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Review

Identification and Elucidation of the Designing and Operational Issues of Trickling Filter Systems for Wastewater Treatment

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Abstract

Water pollution has become a major environmental concern for public and environmental health in developing countries. Water resources are being contaminated mainly due to mixing of domestic, municipal, and industrial wastewaters. The wastewater management and treatment situation is deplorable mainly because of financial constraints, the unavailability of technically trained human resources, and electricity shortages. Moreover, there is a challenge for the scientific community and wastewater management experts to explore cost-effective, simple, reliable, and efficient wastewater treatment systems. Therefore, the present review highlights the option of trickling filter (TF) systems for wastewater treatment in developing countries like Pakistan, India, Bangladesh, and African regions, etc. In addition, the solutions to the operational/performance issues of the TF system are explored and discussed in greater detail for designing/construction of new TF systems and retrofitting the existing TFs.

Keywords: wastewater treatment, trickling filter systems, operational issues, performance issues

Introduction

Water pollution is one of the main impediments to public health in developing countries like Pakistan, India, Bangladesh, and African regions etc. [1-2]. Wastewater generation is increasing day by day due to the rapid development in agricultural and industrial activities [3]. The level of water pollution is also increasing at a fast pace due to the mixing of sewage and industrial effluent into the residential water supply systems in big cities of the country [4]. The brunt of the adverse impacts of water pollution is faced by humans, animals, aquatic biota, agriculture, and so forth [5-6]. An estimated 7.5708×109 L of wastewater is being disposed of into water-receiving environments every day only in the case of Pakistan [7-10]. The main water pollutants present in wastewater are pathogens (i.e.,

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bacteria, protozoas, and viruses), organic compounds (i.e., oil and pesticides), inorganic compounds (i.e, toxic metals and acids salts), anions and cations from industrial effluent (i.e., nitrates, sulphates, phosphate, Ca^{+2}, Mg^{+2}, and F^{-}), and water-soluble radioactive substances, which mainly damage water quality [1, 11-12].

About 6-8% of the generated wastewater receives treatment before disposal into the receiving water environment, but this figure is based on the assumption that all the treatment systems operate at their full designed capacity, which is not true [1-3]. Further, developing economies like Pakistan and Bangladesh are also facing an energy crisis and electricity fluctuations in the shape of load shedding. It has been observed that typically 30-50% of the operating cost of a conventional wastewater treatment plant belongs to energy consumption. Moreover, 50% is utilized for aeration during biological wastewater treatment, and this is the highest percentage compared to other unit operations and processes [13-14]. The key consideration and hindrance in selection of a suitable treatment system is the cost, energy, trained human resources, system compatibility, and operational complications [15]. The right choice of an appropriate and workable technology is very important because of the

Table 1. Studies conducted for wastewater treatment: a case study for Pakistan.

Treatment system	Wastewater type/matrix	Measured parameters and pollutant removed	Reference
Phytoremediation	Aqueous solution of heavy metals	Heavy Metals	[18]
Endophyte-Assisted Floating Treatment Wetlands	Municipal wastewater	COD, BOD_5, TN, PO_4^{3-}	[19]
Membrane Bioreactor	Wastewater	COD, MLSS, MLVSS, ammonium nitrogen, phosphate-phosphorus, and TOC	[20]
Bioremediation (Constructed Wetlands)	Municipal wastewater	BOD_5, COD, and nutrients (nitrogen and phosphorus)	[21]
Constructed Wetlands	Domestic wastewater	TSS, TDS, SO_4^{-2}, PO_4^{-3}, NO_3, NO_2 bacterial counts and fecal pathogens	[22]
Trickling Biofilter System	Municipal wastewater	Ammonium nitrogen, BOD_5, COD, and pathogen	[23]
Bio-Sorption	Synthetic wastewater	NH_4^+	[24]
Anaerobic Reactor and Fenton's Process	Textile wastewater	Color, COD, and turbidity	[25]
Constructed Wetlands	Industrial wastewater	EC, turbidity, COD, TSS, TDS, TS, nitrates, ammonia, phosphates, heavy metals (i.e., Cd, Ni, Hg, and Pb)	[26]
Bio-Sorption	Textile wastewater	COD, TDS, TSS, and color	[27]
Bio-Remediation	Textile wastewater.	BOD, COD, TOC, and cytotoxicity	[28]
Advanced Oxidation Processes	Municipal wastewater	BOD, COD, turbidity, conductivity, pH, and fecal coliform	[29]
Fixed Biomass and Sand Column Reactor	Municipal wastewater	Odor, alkalinity, pH, turbidity, BOD_5, COD, TDS, TSS, EC, PO_4, SO_4, NO_3, NO_2, and DO	[30]
Membrane Bioreactor	Synthetic wastewater	Nutrients	[31]
Hybrid Constructed Wetland (HCW)	Domestic wastewater	NO_3, NO_2, BOD_5, COD, SO_4, PO_4, and pathogenic	[32]
Fixed Biofilm Reactor	Municipal wastewater	Bacterial count (Escheria coli and feacal coliforms), COD, BOD, pH, NO^{-2}, NO^{-3}, PO_4^{-3}, SO_3^{-2}	[33]
Integrated Wastewater Treatment System (i.e., Aeration, Coagulation and Advance Oxidation Processes)	Carwash industry wastewater	COD, TDS, turbidity, DO, pH, and oil contents	[34]
Constructed Wetland	Industrial wastewater	Ni, Cd, Pb, Fe, Cr, and Cu	[35
Constructed Wetland	Industrial wastewater (oil refinery effluents)	TSS, COD, BOD, heavy metals, i.e. Zn^{+2}, Cu^{+2}, and Fe^{+2}	[36]
Waste Stabilization Ponds (WSP) or Lagoons	Domestic wastewater	BOD_5, COD, NH_3-N, total kjeldahl nitrogen (TKN), PO_4-P, and coliforms	[37]

