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Simulated Modelling, Design, and Performance Evaluation of a Pilot-Scale Trickling Filter System for Removal of Carbonaceous Pollutants from Domestic Wastewater

Abdul Rehman [1,2,3], Muhammad Anees [1], Shama Sehar [4], Saleh S. Alhewairini [5], Devendra P. Saroj [2,*] and Safia Ahmed [3]

1 Department of Microbiology, Kohat University of Science & Technology (KUST), Kohat 26000, Khyber Pakhtunkhwa, Pakistan; abdulrehman@kust.edu.pk (A.R.); dr.anees@kust.edu.pk (M.A.)
2 Department of Civil and Environmental Engineering, Faculty of Engineering and Physical Sciences, University of Surrey, Surrey GU2 7XH, UK
3 Department of Microbiology, Faculty of Biological Sciences, Quaid-i-Azam University, Islamabad 45320, Pakistan; safiamrl@yahoo.com
4 Department of Biology, College of Science, University of Bahrain, Sakhir P.O. Box 32038, Bahrain; shamaseher@yahoo.com
5 Department of Plant Production and Protection, College of Agriculture and Veterinary Medicine, Qassim University, Buraidah 51452, Qassim, Saudi Arabia; hoierieny@qu.edu.sa
* Correspondence: d.saroj@surrey.ac.uk; Tel.: +44-(0)1483-686634

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Abstract: The aim of the present study is to assess the wastewater treatment efficiency of a low-cost pilot-scale trickling filter (TF) system under a prevailing temperature range of 12 °C–38 °C. Operational data (both influent and effluent) for 330 days were collected from the pilot-scale TF for various physicochemical and biological parameters. Average percentage reductions were observed in the ranges of 52–72, 51–73, 61–81, and 74–89% for BOD_5, COD, TDS, and TSS, respectively, for the whole year except the winter season, where a 74–88% reduction was observed only for TSS, whilst BOD_5, COD, and TDS demonstrated reductions in the ranges of 13–50, 13–49, and 23–61%, respectively. Furthermore, reductions of about 43–55% and 57–86% in fecal coliform count were observed after the 1st and 6th day of treatment, respectively, throughout study period. Moreover, the pilot-scale TF model was based on zero-order kinetics calibrated at 20 °C using experimental BOD_5 data obtained in the month of October to calculate the k_{20} value, which was further validated to determine the k_t value for each BOD_5 experimental setup. The model resulted in more accurate measurements of the pilot-scale TF and could help to improve its ability to handle different types of wastewater in the future.

Keywords: pilot-scale trickling filter system; carbonaceous pollutants; zero-order kinetic model; fecal coliforms; biological wastewater treatment

1. Introduction

Availability of fresh water has been decreasing continuously over the last few years, resulting in a severe water shortage throughout the world [1]. The increased urbanization, industrialization, and discharge of toxic hazardous wastes into freshwater streams has further resulted in the depletion of freshwater resources and risk to human health as well as aquatic life [2,3]. The treatment of already contaminated wastewater and its reuse could be the best possible remedy to restore existing water reservoirs. Unfortunately, the majority of developing and under-developed countries are facing a lack of proper strategies for the management of large amounts of wastewater discharged from various domestic and industrial sectors [3]. Wastewater treatment processes can be broadly characterized as physicochemical and biological methods [4,5]. Physicochemical processes involved in wastewater treatment systems include the screening of large suspended solids and particulate matters, mixing, flocculation, sedimentation, precipitation, and adsorption [6,7]. These may lead to the production of secondary effluent, which in turn requires additional treatment and, hence, enhanced treatment cost [8].

Biological treatment of wastewater involves the microbial degradation of organic compounds under both aerobic and anaerobic conditions [9]. It results in the emission of gases such as carbon dioxide, methane, sulfate, and molecular nitrogen [10]. A wide range of consolidated wastewater treatment facilities are available, including stabilization ponds, activated sludge, constructed wetlands, and trickling filter (TF) systems [11–13]. Stabilization ponds primarily remove organic compounds present in wastewater by their aerobic oxidation process; however, they require a larger space and extended retention time due to their continuous mode of aeration [14]. In the activated sludge process, microbial suspension is used for the removal of carbonaceous compounds, but the removal efficiency of pathogenic indicators is not constant [15]. Constructed wetlands are ecological contrived systems that employ natural processes; however, they require a large space, continuous monitoring of operating units, and sludge removal [16]. TF systems are an old and deep-rooted technology for wastewater treatment in developed countries, but in developing countries like Pakistan, there is a lack of infrastructure for wastewater treatment. Therefore, the pilot-scale stone media TF system is considered to be a novel technique for the treatment of wastewater. The TF system has numerous advantages in wastewater treatment compared to suspended growth systems, such as low space and operational requirements, cost effectiveness, being environmentally friendly, resistance to toxins and shock loads, operational compliance, increased retention time, enhanced biodegradation rate, and reduced sludge production due to a slower microbial growth rate. Moreover, TF systems also have the ability to regulate reaction rates according to the demand [17,18]. Furthermore, their large air–water interface can remove CO_2, H_2, N_2, and other gases. In the TF system, a portion of liquid in an underdrain system is continuously recycled to dilute the strength of incoming wastewater, thereby improving the treatment efficiency (https://civildigital.com/trickling-filters/, (accessed on 4 October 2021)).

The TF system is an attached growth bioreactor and is one of the most efficient wastewater treatment technologies [19]. It has been reported that TF systems are suitable for small to medium-sized communities with a high filter loading rate and marked by their ease of operation, self-cleaning capacity, and efficient removal of carbonaceous and nitrogenous pollutants [20]. It has three basic structural units: the distribution system, which, as the name indicates, distributes wastewater to the TF system; filter media, which are used to support microbial growth; and the underdrain system, which collects treated effluent. Filter media are the heart of TF system, as they provide a specific surface area for the growth of biomass [21]. Selection of filter media or carriers for the development of biofilm in TF systems is critical because different parameters must be considered, such as the ability to resist toxins and shock loads, having a greater specific surface area for biomass, being economically feasible, and having a high void ratio to evade clogging and ponding issues and also to facilitate aeration [22]. A variety of support materials have been reported to be used in TF systems as filter media, including plastic balls, rubber, polystyrene packing materials, gravel, and pebbles, each of which provide a large surface area per unit volume for the development of a microbial slime layer [23]. Naturally occurring media such as stones are inexpensive and commonly used in pilot-scale TF systems for the treatment of different types of wastewater. Stone media are available in different shapes and sizes and demonstrate a variety rough surfaces which facilitate the growth of microorganisms. Moreover, it has been reported that due to low void spaces and a large unit mass of stone media, TFs often encounter reduced oxygen diffusion rates, clogging, and ponding problems at high organic and hydraulic loading rates under different seasonal conditions [22]. Therefore, to enhance the proficiency and productivity of TFs using stone as a filter media, proper aeration and adjustable recirculation speed would be required, along with a well-operated secondary sedimentation tank [22,24,25]. It has also been reported that with the passage of time, biofilms covering the stone media in TFs thicken, which may lead to a decrease in the specific activity associated with the substrate mass transfer limitation of microorganisms within the biofilm [26]. In other words, the activity of the biofilm is not dependent on fixed biomass, i.e., it increases with an increasing thickness of the biofilm up to a certain point (1–3 mm), defining the upper limit for what is termed as active biomass thickness; above this thickness point, the flow of nutrients to the biofilm is a limiting factor that differentiates active biomass from inactive biomass. Thus, in wastewater treatment plants, a steady, squeaky, and active biofilm would be required to optimally neutralize wastes [26]. Moreover, TFs produce a small amount of sludge during treatment, which is removed in the secondary clarifier to produce a quality effluent suitable for irrigation [27].

