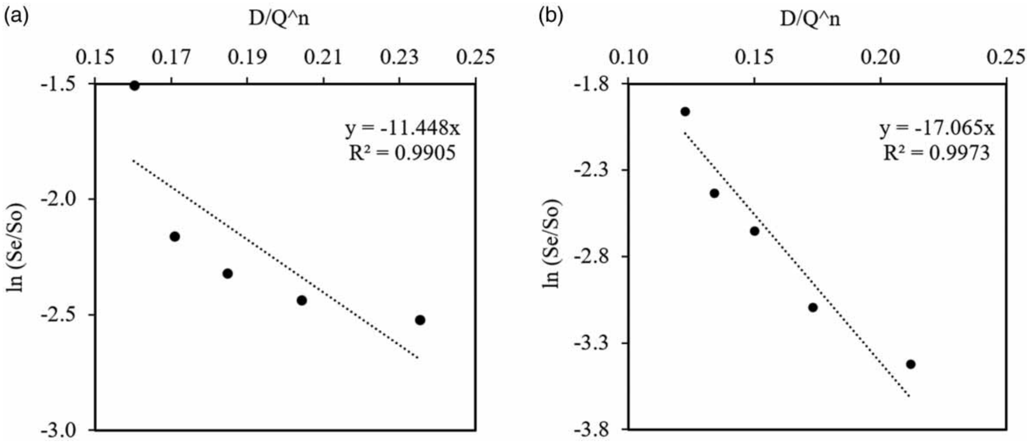


Figure 6 | Plots of $\ln(S_e/S_0)$ vs. (D/Q^n) for first segment of (a) PE and (b) PU media reactors.

3.4. Estimation of energy consumption for the operation of SPTF system

The SPTF system operates as a self-aerated system, offering a distinct advantage in terms of energy consumption when compared with a conventional ASP or any other aerobic biological process. In case of the SPTF system, power is primarily consumed for the pumping of sewage and recirculation of effluent (if any) to the top of the reactor, whereas the ASP system requires power for the aeration system and recirculation of biomass. A comparison was made between the power consumption of the SPTF system and the ASP for the identical COD removal performance. The influent COD concentration of 350 mg/L and a sewage flow equivalent to an HLR of 6 m/d were considered for comparison (under these conditions, COD removal in PU-SPTF and PE-SPTF was 97%). Detailed calculations with relevant data are shown in Supplementary material. The power requirements were found to be 0.222×10^{-3} kWh/L for the ASP and 0.0078×10^{-3} kWh/L for the SPTF system. It is worth noting that the additional power consumption for continuous sludge recirculation in the ASP is not considered in the above values. Considering CO_2 generation of 0.82 kg/kWh in India (CEA 2022), the CO_2 emission contribution by SPTF and ASP will be 6.4 and 182 mg/L of wastewater treated, respectively. These results highlight the extraordinary energy efficiency exhibited by the SPTF system, demanding a mere 3–4% of the energy when compared with a conventional ASP for an identical COD removal efficiency.

4. CONCLUSION

- From initial 350 mg/L COD and ~27 mg/L TN in raw sewage, both the SPTF systems achieved <2 mg/L of TN and <10 mg/L of COD in the effluent at an HLR of 6 m/d, overall OLR of 1.75 kg-COD/m^3·d, and HRT of 0.2 d, thereby conforming to the prevailing sewage disposal standards in India.
- The simultaneous removal of $NO_3^- - N$ and NH_4-N in the first segment of PE-SPTF and PU-SPTF suggested a significant ANAMMOX activity. The TN removal rate in the first segments of PE- and PU-SPTFs increased with the increase in the HLR and OLR.
- As compared with the PE-SPTF, the PU-SPTF consistently achieved superior COD and TN removal. Based on the kinetic parameters, the equations for COD removal in first segment, related to the HLR were: $S_e/S_0 = e^{-11.45D/Q^{0.35}}$ and $S_e/S_0 = e^{-17.06D/Q^{0.5}}$ for PE-SPTF and PU-SPTF reactors, respectively. These equations were validated with the predicted COD removal correlating with the actual COD removal with $R^2 > 0.97$.
- Under similar conditions, as compared with a conventional aerobic biological treatment system such as the activated sludge system, the energy consumption per liter of sewage treated in the PU-SPTF was almost 25 times less.
- The SPTF system with randomly packed sponge media emerges as a cost-effective, reliable, and straightforward solution for DWT.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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