economic limitations and consequences of the decision [16]. Unnecessarily costly treatment will divert scarce resources away from other development projects [17]. In this regard, many local research groups are actively involved in research related to the selection of wastewater treatment systems for developing countries such as constructed wetlands, fixed-film bio reactors, membrane bio reactors, bio sorption-based processes, anaerobic process-based treatment, and advanced oxidation processes, but the level of research is too low and just focuses on the removal of conventional pollutants. It was also observed that the adopted technology is just suitable for lab-scale experiments and these technologies demand extensive research for practical applications. A short summary of these experimental works is discussed in greater detail in Table 1.

Trickling Filter System Design, Operation, and Application

Keeping in mind these facts, it is fairly difficult to propose a suitable wastewater treatment system for developing countries because of financial constraints, lack of technically trained staff, and electricity shortages. Therefore, to the best of our knowledge this is the first review paper mainly focusing on the technical aspects of Trickling filters (TFs), their suitability, and applications in water and wastewater treatment, and the identification of operational and performance problems with their corresponding solutions are discussed in light of available published literature. However, the success rate of the TF system is poor because of unskilled operating staff, unawareness about process philosophy, and/or inadequate aeration of biological units owing to the low availability of electricity [1]. Therefore, first of all it is important to identify the basic complications regarding existing wastewater treatment systems and to then explore the possible solution approaches, although limited evidence is present in the published literature (TF systems) and their subsequent solutions. Furthermore, this is the very first time anyone has identified and summarized operational and performance issues of TFs with subsequent solutions because the success of a wastewater treatment plant not only depends upon technical expertise and planning, but also on skilled operation.

TFs are well known in the field of biological wastewater treatment systems because the microorganisms play a key role in minimizing pollutant strength. Microbial communities have natural physiological and metabolic capabilities to remove a wide range of pollutants [14]. Microorganisms have a natural ability to stick to wet faces, multiply, and embed themselves in a slimy environment composed of the extracellular polymeric substances (EPSs) they produce, forming a biofilm [38]. Mostly high-specific surface area is available in attached growth systems, which are essential for healthy growth of biofilm. Importantly, a TF system has the ability to retain higher biomass with higher metabolic capacity than suspended growth treatment systems when operated under the same conditions [13]. Now TFs are getting attention rather than other attached growth systems because of their low operating and maintenance requirements and especially their capability to treat and handle shock organic loads. Furthermore, the TFs have been designed using different kinds of biofilm packing materials to improve treatment efficiency as listed in Tables 2 and 3. System performance depends mainly on the health and growth of the biofilm onto packing material.

After the development of the biofilm layer, as the influent flows over the slime layer of 0.1-0.2 mm thickness, organic pollutants such as biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), ammonia, and dissolved oxygen (DO) disperse into the slime layer where they will degrade organic matters with the help of microorganisms. Mass transport and biotransformation are the two main processes for the removal of pollutants in TFs [14, 39]. Anaerobic condition is maintained at the bottom of the biofilm layer, as the thickness of the slime layer increases. The biofilm layer loses its ability to adhere to the media because of the absence of the extra organic source available for the attachment of the cell carbon. The incoming wastewater then washes down the biofilm from the support medium and a new slime layer starts to develop [40]. The attached growth systems, such as TFs, are comparatively superior to other biological wastewater treatment systems, as it is not an electricity-intensive process, is technically less complicated, and is cost effective [41].

TFs are relatively simple and reliable, and require less space, making it suitable in areas where large strips

Table 2. Potentials of trickling filter systems for water purification.