In many developing countries, it has been common practice for wastewater from the residential and recreational areas to be discharged directly into the natural environment and also be used for irrigation purposes, resulting in many water-borne diseases [28,29]. In addition, the high organic waste in wastewater may lead to eutrophication in the receiving water bodies, thereby decreasing the water quality and resulting in the accumulation of toxic compounds within vegetables and crops, which ultimately affects human life [15,30]. However, the treatment of wastewater is considered to be an essential component with respect to public health, locals' sense of community, and religious beliefs [31]. The safe use of treated water has simply been the use of retrieved water following use in the home, industry, or agriculture. To ensure that treated water is suitable for safe use in public and irrigation sectors, it must have low levels of total dissolved solids, pathogenic organisms, BOD_5, and salt concentration. Furthermore, treated water allows a community to become less reliant on natural water reservoirs [32–35]. Tang et al. [36] also reported that treated water enhanced agricultural productivity by 10–30% compared to using untreated wastewater. Therefore, it is essential to develop a low-cost biological wastewater treatment facility to eradicate potential hazards from wastewater before its disposal into the natural environment.

In the current study, a pilot-scale stone media TF system was evaluated under varying environmental conditions. As Pakistan's temperature varies significantly during the year (especially in Islamabad), a humid subtropical climate exists with five different seasons, comprising winter (November, December, January, and February), spring (March and April), summer (May and June), rainy monsoon (July and August) and autumn (September and October). This work contributes to new knowledge in the area of novel TF application in specific climatic conditions. The present study is focused on a simplified approach to establishing design, operation, and management aspects of TF systems for low-cost wastewater treatment. Data was collected for carbonaceous and microbial loads for the safe use of effluent in different daily activities, i.e., ornamental, recreational, and horticulture purposes. Subsequently, a simplified zero-order kinetic model was developed to judge the productivity of the pilot-scale TF system with respect to the oxidation of carbonaceous compounds.

2. Materials and Methods

2.1. Experimental Setup and Operation

A pilot-scale TF system was installed in the workstation under shade located at the vicinity of the Department of Microbiology, Quaid-i-Azam University, Islamabad, Pakistan. The main body of the TF system was made up of stainless steel (diameter, 1.28 m; height, 2.29 m) to support the stones (trapezium shape) used as filter media. Each stone had the following dimensions: average height, 0.1 ± 0.02 m; base, 0.07 ± 0.01 m; top, 0.09 ± 0.01 m. The surface area of the stones was calculated using the standard equation, i.e., $A\ (trapezium) = 0.5(base + top) \times height$. It was found that the average exposed surface area of one stone was 0.008 m^2, calculated for the configuration of biofilm. A rotating arm distributor (diameter, 0.05 m; length, 0.73 m), with 28 small pores to distribute wastewater uniformly, was installed at the top of the filter bed. Electric pumps of 1.3 horse power were connected to the wastewater distribution system through a polyvinyl chloride

(PVC) pipe system. To collect treated effluent and sludge, an underdrain system (diameter, 0.92; m; height, 0.37 m) was installed at the bottom of the TF system, with a total capacity of 0.24 m^3. This was followed by a recirculation tank, which also assisted as a final clarifier, with a final effluent holding capacity of 0.267 m^3. From there, the effluent was discharged to open lands for different activities. A schematic illustration of the treatment units is shown in Figure 1.

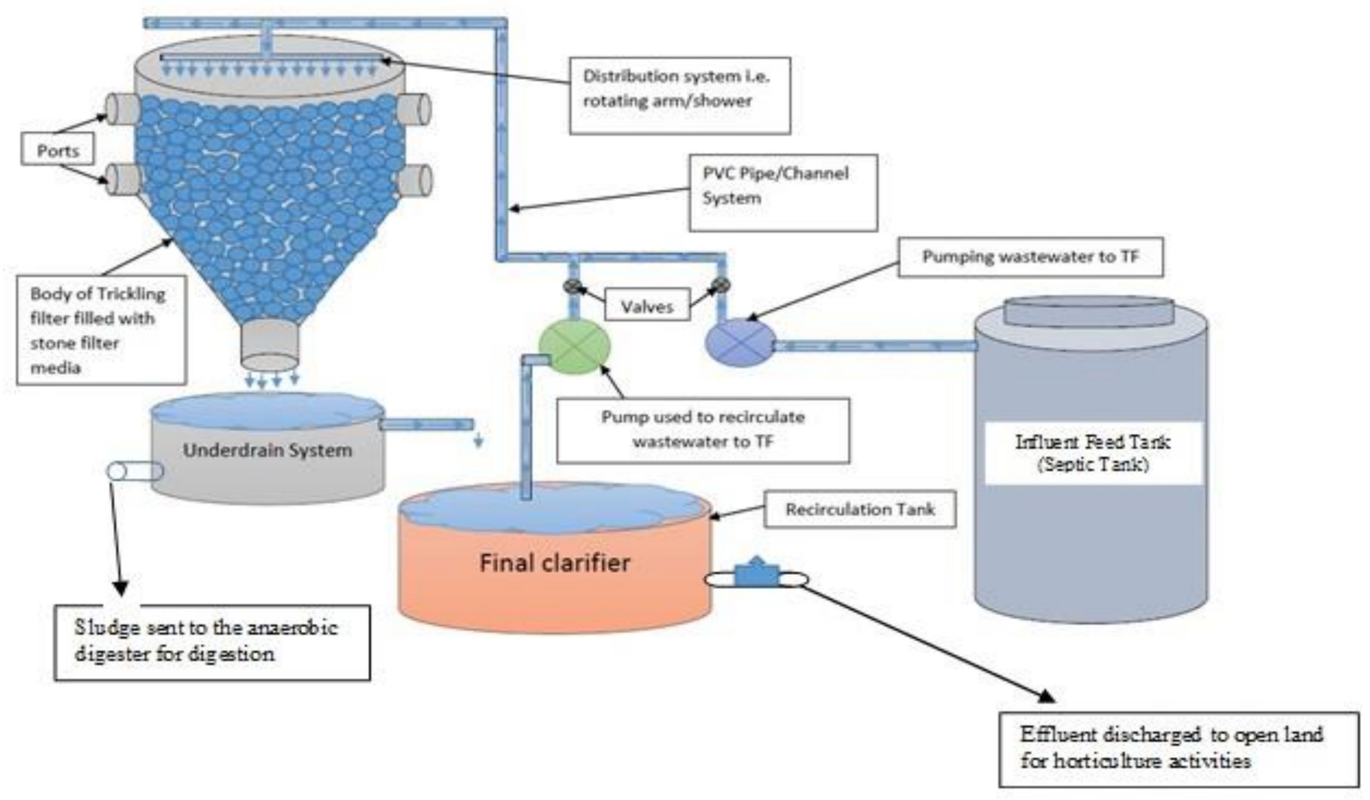

Figure 1. Schematic illustration of treatment units in the pilot-scale TF system.