Filter media	Pollutant removed	Study area	Reference
Stone	Ammonia	Greece	[46]
Gravel	Iron	Greece	[47]
Gravel	NH_3, Fe, and Mn	Greece	[48]
Gravel	Chromium(VI)	Greece	[49]
Silicic gravel	Iron	Greece	[50]
Hollow plastic tubes and calcitic gravel	Cr(VI)	Greece	[51]
Silicic gravel	Manganese	Greece	[52]
Polypropylene Plastic	Ammonia	Australia	[53]
Gravel	Nitrate	Greece	[54]
Gravel	Ammonia	Greece	[55]
Gravel	Ammonia, iron, and manganese	Greece	[56]

Table 3. Potentials of trickling filter systems for wastewater treatment.

Wastewater type/matrix	Filter media used	Pollutant removed	Study area	Ref.
Municipal wastewater	Mixed-media (granite, clinker blast furnace slag, and RC plastic)	BOD, SS, TN, Ammonia, pH, conductivity and turbidity, synthetic detergent, total phosphate, chloride, and heavy metals	Cardiff, Wales	[57]
Municipal wastewater	Sand	COD, microorganisms and pharmaceuticals (e.g., Ibuprofen or Naproxen)	Germany	[58]
Dye wastewater	Silica gravel	COD	Greece	[59]
Synthetic wastewater	NG	Cooper (Cu)	UK	[60]
Textile Wastewater	Polyurethane foam (PUF)	Color, dyes, and TOC	Czech Republic	[61]
Domestic Wastewater	Coal cinder	COD, NH_4^+, TP, and SS	China	[62]
Domestic Wastewater	Polyurethane foam pores	COD	China	[63]
Mine water	Plastic	Iron	UK	[64]
Industrial wastewater	Mineral (Synthetic prepared)	Phenol	Greece	[65]
Industrial wastewater	Mineral (Synthetic prepared)	Phenol	Greece	[66]
Synthetic wastewater	Porous medium	Toluene, o-cresol, phenol, 1,2,3-trimethylbenzene, and naphthalene	Greece	[67]
Municipal wastewater	Gravel	BOD and nitrogen	USA	[68]
Synthetic wastewater	Plastic	Hexavalent chromium (Cr(VI))	Greece	[69]
Municipal wastewater	Corrugated plastic sheet	TSS, BOD_5, COD, TKN, NO_3–N, and TP	France	[41]
Domestic sewage	Stones	pH, odor, turbidity, alkalinity, COD, BOD_5, TDS, TSS, EC, PO_4, SO_2^{-4}, NO^{-2}, NO^{-3}, and bacterial count	Pakistan	[70]
Synthetic wastewater	Crushed leca and plastic media	Ammonia nitrogen	Norway	[71]
Swine lagoon wastewater	Plastic (Bioballs and recycled soda six-pack rings)	BOD_5, COD, NH_3-N, and TKN	USA	[72]
Synthetic wastewater	Plastic media and calcitic gravel	Cr(VI)	Greece	[51]
Municipal wastewater	Oyster shell and plastic balls	COD, NH_3-N, and TP	China	[73]
Combined wastewater	Oyster shell	COD, BOD, NH_3-N, TP, and TSS	China	[74]
Domestic sewage	Luffa cyllindrica	$BOD_{5,20}$, COD, SS, and settleable solids	Brazil	[75]
Synthetic wastewater	Geotextile	Organic nitrogen and phosphorus COD,	Canada	[76]
Synthetic wastewater	Nylon pot scrubber	Ammonium	India	[77]
Domestic wastewater	Plastic balls	COD, BOD_5, TSS, turbidity, NO_3, NO_2, SO_4, PO_4, and pathogenic indicator microbes	Pakistan	[78]
Domestic wastewater	Tire derived rubber (TDR)	BOD, COD, pathogen indicators, pH, NO^{2-}, NO^{3-}, PO_4^{3-}, and SO_3^{2-}	Pakistan	[33]
Municipal wastewater	Stones	BOD_5, COD, NH_4-N), and pathogen	Pakistan	[79]
Municipal wastewater	Rubber, polystyrene, Plastic, and stone	Chemical oxygen demand and BOD, faecal coliforms	Pakistan	[23]
Municipal wastewater	Stones	Odor, alkalinity, pH, turbidity, BOD5, COD, TDS, TSS, EC, PO_4^{3-}, SO_3^{2}, NO^{2-}, NO^{3-}, and pathogens	Pakistan	[72]

Table 3. Continued.

Synthetic wastewater	Ceramic particles	Methyl acrylate	China	[80]
Municipal wastewater	Stones	Di-(2-ethylhexyl) phthalate and diethyl phthalate	UK	[81]
Synthetic wastewater	Sponge	COD and TN	UK	[82]
Industrial wastewater	Ceramic foams	Phenol	Spain	[83]
Textile wastewater	TM foam	Organic dyes	Czech Republic	[84]
Industrial wastewater	Ceramic material	COD and ammonia nitrogen (NH4+-N)	China	[85]
Synthetic Wastewater	PORAVER particles	Phenol and TOC	Portugal	[86]
Synthetic Gold mill wastewater	Plastic rings of polypropylene	COD, copper, thiocyanate, free cyanide, iron, and zinc	Brazil	[87]
Landfill leachate	Polypropylene plastic media	Ammonium and organic carbon (TOC)	UK	[88]
Synthetic wastewater	Sponge-bed	NH4 +-N and total nitrogen	Netherlands	[89]
Synthetic wastewater	Biochar chips	NH4+-N and TP/NOx-N	China	[44]
Domestic wastewater	Sponge, zeolite and ceramsite	COD and ammonia	China	[90]
Synthetic wastewater	Sponge-bed	Total nitrogen	Netherlands	[91]
Municipal wastewater	Corrugated plastic sheet	TSS, BOD_5, COD, TKN, NO3–N, and TP	France	[41]
Municipal wastewater	Plastic media	Phosphate	France	[92]
Synthetic wastewater	Lantec HD Q-PAC®	Organic matters	Belgium	[93]
Real Wastewater	Agricultural Waste (Maize cobs)	BOD_5, COD, TSS, TDS, turbidity, and color	Pakistan	[94]

of land are not vacant for treatment systems. It is also an appropriate wastewater treatment option for small- to medium-sized communities. It takes less time to minimize BOD_5 from wastewater with low power requirements. TF system design advantages compare to other secondary wastewater treatment systems can be summarized as TFs require less operational energy in the shape of energy-consuming aeration blowers. The only energy consumed is when we use an electrical device for the rotation of distributor arms. Natural ventilation is historically the primary means of providing airflow, but somehow we use low-pressure fans for requirements of controlled airflow. The operational and maintenance cost of TFs is 47% less than compared to an activated sludge system. The TF system has a low mechanical complexity compared with the activated sludge system because it has simply a rotating arm for wastewater distribution in trickle form. TFs use natural ventilation while an air diffuser is used in an activated sludge system for aeration purposes. TFs are less reactor resilient for power failure and shock organic loads because TF systems have the ability to handle and recover from shock loads. However, in an activated sludge system the shock load increases the retention time of treatment systems [13].

TF systems are known as attached growth biological systems, where the wastewater contact with bacteriological communities is attached to the surface of the filter media. The influent is distributed over the bed of filter media. After the development of synthetic media used in place of stone, the term "biological tower" is introduced instead of TFs. Primary clarification is necessary before rock TFs, helping settle most heavy particles, which can clog the filter. In some installations, a wire-mesh screen is placed over the top of the plastic packing to collect debris that can be vacuumed off periodically [42]. The influent trickling over the filter media produces biofilm that covers the filter media. This biofilm consists primarily of bacteria, protozoa, algae, and fungi (about 0.1 to 0.2 mm thick) [13-14, 33]. As the wastewater flows over the biofilm, organic matters are degraded into carbon dioxide and water due to the metabolic activity of the microbes. In the bottom of the filter, the nitrifying bacteria are present for nitrification. The fungi present may also be responsible for minimizing pollutants, but this will work only at low pH. The job of protozoa is to feed the biological films and, as a result, effluent turbidity decreases and the biofilms are maintained at a higher growth state. Sloughing is the phenomenon of losing or breaking the biofilm layer due to endogenous respiration conditions of the bacteria to lose their power to stick to the filter media. Then the incoming flow will slough off the biomass from filter media, and a new biofilm layer will start to develop. This phenomenon

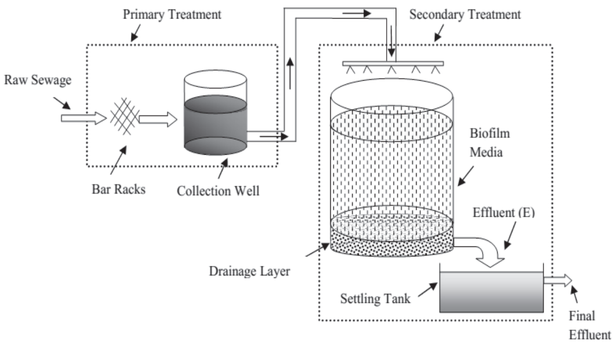

Fig. 1. Schematic illustration of trickling filter wastewater treatment system.

is mainly a function of incoming organic and hydraulic loading [13, 43].