The pilot-scale facility was operated in batch mode to treat about 0.195 m^3 (51.5 US gallons) of wastewater per day, with a hydraulic flow rate (Q) of 1.9293 m^3/d and hydraulic loading (Q/A) of 1.51 m/d. For the development of biofilm, stones were collected from a nearby stream and were kept in a container containing untreated wastewater for about 1 week. Activated sludge was used for seeding in order to facilitate the process of biofilm development. The treatment of wastewater through the pilot-scale TF system was carried out in batch mode using standard protocols. Initially, about 1–2 h settling time was given to the wastewater in the influent feed tank (septic tank) in order to remove large suspended particles. Then, it was circulated and recirculated through the pilot-scale TF at a flow rate (Q) of 1.9293 m^3/d for about 6 days, collecting the effluent after every 1st and 6th day of treatment. After the completion of one cycle, another cycle started with a new sample of wastewater following a similar scheme of treatment. This batch mode of treatment operation was followed for 11 months (August 2014–June 2015). The temperature was regularly monitored during whole experimental trial; it was in the range of 12 °C–38 °C.

2.2. *Microbial Profiling of Wastewater*

Most Probable Number Test (MPN Index) for Fecal Coliforms

The Most Probable Number (MPN) test was performed for the examination and enumeration of fecal coliforms within influent and effluent samples. In this test, three sets of test tubes (with each set containing three test tubes filled with lactose broth along with inverted Durham tubes) were inoculated with influent and effluent samples and then incubated at 37 °C for 48 h. After incubation, test tubes with bubbles in the Durham tubes were considered to be positive, which were then streaked on nutrient agar plates (NA) and incubated at 37 °C for 24 h. After incubation, positive isolates of bacteria were confirmed by general microscopy techniques. The number of tubes that were considered positive for gas production were measured against the standard dilution table for the MPN index.

2.3. Determination of Physicochemical Parameters of Influent and Effluent Samples

To assess the efficiency of the pilot-scale TF system with respect to wastewater treatment, physicochemical parameters of influent and effluent samples—including biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total dissolved solid (TDS), and total suspended solid (TSS)—were determined in triplicate after every 1st and 6th day of treatment operation using standard protocols for water and wastewater analysis [35,36]. Moreover, for BOD_5 assessment, we used a dilution method in which four different types of reagents (phosphate buffer solution, magnesium sulphate solution, calcium chloride solution, and ferrous chloride solution) were used in a ratio of 1:1000. For COD assessment, different ranges of COD kits (0–40, 40–1500, and 1500–5000 mg/L) and instruments such as a thermoreactor and Spectroquant (Merck, Pharo 300) were used. The filtration assembly equipped with Whatman filter paper. A weighing balance, china crucibles, a hot plate, and oven were used for the assessment of TDS and TSS.

2.4. Model Expansion and Standardization

For the optimum design and operation of a wastewater treatment system, empirical modelling was considered to be an integral part. The modelling of wastewater treatment technologies is increasing day by day, and a number of theoretical, physical designs and systematic models are available in practice. In the current study, a basic systematic model was developed by assuming that the reduction of carbonaceous compounds (BOD_5) present in wastewater by a pilot-scale TF system was a single-phase process. Heterotrophic bacteria within the biofilm are most commonly involved in the degradation of organic compounds to obtain energy for their growth; as a result, the concentration of substrates in wastewater decreases with time during treatment. There are many complex dynamic models proposed by researchers [22,37]. These models are focused on describing highly complex biological processes using higher-order kinetic models (e.g., first-order or Monod kinetics) in order to simulate the process with high accuracy. However, they are difficult to apply in many real-life scenarios where the calibration of complex models may not be feasible. Therefore, a zero-order kinetic model was used to mathematically describe the nature of the pilot-scale TF system in this study. A zero-order kinetic model describes the process in a simplified way with less accuracy, but without the need for rigorous calibration exercises.

$$\frac{dS}{dt} = -\, k_t X \tag{1}$$

$$dS = -\, k_t X dt \tag{2}$$

$$\int_{So}^{St} dS = -k_t X \int_0^t dt \tag{3}$$

$$S_t - S_o = -\, k_t X (t - 0) \tag{4}$$

$$S_t - S_o = -\, k_t X t \tag{5}$$

where S_t denotes the final BOD_5 of one treatment unit at any time, S_o represents the initial BOD_5 of the untreated wastewater, k_t is a specific bioreactor coefficient at a specific temperature, and tis the time required (in days) for the treatment of wastewater. Moreover, X represents biomass that should remain unchanged during the steady state. For practical purposes, X was assumed to be constant. As reported by Naz et al. [22], the initial BOD_5 can be represented as the volumetric loading rate (O_{LR}):

$$O_{LR} = \frac{QS_o}{HA} \tag{6}$$

$$S_o = O_{LR}\frac{HA}{Q} \tag{7}$$

Substituting S_o from Equation (5),

$$S_t = O_{LR}\frac{HA}{Q} - k_t Xt \tag{8}$$

This equation was used to mathematically describe the ability of the pilot-scale TF system to reduce carbonaceous compounds within wastewater. In this study, 11 months' data was collected by operating the pilot-scale TF system under a temperature range of 12 °C–38 °C; in this way, the model could be applied to all experimental results. The model calibration was done on experimental data obtained at 20 °C in order to determine the k_{20} value using the equation $k_{20} = (S_o–S_t)/Xt$, as shown in Figure 2, which was further validated for each experimental setup to produce a k_t value for a particular temperature range.

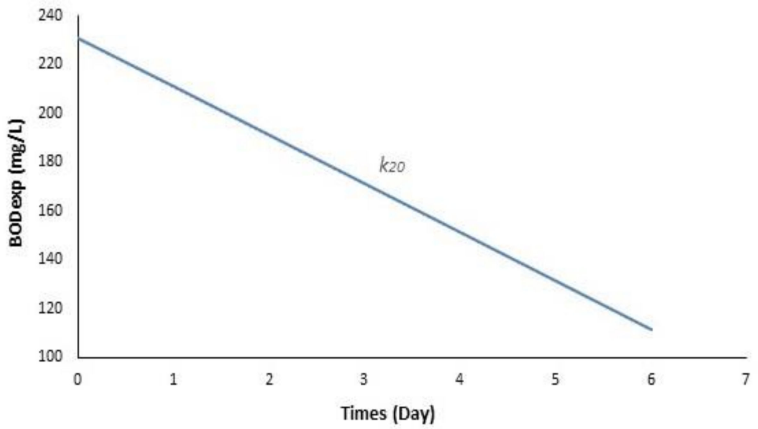

Figure 2. Determination of k_{20} value from the model calibration of BOD_{exp} vs. Time data at 20 ± 1 °C.