The major components of the typical TFs are a rotary distributor, under-drain system, and filter media as shown in Fig. 1. The influent wastewater is pumped up a vertical riser to a rotary distributor for spreading uniformly over the filter media surface. Rotary arms are driven by the reaction from the wastewater flowing out of the distributor nozzles. Bed under-drains carry away the effluent and permit air circulation. The floor and under-drain block slope to a central or peripheral drainage channel at a 1-5% grade. Ventilation risers and the effluent channel are designed to allow free opening of air. In some installations, the under-drain blocks empty into a channel between double exterior walls to allow improved aeration and access for flushing of under-drains. The most common media in existing filters are crushed rock, slag, or field stone that are durable, insoluble, and resistant to spalling. The size range preferred for stone media is 3-5 inches in diameter. Although smaller stone provides greater surface area for biological growth, the voids tend to plug and limit passage of liquid and air [13, 38]. Distribution systems are provided for spray of wastewater in trickle form into media surface. Nozzles are arranged unevenly so that greater flow per unit of length is achieved near the periphery of the filter than at the center. Head loss through the distributor is in the range of 0.6 to 1.5 m [13, 44].

Typically, TFs achieve 85-90% BOD removal efficiency and 80-85% COD removal efficiency. Such systems have high process stability, low sludge processing requirement, and low hydraulic retention time (HRT) as compared to activated sludge and rotating biological contactors [45]. Its low sludge production is related to a primary settling tank for influent collection before going toward a filter. A new revelation has come in the form of TF performance after using plastic filter media instead of rock or stones because plastic filter media are different in shape and arrangement and have good properties of aeration and are more durable. Having reviewed the published literature related to TF performance, a brief summary of its application in water purification and wastewater treatment is discussed in Tables 2 and 3. Having discussed the advantages of the TFs, it is also a fact that like any other treatment system, it has its own limitations, problems, and operational troubles, and if not dealt with properly it will adversely affect the treatment performance. It is important to identify the causes of frequent problems encountered during the operation of TFs and to explore their solutions for smooth and satisfactory operation.

Trickling Filter Operational Problems and Proposed Solutions

Filter flies and predators are a nuisance in the operation of a TF system. They pose a serious problem to the plant operating staff as well as the neighboring environment and community. It has been reported that species such as *Parischnogaster alternata, Pseudocolaspis severini,* and *Astraeus hygrometricus* were abundantly found during TF operation [95]. We also have noticed that ambient air temperature was a major factor influencing the growth of these species [95]. Coombs et al. [96] conducted a study to control the formation of filter flies by using a microbial insecticide such as *bacillus thuringiensis var. israelensis (Bti)* at Rossendale Sewage Works, Lancashire. The results indicated that the technique was very effective in controlling the filter fly *sylvicola fenestralis* without changing system performance. Currently, chemical and biological agents are being used to control filter flies and can be removed rapidly from the filter media [95]. Periodic flooding may eliminate filter flies [96]. Another common problem in TF operation is the development of snail populations, which may scuff the slime layer to minimize the nitrifying bacteria population and system performance. The increase in snail populations can cause problems with plugging of channels and pumps, accumulating in digesters, and causing wear and tear on system equipment. Several techniques have been used to control snails (e.g., periodic flooding of the TF system, lowering the distributor speed to create higher flushing rate, high pH dosing, chlorination saline water dosing, recycling higher levels of ammonia through the process to kill the snails and prevent their growth, and dosing with copper sulfate at 0.4 g/L). All these solutions have some limitations as well [45]. Tekippe et al. [97] reported an alternative way to remove snail shell from TFs by introducing a baffle system in the aeration basins and the use of grit pumps and classifier systems, which were low-cost compared to the previous manual labor method (Table 4).

The operation of TFs is an aerobic process, thus foul odors indicate that anaerobic environments are becoming predominant due to the presence of odor-producing substances such as methyl mercaptan, toluene, alpha-pinene, hexane, etc. [98-99]. There are several other reasons for foul odors in TFs, such as sloughing off biomass accumulation in the filter media, low oxygen transfer rate (OTR), and uneven moisture content. Loading concentration and oxygen utilization are the main parameters in odor control. It was reported previously that OTR may become inadequate when ultimate BOD value increased from 500 to 600 mg/L, and the chance of odor

Table 4. Trickling filter system problems, causes, and proposed solutions.