3. Results and Discussion

3.1. Efficiency of Pilot-Scale TF for the Removal of Fecal Coliforms

Fecal coliforms are commonly used as an indicator of disease-causing pathogens in the aquatic environment. Influent from a municipality would contain large quantities of fecal coliforms, including pathogenic microorganisms in the range of 1100–5000 per 100 mL [38,39]. Furthermore, it has also been reported that influent containing large quantities of fecal coliforms, if not treated through treatment facilities, would be discharged as such into the surrounding natural environment and would be responsible for life-threatening consequences [1].

In the present study, it was observed that the MPN index of influent samples was more than 1100 per 100 mL during the entire treatment operation, and the removal efficiency of fecal coliforms by the pilot-scale TF system varied between 43–55% and 57–86% after the 1st and 6th day of treatment, respectively (Figure 3). Similar observations with respect to the reduction of coliforms by bench-scale stone media TF systems were found by Khan et al. [23]. A higher removal of pathogens was observed in the rainy monsoon (August), autumn (September, October), spring (March and April), and summer (May and June) seasons compared to the winter season (November–February) (Table 1). A basic reason for this might be that during these seasons, the temperature was in the range of 20 °C–38 °C; therefore, the metabolic activities of microorganisms would be at their peak, and as a result, natural die-off processes and predation by protozoa would take place [21,40]. Another reason for pathogen removal during the treatment of wastewater by the pilot-scale TF system at 20 °C–38 °C might be extended retention time, reactor configuration, microbial competition for survival, and chemical interaction [41]. The removal efficiency of fecal coliforms by the reactor decreased to 43–47% in the winter season (10 °C–15 °C), which clearly indicated that fecal coliforms resisted inactivation when temperatures were lower than 20 °C. This resistance to inactivation was valid because this group of bacteria were mesophilic in nature, and the method to enumerate the fecal coliform bacteria includes incubation at 35 °C–37 °C. However, many of the pathogenic bacteria found in the wastewater were either bound to the solids matrix or trapped to form floc by absorption, coagulation, or precipitation processes that in turn provide better conditions for the survival of pathogenic microorganisms [42].

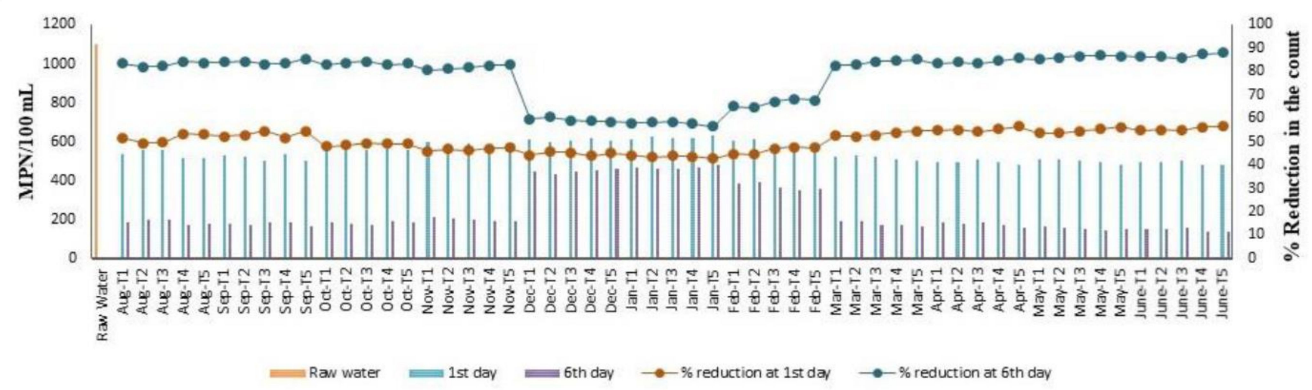

Figure 3. Monthly variation in the percentage removal of fecal coliform by the pilot-scale TF system.

Table 1. Average percentage removal of fecal coliforms under different seasonal conditions through the pilot-scale TF system.

Seasons	Months	Average Fecal Coliforms MPN/100 mL			Treatment Efficiency (Average % Reduction)	
		Influent	Effluent at Day 1	Effluent at Day 6	At Day 1	At Day 6
Rainy Monsoon	Aug	>1100	534.2	185.4	51.44	83.15
Autumn	Sep	>1100	516	175.2	53.10	84.07
	Oct	>1100	563.4	181.6	48.78	83.51
Winter	Nov	>1100	586.8	200.6	46.65	81.8
	Dec	>1100	607.2	447.6	44.8	59.31
	Jan	>1100	620.8	464.8	43.56	57.75
	Feb	>1100	591	368.2	46.273	66.53
Spring	Mar	>1100	515.2	177.6	53.2	83.85
	Apr	>1100	492.8	173.2	55.2	84.32
Summer	May	>1100	499	151	54.64	86.31
	June	>1100	490	145.4	55.45	86.78

Key: MPN—Most Probable Number; mL—milliliter; %—percentage.

Shoushtarian and Negahban-Azar [43] also reported standard guidelines that treated water used for the irrigation of fodder crops must contain less than 200 fecal coliforms/100 mL, while Nnaji and Nnam [34] reported that the acceptable MPN index for irrigation with river water containing wastewater discharge was up to 1000 fecal coliforms/100 mL. In the current study, the MPN index of the treated water lay within standard limits; therefore, it is highly recommended that wastewater treatment plants should be designed in such a manner that not only reduces the organic pollution of rivers and streams but also reduces the load of pathogenic microorganisms.

3.2. Evaluation of the Pilot-Scale TF System for the Removal of Carbonaceous Compounds

3.2.1. Pre-Treatment Characterization of Wastewater

In the current study, the quality of domestic wastewater was examined in triplicates. It was dark grey in appearance and the average values of parameters such as BOD_5 (227.3 ± 23.4 mg/L), COD (334.3 ± 34.5 mg/L), TDS (537.3 ± 76.5 mg/L), and TSS (466.3 ± 45 mg/L) during the whole treatment operation showed considerable deviation from the standard limits as prescribed by Shoushtarian and Negahban-Azar [43], indicating a high level of contamination. Moreover, the BOD_5/COD ratio for the whole period ranged from 0.64 to 0.72, with an average of 0.68. The high BOD_5/COD ratio indicated a decline in DO concentration—the free oxygen in the water was utilized by microbes and organic compounds, leading to the failure of fish and other aquatic organisms to thrive. Based on these values, wastewater obtained from the residential area of QAU, Islamabad, has been considered as heavy-duty wastewater due to high loads of organic pollutants, as represented by high COD, BOD_5 values, total suspended solids (TSS), and total dissolved solids (TDS), as shown in Table 2. Therefore, a pilot-scale TF system was designed to treat highly contaminated domestic wastewater with high BOD in the range of 195.3–264.8 mg/L.

Table 2. Mean values of different physicochemical parameters of influent and effluent samples and average % reduction at Day 1 and Day 6 under different seasonal conditions.

Season	Months and Temperature (°C)	Parameters (mg/L)	Mean Influent	Mean Effluent at Day 1	Mean Effluent at Day 6	Avg. % Reduction at Day 1	Avg. % Reduction at Day 6
Rainy Monsoon	August (40 ± 4)	BOD_5	222.4 ± 5.7	147.7 ± 9.03	69.4 ± 6.7	33.58	68.84
		COD	327 ± 8.4	217.6 ± 13.3	102 ± 9.95	33.45	67.83
		TDS	601 ± 7.6	249.7 ± 8.83	153 ± 12.5	58.45	74.55
		TSS	429.3 ± 10.2	228.5 ± 17	103.2 ± 13.7	46.77	76.1
Autumn	September (24 ± 3)	BOD_5	195.3 ± 7.02	137.65 ± 7.2	69.7 ± 4.3	29.51	64.34
		COD	287.2 ± 10.3	202.4 ± 10.6	102.6 ± 6.4	29.52	63.2
		TDS	382.1 ± 10.7	304.5 ± 15.35	149.27 ± 4	20.30	60.89
		TSS	430.1 ± 3.3	259.8 ± 2.75	108.37 ± 3.2	39.59	74.82
	October (20 ± 1)	BOD_5	235.5 ± 3.2	215.6 ± 3.2	112.8 ± 3.1	8.45	52.1
		COD	346.36 ± 4.7	317 ± 4.67	165.89 ± 4.1	8.47	51.85
		TDS	563.5 ± 10.6	354.7 ± 16.1	143.1 ± 4.25	37.05	74.6
		TSS	419.7 ± 10.1	257.53 ± 7.8	109.1 ± 6.4	38.63	74.04
Winter	Nov (18 ± 3)	BOD_5	244.2 ± 4.5	194.63 ± 3.3	128.55 ± 7.6	20.29	47.33
		COD	359.1 ± 6.7	286.23 ± 4.9	189.1 ± 11.2	20.29	46.77
		TDS	626.8 ± 5.5	485.05 ± 5.4	268.6 ± 11.6	22.61	57.15
		TSS	419.8 ± 7.3	178.41 ± 4	90.06 ± 5.6	57.50	78.55
	December (12 ± 2)	BOD_5	264.8 ± 4.2	241.05 ± 2.1	193.22 ± 6.0	8.96	27.03
		COD	389.5 ± 6.1	354.5 ± 3.1	284.2 ± 8.6	8.98	26.84
		TDS	541.3 ± 7.0	490.1 ± 3.06	309.55 ± 9.2	9.45	42.8
		TSS	478.1 ± 8.2	256.84 ± 3.3	122.7 ± 3.1	46.27	74.33
	January (10 ± 2)	BOD_5	245.8 ± 3.5	231.67 ± 3.3	212.78 ± 3.9	5.74	13.42
		COD	361.5 ± 5.14	340.7 ± 4.85	312.9 ± 5.8	5.75	12.94
		TDS	608.1 ± 10.7	574.84 ± 10.8	467.3 ± 21	5.46	23.16
		TSS	463.5 ± 7.3	217.8 ± 8.3	107.4 ± 7.3	53.0	76.82
	February (15 ± 1)	BOD_5	196.6 ± 12.5	132.5 ± 4.6	96.97 ± 2.75	32.6	50.48
		COD	289.1 ± 18.2	194.85 ± 6.8	142.6 ± 4.05	32.6	49.37
		TDS	492.3 ± 13	288.62 ± 9.44	189.52 ± 6.1	41.37	61.5
		TSS	518.8 ± 4.1	220.23 ± 2.1	99.8 ± 3.1	57.5	80.76

Table 2. *Cont.*

Season	Months and Temperature (°C)	Parameters (mg/L)	Mean Influent	Mean Effluent at Day 1	Mean Effluent at Day 6	Avg. % Reduction at Day 1	Avg. % Reduction at Day 6
Spring	March (23 ± 3)	BOD_5	218.5 ± 4	153.13 ± 5.22	71.38 ± 3.73	29.9	67.34
		COD	321.3 ± 5.7	225.2 ± 7.7	104.9 ± 5.48	29.9	67.11
		TDS	539.4 ± 7.8	246.4 ± 13.47	103.75 ± 6.5	54.3	80.77
		TSS	484.1 ± 6.7	226.35 ± 5.4	106.7 ± 3.12	53.2	77.96
	April (27 ± 2)	BOD_5	197.8 ± 4.8	110.01 ± 6.8	55.75 ± 4.5	44.38	71.8
		COD	290.8 ± 7.1	161.78 ± 10	81.98 ± 6.63	44.36	72.5
		TDS	428.3 ± 4.5	234.5 ± 15.5	112.2 ± 14.7	45.24	73.8
		TSS	562.5 ± 9.9	244.9 ± 21.7	64.08 ± 6.8	56.46	88.62
Summer	May (32 ± 2)	BOD_5	247.8 ± 2.87	174.86 ± 9.5	74.67 ± 2.72	29.43	69.88
		COD	364.5 ± 4.2	257.15 ± 13.9	109.8 ± 4	29.45	68.76
		TDS	536.6 ± 5.7	328.57 ± 4.4	143.6 ± 4.1	38.76	73.24
		TSS	481.7 ± 3.8	239.4 ± 10.8	110.84 ± 8.6	50.3	77.2
	June (38 ± 3)	BOD_5	231.5 ± 2.3	145.9 ± 2.46	61.26 ± 1.45	36.9	73.54
		COD	340.5 ± 3.4	214.57 ± 3.63	90.08 ± 2.14	36.98	72.63
		TDS	590.3 ± 6.2	336.7 ± 6.8	128.83 ± 4.4	42.9	78.2
		TSS	441.3 ± 6	212.1 ± 6.3	93.1 ± 3.25	51.9	79.22

3.2.2. Post-Treatment Characterization of Wastewater

In the present study, it was observed that the pilot-scale facility worked in all seasons, but the highest average BOD_5 percentage reductions (68–71, 53–65, 67–72, and 70–74%) were observed in August (rainy monsoon season), September–October (autumn season), March–April (Spring season), and May–June (summer season), respectively, while in the winter season (November–February), it achieved removal of carbonaceous compounds in the range of 13–57% after Day 6 of treatment (Figure 4a). A similar pattern of percentage reduction was also noted for COD after Day 6 of treatment under different environmental conditions (Figure 4b). On the other hand, considerable average BOD_5 and COD percentage reductions were observed in May–June (29–37%), March–April (30–44%), August (32–34%), and September–October (8–29.5%), while very low percentage reductions were observed in November–February (5–32%) after Day 1 of treatment (see Figure 4a,b). A similar trend in removal proficiency for BOD_5 and COD had been reported previously, and the primary mechanism for BOD_5 and COD removal was found to be sedimentation, adsorption, and microbial digestion of organic compounds [14,44]. Furthermore, the TF system was found to be more efficient in the hot season (May–June), with a temperature range of 32 °C–38 °C, in comparison to the cold season (November–February), with temperatures lying in range of 10 °C–20 °C. A basic reason might be that the biochemical reactions are temperature dependent and the activity of the microorganism increases with the increase in temperature up to certain value, dropping with a decrease in temperature. A similar trend in BOD_5 and COD removal efficiency due to metabolic activities of microbial communities and seasonal variation had also been reported previously [45,46].