Problem(s)	Cause	Solution	Reference
Operational			
Filter flies and predator	Variation in ambient air temperature Long rest period Uneven running of the system Uneven distribution of the influent from nozzle	Apply microbial insecticide for, e.g., *Bacillus thuringiensis var. israelensis (Bti*) for the control of nuisance fly Periodically flood the TF System Lower the distributor arm speed to create a higher flushing rate High pH dosing Chlorination with saline water dosing Recycling higher levels of ammonia through the process to kill the snails and prevent their growth Dosing with copper sulfate at 0.4 g/L for snail removal Introducing a baffle system to the aeration basins and the use of grit pumps and classifier systems for snail shell removal Install birdhouses as a natural technique	[45, 95-97]
Odors	Predominant anaerobic conditions in the system Excessive biomass accumulation in the media surface Improper oxygen transfer rate in the filter	Pre-aerating and pre-chlorinating the TF influent Increasing recirculation rate to provide more oxygen to the filter bed and increase sloughing Clean the nozzles on a weekly basis for proper influent distribution Use chemical scrubbers and sodium hypochlorite doses Minimize the incoming organic loading by reducing BOD concentration Remove slough off biomass by increasing hydraulic loading	[98-103]
Nutrient imbalance	Improper media selection Uneven hydraulic surface loading Uneven development of biofilm	Apply measured nutrient loading to achieve better performance Keep the TF influent flow warm by minimizing the recirculation rate	[13, 91, 104]
Weather concerns	Decrease the biological reaction rates of the treatment process Low quality/uneven biofilm development Ice clogging the filter, which causes ponding and structural damage to the media	Use microwave radiation to maintain required temperature Periodically flood the TF system to break up the solid	[13, 78-79]
Filter clogging and ponding	Improper media selection during targeted pollutant removal Slough off biomass accumulation into the void pores Loss of open area in the filter Excessive organic loading Lack of good primary clarification Excessive growth of insect larvae or snails Shock load and lower transport of air	Use proper flashing with low doses of chlorine to remove deposited solids and kill excess biomass Enhance the recirculation rate Optimize organic loading and apply low organic loading by enhancing the performance of a primary settling tank Replace the TF media if needed	[13, 105]
Bio-film slough off	Clogging the filter media Changes in waste load Insufficient nutrients Uneven distribution of influent Low moisture content and High hydraulic loading rate	Optimize organic and hydraulic loading or use a parallel or series TF system to handle shock variations	[13, 106-109]
Shock loads	Strom events will increase the hydraulic loading, which slough off the biofilm Industrial effluents upset the biological processes and increase the organic loading or toxic loading	Neutralized the toxic shock load by using a TF system in series; this technique will save the biofilm growth Dilute the toxic shock load by increasing the recirculation rate	[13, 110-111]

Table 4. Continued.

Distributor arm	Uneven oxygen utilization Uneven growth of slime layer Low BOD and COD removal	Increase the oxygen transfer rate by adjusting the speed of the distribution arms Adjust the proper hydraulic flow rate according to system design Use innovative nozzles in distributor arms to increase system efficiency	[13, 43, 121-123]
Filter media	Clogging Uneven growth of biofilm Decrease efficiency in terms of BOD & COD removal	Use proper media that support the growth of biofilm Uniform the media by passing through a sieve before installation Increase the filter media installation width and decrease the depth Apply active aeration to increase operational efficiency	Table 1 & 2
Performance			
High total suspended solids	Excessive biomass sloughing	Optimize the hydraulic loading rate (HRT) Use proper flushing if slough-off of biomass is excessive	[13, 95, 99, 117]
High biochemical oxygen demand	Increase in organic loading rate Anaerobic conditions in the system Low oxygen transfer rate Improper slime layer growth in the media surface	Optimize the loading and remove the clogging and slough-off biomass by proper flushing Optimize weather conditions by artificial means for keeping optimum oxygen transfer rate (OTR)	[13, 101]
High settleable solids	Uneven sloughing of slime layer	Minimize the shock loads and optimize the loading rate or use a TF system in series to handle shock loads	[13, 99]
Low dissolved oxygen	Mixing of industrial waste due to odor	Optimize the loading and oxygen transfer rate (OTR) Increase recirculation rate	[13]
High chlorine demand	Filter clogging and poor oxygen transfer Improper distribution of influent	Control the industrial effluents or shock loads and enhance primary settling tank efficiency for removing solids from TF influents	[13, 120]
Low or high pH	Mixing of industrial wastewater in influent during VOC degradation Anaerobic conditions in the system	Try to neutralized the TF influents by using buffer materials for, e.g., calcium carbonate and dolomite Use nutrient solution, for example $Ca(OH)_2$, NaOH, $NaHCO_3$, and urea	[13, 126, 129]
Biofilm/Slime layer	Improper media selection Uneven nutrients supply Uneven aeration High organic and hydraulic loading rates Uneven sloughing Weather Conditions	Control the slime layer thickness by sloughing process Create aerobic conditions by maintaining optimum oxygen transfer rate Use good filter media that support microbial growth Use a chemical addition like ferric chloride and polymers to enhanced the growth of the slime layer and also trickling filter efficiency Use optimum oxygen levels for proper growth of bio-film Optimum amounts of nutrient solutions can be applied for microbial growth Increase the DO level of influent by recirculating the effluent Optimize the organic loading rate to maintain bio-film structure	[13, 23, 80, 136-143]

production will also increase [100]. The moisture content of the media bed is a key element for maintaining TF performance because of a bacterium's required optimal moisture to perform their metabolic activity [101]. The imbalance level of moisture content leads to drying of the filter bed and may cause channeling and short-circuiting [102]. Moreover, the rate of biodegradation will also lower [103]. Chemical scrubbers and sodium hypochlorite dosage can be used for controlling odor, as illustrated in detail in Table 4.