Furthermore, a high degree of reduction in TSS concentration (74–88%) during the entire treatment operation clearly indicated that TSS is a temperature-independent parameter, as shown in Figure 5a. Heavier particles, such as gravel and sand, often settle out in the primary sedimentation tank, while the remaining particles that do not settle out are termed colloidal or non-settleable solids. These non-settleable solids enter the reactor, where they are retained on the surface of the filter bed, and microbes present in the slime layer had sufficient contact time to utilize them as a source of nutrients [47,48]. In addition to this, Pungrasmi et al. [49] reported that continuous recirculation of wastewater over the surface of the filter bed at preeminent flow rates played a significant role in the removal of TSS from wastewater. A 1.9293 m^3/day recirculation flow rate was maintained throughout the current study, which produced the highest percentage reductions in all seasons for TSS.

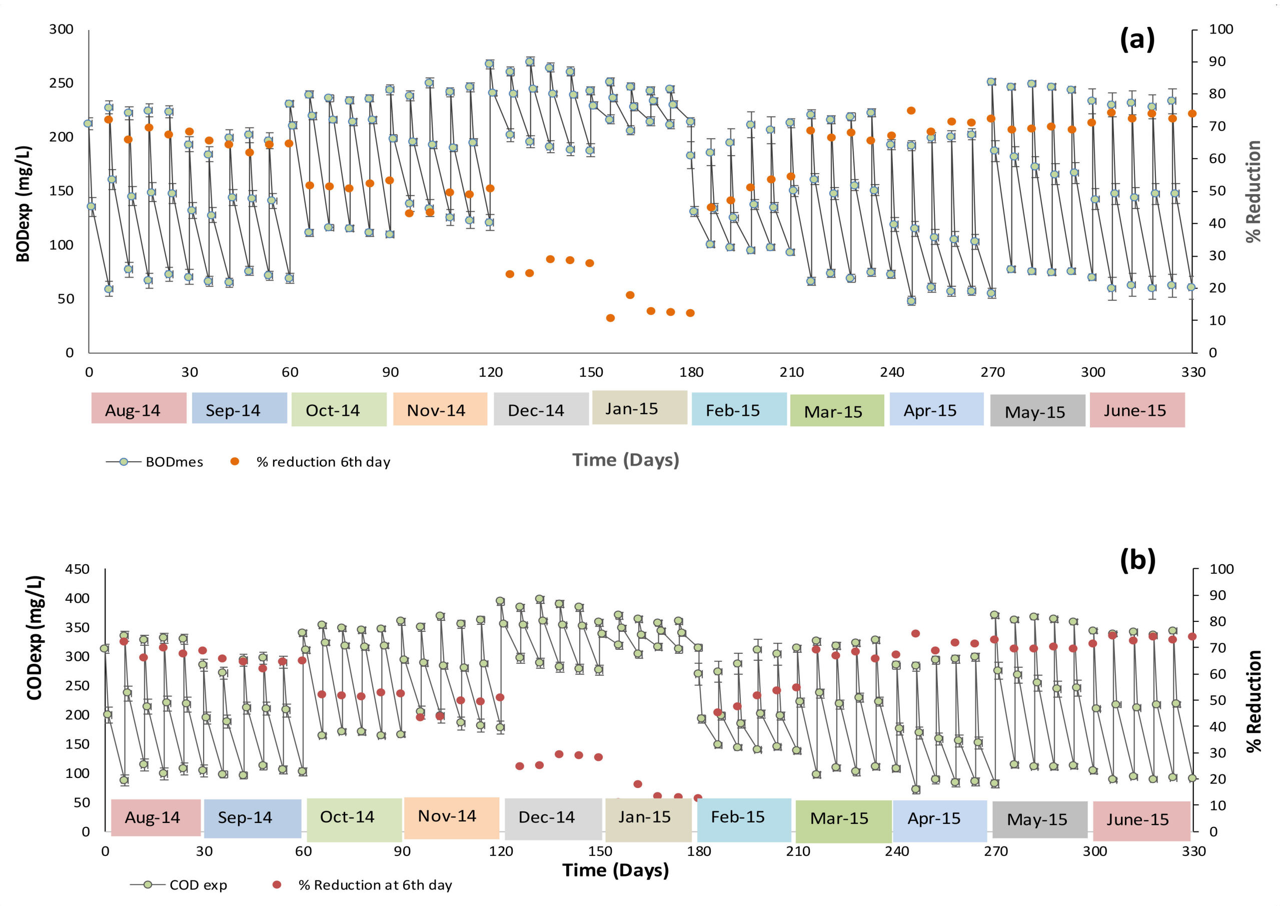

Figure 4. Efficiency of pilot-scale TF system in the reduction of (**a**) BOD_5 and (**b**) COD during entire treatment operation.

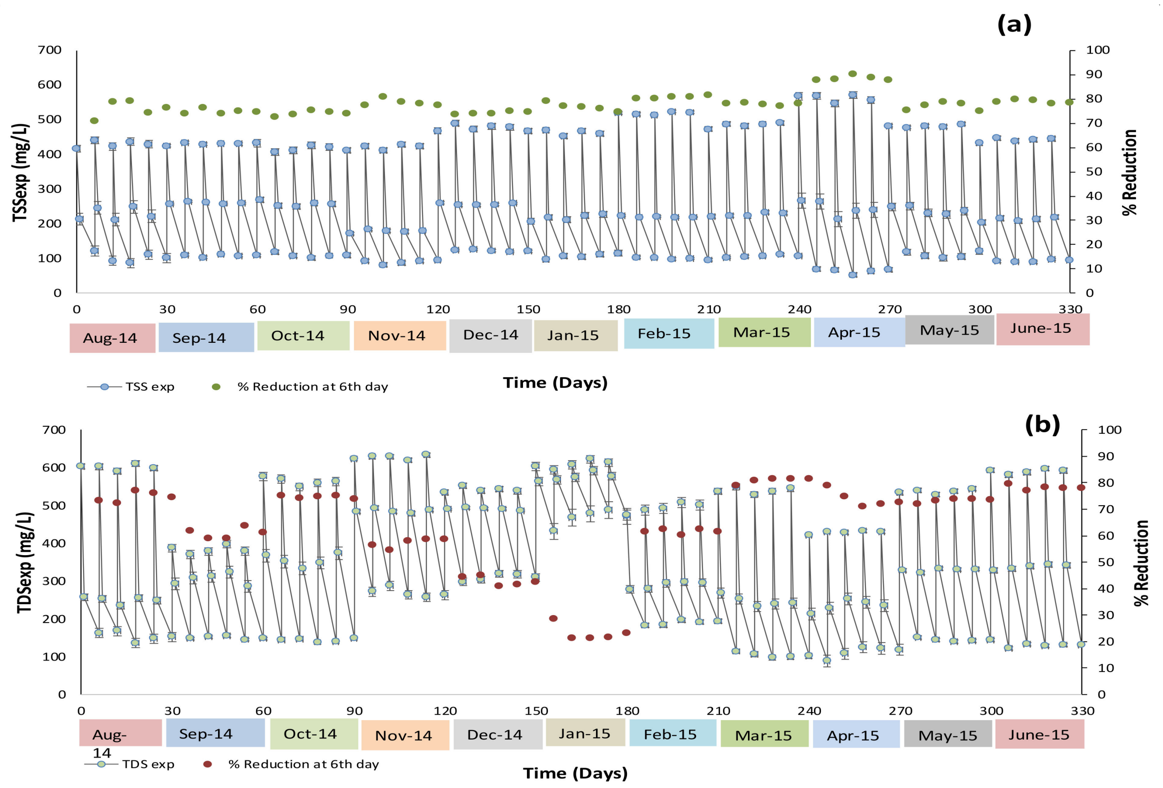

Figure 5. Efficiency of pilot-scale TF system in the reduction of (**a**) TSS and (**b**) TDS during entire treatment operation.

Another important parameter in water quality studies is TDS, although there is no health risk associated with it. However, the standard limit for TDS in water provisions reported by Khalid et al. [28] was 500 mg/L. In the case of TDS, the highest percentage reductions were obtained in March–April (73–80%), May–June (73–79%), August (58–74%), and September–October (61–75%). In the winter season (November–February), the concentration of TDS decreased in the range of 23–60% (Figure 5b). Reduction in TDS content with increasing hydraulic retention time (HRT) was also due to continuous recirculation of wastewater for an extended period of time. As a result, microorganisms within the biofilm had sufficient time to degrade dissolved organic components [41]. Furthermore, during their study, Khan et al. [23] reported 23 and 66% reductions in the TDS values after 24 and 48 h of recirculation, respectively, while using a stone media TF system integrated with a sand column filter. Furthermore, it was also observed that the influent TDS seemed to decrease as the temperature decreased; the reactor efficiency with respect to the removal of TDS also decreased in comparison with high temperature months. These differences might be a result of the varying domestic waste loads on the QAU campus, impacted by resident numbers, commercial activities, and sampling and analytical procedures.

3.3. Mathematical Model Applications

Modelling was considered to be an essential component to describe the reality of all processes occurring in human life [50]. The empirical model was designed using modelling data of BOD_5 obtained from experimental work done under different prevailing environmental temperature conditions. Such a model should be simple enough in order not to overly increase the level of intricacy and computational demand when coupled with other sub-models.

In the current study, the pilot-scale TF model was based on a simple zero-order kinetic model, which was calibrated at 20 °C using experimental BOD_5 data obtained in the month of October, to calculate the k_{20} value, which was further validated to determine the k_t value for each BOD_5 experimental setup performed under different temperature conditions (Table 3). The value of k_t obtained from experimental results showed better performance at six different temperature data sets: November (18 °C), December (12 °C), January (10 °C), March (23 °C), May (32 °C), and June (38 °C). In these different temperature data sets, the value of k_t relates to higher removal of BOD_5 through the pilot-scale treatment system due to the excellent mass transfer coefficient, as shown in Figure 6. This type of simple model calibration of a zero-order kinetic model offers an advantage over complex and higher-order models which may describe the dynamics of the process more accurately. For design, operation, and maintenance points of view, this less accurate but easy-to-apply model offers a good alternative to complex models for low-cost TF systems for wastewater treatment.

Table 3. Parameters of pilot-scale TF system under different seasonal conditions.

Seasons	Months	Temperature of Environment (°C)	Biomass (X) (mg/m^3)	Flow Rate (Q) (m^3/d)	Height × Area of Reactor (m^3)	k_t Value	O_{LR} (Kg/m^3/d)
Rainy Monsoon	Aug	40 ± 4	44	1.9293	2.945	1.11	145.23
Autumn	Sep	24 ± 3	42	1.9293	2.945	0.809	127.55
	Oct	20 ± 1	32	1.9293	2.945	0.624	153.82
Winter	Nov	18 ± 3	31	1.9293	2.945	0.589	159.50
	Dec	12 ± 2	21	1.9293	2.945	0.496	172.94
	Jan	10 ± 2	19	1.9293	2.945	0.468	160.56
	Feb	15 ± 1	34	1.9293	2.945	0.54	128.4
Spring	Mar	23 ± 3	37	1.9293	2.945	0.68	142.67
	Apr	27 ± 2	42	1.9293	2.945	0.763	129.18
Summer	May	32 ± 2	42	1.9293	2.945	0.882	161.84
	Jun	38 ± 3	47	1.9293	2.945	1.048	151.20

Key: OLR—organic loading rate; k_t—specific bioreactor coefficient at a specific temperature.