The optimum level of C:N:P (redfield ratio) are the key nutrients for growing and reproducing biofilm in TF operation [91]. Although municipal wastewater normally contains a suitable quantity of nutrients, its concentration varies in the case of industrial effluents [104]. It was reported previously that the shape and type of filter media may also influence nitrification performance and biofilm development due to nutrient imbalance [105-106] (Table 4). The environmental conditions such as air and influent temperatures have an effect on TF operation that eventually influences TF performance [104]. Cold weather can lower the degradation rate of pollutants and reduce the growth of slime layer in the TF systems. While under very low temperatures, ice clogging causes the bonding effect in TF systems. It was also observed that biofilm thickness also fluctuates seasonally and the thickness was increased in winter and decreased in summer [13, 79]. Natural ventilation has historically been the primary means of providing airflow, but it is not always adequate and forced ventilation using low-pressure fans to provide more reliable and controlled airflow [78]. Naz et al. [79] conducted a study and reported that most of the microorganisms flourish well in the temperature range 25-40ºC. However, greater detail regarding the effect of weather on TF performance is discussed in Table 4.

Ponding is another problem regarding the collection of wastewater on the surface and results in complete choking of the TFs. Major causes of ponding include excessive organic loading, insufficient recirculation, improper or no primary clarification, small-sized media or non-uniform media, accumulation of fibers or trash in the interstices, excessive slough-off, and excessive growth of insect larvae, snails or, other insects [13, 105]. Further details of the various causes and suggestions to solutions for ponding are discussed in Table 4. Moreover, uncontrolled sloughing from the filter media is one of the most common problems in TF operations [13]. It may occur due to uneven hydraulic loading rates (HLR) or sheering force of the influents [106]. Wik [107] reported that low organic loading may not clog the TF system. Moreover, periodic recirculation of the TF system with water/wastewater may control the biofilm slough off problem [108-109]. Details about different issues of sloughing and its solution approaches are given in detail in Table 4.

Storm events and industrial discharge also are identified as two main factors of shock loads in TF operations as inflow increases the HLR to the plant [110]. The high loading rate consequently forces the slime layer to slough off the filter media. The oil factory organics or other toxic chemicals are allowed to enter the treatment plant without specialized treatment provisions, and the biological process is hindered and disturbed. The organisms might become inactivated or completely die. Industrial discharges can either increase the organic loading rate or the toxic shock loading, or both. Increased organic loading rate depletes the oxygen and microorganisms die off. Biological growth sloughs off clogging the filter and ultimately resulting in ponding. Increased toxic loads disturb the microbial populations [111] (Table 4).

The distributor arm is the main parameter in design of TF systems because it helps in uniform distribution of wastewater into filter media and maintains a proper wetting for slime layer growth [13, 112-114]. Maulik [43] conducted a study to apply special nozzles with a flat spray pattern for constant distribution of influents and reported that such nozzles can enhance the influent distribution pattern over the filter media, but could not improve OTR (detailed discussion about different designs of the distribution arms is available in Table 4). Moreover, filter media in TFs support slime layer growth, and selection of the suitable support media is very important for TF operation and performance. The filter media play a vital role in development of the microbial community/biofilm. The performance of TFs varies with media to media due to its surface, depth, and size. Scientists have used several packing media to enhance TF performance, e.g., rocks, plastic [13], nylon pot scrubber [77], groups of commercial rings (such as crushed leca, kaldnes, and Norton), calcitic gravel [115-116], geotextile [117], pall rings [118], polyurethane foam pores [119], coal cinder [42], tire-derived rubber [45], oyster shell [120], corrugated plastic sheet [41], stone [70], gravel and zeolite [118] sponge [38], zeolite and ceramsite [40], polypropylene plastic [39], biochar chips [44], ceramic particles [121], etc. (Brief summaries of the different filter media used in TFs with their targeted pollutants removed are given in Tables 2 and 3). It was also reported that TF performance can be enhanced by maintaining media surface wetting and maintaining the aerobic environment during operation [122]. Wang et al. [119] reported the performance of hybrid biological rectors using polyurethane foam pores as filter media and observed that the total biomass concentration in hybrid reactors increased to 4.30-5.75 g/l when the volumetric portion of the carrier was 15-30%. Kumar et al. [123] reported the performance comparison of two different biogenic filter materials (such as corn cobs and wood chips) inoculated with a defined microbial community. Corn cobs of specified dimensions were found to be more suitable than wood chips. Corn cobs with hollow surface produced remarkable results. The time duration was also less for initiation of purification activity. Yao et al. [124] reported the removal efficiency by comparing the oyster shell and plastic ball used as filter medium for the treatment of municipal wastewater in two lab-scale upflow biological aerated filters (BAFs) under different HRTs of 2, 4, 8, and 12 h. Further detail is discussed in Table 4.