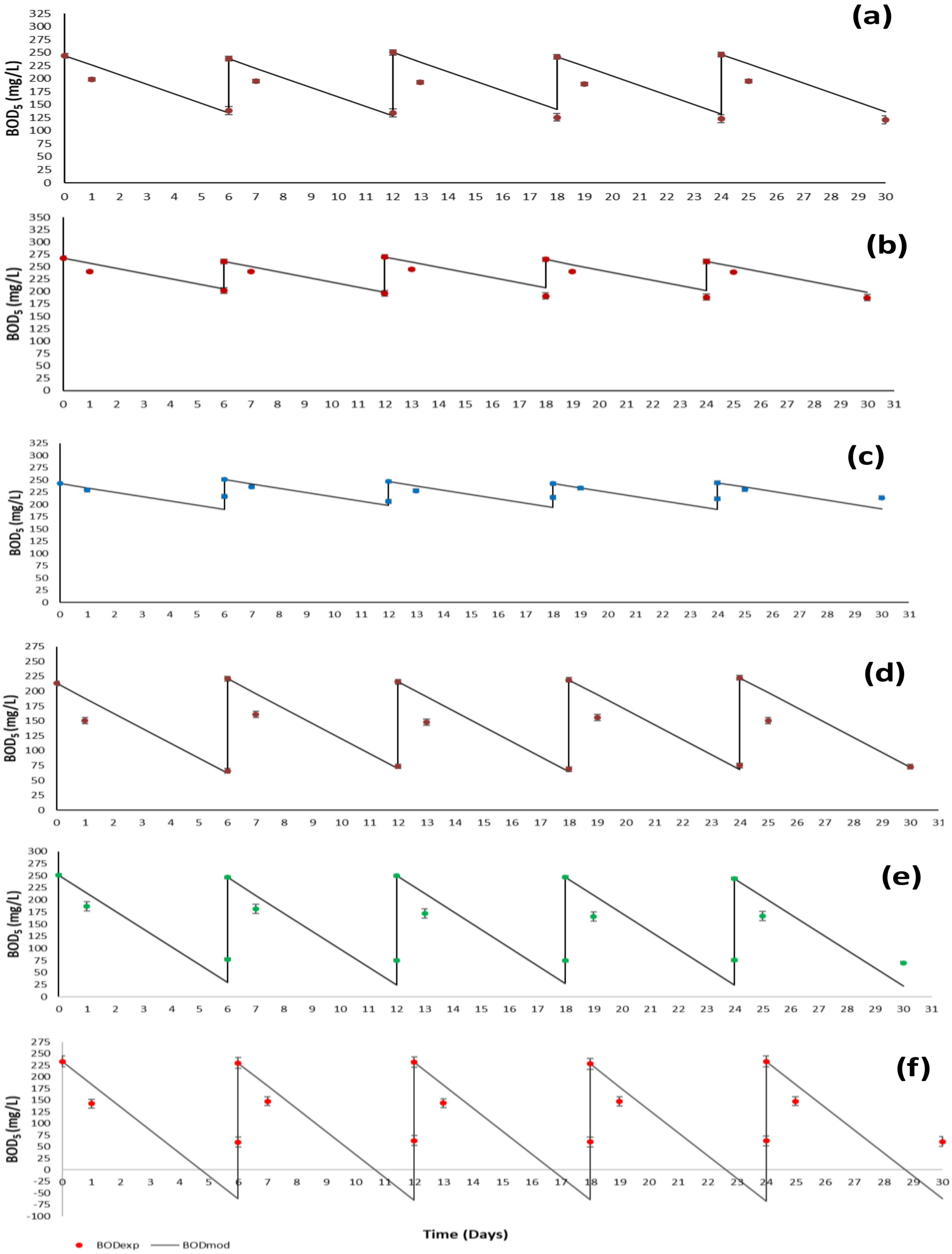

Figure 6. Removal of BOD_5 by pilot-scale TF system in the months of (**a**) November (18 ± 3 °C), (**b**) December (12 ± 2 °C), (**c**) January (10 ± 2 °C), (**d**) March (23 ± 3 °C), (**e**) May (32 ± 2 °C), and (**f**) June (38 ± 3 °C). • denotes experimental data and — denotes model results.

From zero-order kinetic modelling, it was observed that the value of k_t was specific for each experimental data set. Furthermore, minor differences between the experimental data and the modelling ones were observed on some days, especially Day 1. A basic reason for this might be that in a fixed film system, microorganisms are attached to the surface;

therefore, the supply of nutrients to the microbes in the slime layer might be restrained by bulk liquid and surface transport mechanisms. Normally, in fixed film growth systems, nutrients or organic substances present in wastewater are transported to the outermost surface of biofilm; from there, they diffuse into the biofilm for utilization. According to Fick's law and the Monod expression, there are different factors that affect the rate of substrate utilization within a biofilm, i.e., the transport of nutrients to the outer surface of the biofilm from the bulk liquid, the diffusion of nutrients from the outer surface into the biofilm, and the utilization kinetics within the biofilm. Beside this, there are some other factors which affect the efficiency of attached growth bioreactors, including hydraulic loading rates, temperature, recirculation flow rates, etc. In the literature, very few empirical models have been reported that can forecast the efficiency of a TF system, and among them, most models are based on steady state conditions. A major drawback of the steady state model is that it does not give sufficient information regarding biomass growth with time, void ratio of filter media, and recommended depth for the filter bed [51,52].

Moreover, modelling results describe about 21–45% removal of BOD_5 in low temperature range data sets (November, December, and January) and 67–90% in high temperature range data sets (March, May and June), as shown in Figure 6, which exhibited that the model for the pilot-scale TF system worked seamlessly in the removal of carbonaceous compounds from wastewater. Hvala et al. [51] also used an empirical model to evaluate the efficiency of wastewater treatment in terms of BOD_5 and observed a considerable reduction in the BOD_5 content. Furthermore, they concluded that bioreactor efficiency was greatly affected by changes in the organic and hydraulic loading rates. In an interpretation of this study, a significant correlation might exist in experimental as well as mathematical data for BOD_5 under different temperature conditions. Therefore, it gives more reliable and precise appraisals with regard to hydraulic load rates, biomass concentration, and their specific activity in wastewater research as well as the design of wastewater treatment plants. The model foretells that the percentage reduction of BOD_5 surpasses the maximum possible for the assumed size distribution of soluble organics. The key drawback of the existing model was that wastewater must have related features to those used for model calibration. This drawback not only incorporates the diffusion coefficients of dissolved organics but also microbial activities for these substrates. The model also assumes that recirculation of wastewater enhances the overall level of wastewater treatment efficiency by the pilot-scale TF system. Oliynyk and Kolpakova [53] also developed a mathematical model describing removal of BOD_5 from domestic wastewater by attached growth systems under many loading and design conditions. They reported that their simulated model was perfect to precisely predict percentage removal of BOD_5 as a function of hydraulic loading rate, recirculation rate, depth of filter bed, and microbial activity within the biofilm under different temperature conditions.

4. Conclusions

The wastewater treatment performance of the locally designed and constructed pilot-scale TF system was good in all seasons apart from winter in terms of the removal of organic as well as microbial pollutants from domestic wastewater. It was concluded that in the rainy monsoon (August), autumn (September–October), spring (March–April), and summer (May–June) seasons, average percentage reductions were in the range of 52–72, 51–73, 61–81, and 74–89% for BOD_5, COD, TDS, and TSS, respectively. However, in the winter season (November–February), an excellent percentage reduction was only observed for TSS (74–88%), while for other parameters such as BOD_5, COD, and TDS, it was in the range of 13–50, 12–49 and 23–61%, respectively. Moreover, a substantial reduction in microbial content of the wastewater was also observed in all seasons of treatment due to nutrient depletion in the effluent samples, predation, and natural die off-processes. The MPN index of treated effluents decreased to significantly lower values in all the seasons. During the non-winter seasons, the TF system showed high potential for wastewater use in the irrigation sector, for which an MPN/100 mL of lower than 200 colonies is desired. This is particularly relevant to developing countries where water sources are under significant threat due to increasing pollution. The zero-order kinetic model provided a simplified mathematical interpretation of a composite set of biological, chemical, and physical interfaces that occur in TFs. Therefore, it was also concluded that the model resulted in a better understanding of pilot-scale TF design aspects and could help to improve their ability to handle different types of wastewater in the future, using such TFs at different scales. The results provide a simplified approach to assessing the potential application of TF systems in developing countries.

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