Trickling Filter Performance Issues and Solution Approaches

The higher concentration of the total suspended solids (TSS) in the TF effluents may be caused due to uncontrolled biomass slough-off. High HLR displace the solids from the primary clarifier to the TFs and also cause the biofilm to strip off [99]. On the other hand, less than optimum HLR to the system makes the biofilm slough off [95]. Clogging occurs due to the presence of high solids or sloughed-off biological growth and creates an anaerobic environment that destabilizes the process [13, 125]. It might occur due to inadequate ventilation in the filter media [13, 99]. If the industrial effluents are allowed to enter the influent stream of the wastewater treatment plant, it may cause high chlorine demand [96]. If excessive slough off is there, TSS will be high in the effluent and will exert a high chlorine demand. This may cause failure to gain downstream disinfection [95, 98-99]. While pH can be considered as the main checking parameter of TF performance, septic conditions typically are caused in wastewater due to increases in pH [78, 126]. pH can vary due to industrial effluent discharges, depending on the type of industry.

Microbial activity is influenced due to variation in influent pH [127]. Lu et al. [128] reported maximum degradation of Benzene, Toluene, Ethylbenzene, and Xylenes (BTEX) between pH values of 7.5 and 8.0. Lu et al. [128] also reported a pH of 7.0 to be optimal for BTEX degradation. Arnold et al. [129] reported styrene eliminations were enhanced in a neutral medium. To keep the pH (at 7) some scientists have reported supplementing buffer solutions in the media beds for, e.g., calcium carbonate [130-131] and dolomite [132]. The pH can also be controlled by bed irrigation of nutrient solutions that contain pH buffers, for example $Ca(OH)_2$, NaOH [133], $NaHCO_3$ [134], and urea [135] (Table 4).

Biofilm is the community of organisms; a key element of TFs developing on the surface of the support media is carrying out catabolic activity and transforming the pollutants into harmless products [136]. The thickness and shape of the biofilm is influenced by several environmental factors such as the type of pollutant, packing material used, ambient air and wastewater temperature, humidity, moisture content, system design, and configuration of the treatment system [13, 23, 137]. Wijeyekoon et al. [112] reported that organic loading influenced biofilm internal microstructure as with the increased organic load that produced a compact biofilm layer with lower porosity. It was reported that TF filter media should possess high specific surface area, high porosity, good water retention capacity, availability of intrinsic nutrients, and the presence of a dense and diverse indigenous microflora [138]. Further, various approaches for the development of metabolically competent biofilm on the filter media of the TFs are discussed in Table 4.

Conclusions

Given the deplorable situation of wastewater treatment in developing countries, it is imperative to explore cost-effective, technically less complicated, and less energy-consuming treatment options. Conventional systems like activated sludge do not fit in this criterion and either new treatment systems have to be developed indigenously or the available technologies must be appropriately modified before implementation to make them appropriate for local conditions. The trickling filter in this regard is potentially a viable option, as it is a simple and reliable biological treatment process and an appropriate option for small- to medium-sized communities, and requires less space and time for removal of BOD_5. It has durable process elements, low power requirements, a moderate level of technical training requirement for the staff, and resilience against power failures and shock loads. However, TFs have their own limitations, performance issues/operational troubles identified in the present review paper, and the corresponding solutions/approaches are also suggested for smooth and satisfactory operation.

Wastewater management and treatment is indeed an alarming appeal for developing countries because wastewater contains biodegradable and non-degradable organic and inorganic matter, toxic chemicals, and disease-causing organisms that can destroy public health. The mixing of untreated wastewater into natural receiving water is polluting drinking water sources – both surface and ground. While the parameters set by WHO and Pak EPA related to wastewater disposal and drinking water are frequently violated, the situation of wastewater management and treatment is not acceptable because only about 6% of wastewater is receiving treatment before disposal. Therefore, this review paper was designed to propose a suitable and affordable wastewater treatment system for developing countries like Pakistan, India, Bangladesh, and African regions, etc. Keeping in mind the past experiences and problems, the trickling filter is a suitable and viable option for developing countries. Although past practice was not good, this was only due to lack of technical knowledge and trained human resources. This review paper is an effort to present the importance of the trickling filter system with special emphasis on identifying the operational and performance issues that mainly hindered its operation. Furthermore, corresponding solutions are also suggested against each problem for its smooth running.

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