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Municipal Wastewater Treatment Using a Packed Bio-tower Approach

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Authors' contributions

This work was carried out in collaboration between both authors. Author KD supervised the study, wrote the final draft and approved the final manuscript.

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ABSTRACT

The study tested a designed and built pilot scale packed bio-tower system under continuous operation using pre-clarified municipal wastewater. Performance was evaluated by measuring the removal of chemical oxygen demand and nitrogen ammonia.

The pilot scale packed bio-tower system had a diameter of 1209 mm (4 ft.) and a height of 3,962 mm (13 ft.) and contained Bentwood CF-1900 bacteria growth media with a surface area of 6,028.80 ft² (560.09 m²). The municipal residential sewage was fed into a 1,481 l (375 gal.) recirculation reservoir at a temperature of 15°C (59.0°F) and a flow rate between 7,571 l/d (2000 gal/d) and 90,850 l/d (24,000 gal/d) and recirculated through the bio-tower with a fixed recirculation rate of 75.7 l/min (20 gal/min).

The influent COD value reduction achieved is between 63.4% and 84.8%, whereas the COD influent value varied between 87 mg/l and 140 mg/l. The influent NH_3-N reduction achieved was between 99.8% and 91.8% whereas the influent NH_3-N value was between 28.8 mg/l and 18.6 mg/l at a flow rate between 7571 l/d (2000 gal/d) and 90,850 l/d (24,000 gal/d).

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1. INTRODUCTION

Clean water is the most significant challenge our society faces in the future. The increasing needs for water resources for residential, commercial, industrial and recreational use accelerate the depletion of the water resources [1] and increases waste water streams that are a combination of domestic, industrial, commercial or agricultural activities, surface runoff/ stormwater, and any sewer inflow/infiltration [2]. In this research we focus on the constantly increasing needs for water resources for recreational purpose on golf courses.

Wastewater consists of approximately 99.9% water and 0.1% waste [3]. The waste is comprised of organic and inorganic matter, dissolved and suspended solids, and microorganisms [3]. Reuse of the effluent water after treatment becomes an effective solution to reduce the shortage of water resources [4]. However, a modern wastewater infrastructure is needed for wastewater treatment to assure healthy river, streams, lakes, and wetlands where discharged effluent and storm water often end up. According to the EPA, an estimated 56 million new users will be connected to the existing centralized treatment systems of 14,748 Public Operated Treatment Works (POTWs) in the next two decades. This will require at least $271 billion in funding for modernization and additional plants to meet future demands [5].

Today mostly fresh water or well water resources are used for irrigation purposes on golf courses. To limit fresh water usage on golf courses, irrigation water might come in the future from resources such as: Storm runoff from impervious surfaces captured in retention ponds, high flow (flood) water diversion into storage ponds, secondary or tertiary effluent from a Waste Water Treatment Plant (WWTP), grey water, and treated or raw water from a local public water supply distribution systems [6] to offset freshwater usage on golf courses that require today on average of 48.2-acre-feet to 386.2 acre-feet (15,706,000 to 125,844,000 gal/year) of water for irrigation purpose annually [7].

A bio-tower or sometimes known as trickling filter is one of the two main types of biological control units in wastewater treatment plants [8]. Industrial and municipal WWTP use bio-towers as part of the secondary treatment process [9]. A bio-tower is a round tank structure and contain usually engineered growth media with a high surface area [10]. Rock, slag and wood was a common growth media in the past. Today, materials such as Polyvinyl Chloride (PVC), Polypropylene (PP) with a defined specific surface area between 90 to 226 m^2/m^3 are utilized [11,12].

In bio-towers, a distribution system equally spreads the wastewater (WW) over a biofilm covered growth media. The wastewater then trickles over the medium and is collected at the bottom of the bio-tower. The growth media is located above the bottom of the bio-tower to ensure air transfer throughout the filter media. A pump lifts the inflowing wastewater to the distributor as well as can partially recirculates the effluent [13].

Even though, bio-towers traditionally remove organic matter by heterotrophic bacteria, this process can be successfully combined with a nitrification process. Nitrification is the sequential reaction from ammonium over nitrite to nitrate, carried out by the autotrophic nitrosomonas and nitrobacter bacteria [14]. In the upper portion of the bio-tower, the heterotrophic bacteria outgrow the nitrifying species. As soon as the organic matter in the WW is subsequently decreased below a threshold concentration of approximately 20 mg/l soluble BOD5 (biochemical oxygen demand), the nitrifying bacteria can compete and initiate nitrification [13,15].

Past studies provide good empirical data for setting up combined carbon oxidation and nitrification trickling filters. Choosing the right BOD-loading is of primary importance to achieve proper nitrification, whereas a low BOD-loading generally means good nitrification. The United States Environmental Protection Agency has recommended organic loading rates per unit volume for different filter media and Richards and Parker (1986) have published comparable data on a surface area basis [13,14,15].

According to the Unites States Environmental Protection Agency (USEPA), temperature highly influences the nitrification and must be set in a temperature range between 4 and 45 degree Celsius. Even though there is no consistent data that quantifies the effect of different temperatures on nitrification, satisfactory nitrification occurs in the range from 15 to 25°C. The pH-value of the wastewater should range from 6.5 to 8.0 to ensure process stability [13]. The rate of dissolved oxygen usually does not limit combined nitrification and carbon oxidation processes with natural air draught, as they are typically operating with low organic loading rates. Recirculation of the effluent and therefore increasing hydraulic loading can improve nitrification rates above 50% for moderate or high temperatures. Recirculation has also a quite pronounced effect on removal of organic matter for deep bio filters, as in a bio-tower [15,16,17]. A recent study shows that a bio-tower can remove volatile organic compounds, which would harm humans and the environment [18].

The following study is and continuation of a laboratory study [19] and explores the combined nitrification and organic matter removal measured by Chemical Oxygen demand (COD) from Municipal Residential Sewage (MSR) using a pilot scale Packed Bio-Tower (PBT) System.

2. MATERIALS AND TESTING

2.1 Pilot Set-up of the Packed Bio-tower

As shown in Fig. 1, approximate 950,000 l/d of Municipal Residential Sewage (MRS) from the influent structure is first directed into a Primary Clarifier (PC). After PC treatment, half of this flow is directed to a constructed wetland (CW) for treatment and then discharged into a wet well. A portion of the pre-clarified MRS is forwarded to the packed bio-tower (PBT) in a bypass operation as it enters the influent box (IB). The treated WW from the PBT is discharged into the wet well. From there the CW and PBT effluent is forwarded into the IB. This operation setup assured that the WW used for the PBT pilot system is contained in the WWTP operation.

The treated MRS from the CV and PBT mixes with the pre-clarified MRS in the IB and is then forwarded into a trickling filter (TF). After the TF treatment the treated WW passes through a secondary clarifier and a disinfection unit before it is discharged into a stream [20,21].

2.2 Packed Bio-tower Pilot System Design

The PBT pilot system was designed and installed according to Fig. 3 for testing the removal of compounds contained in the WW. The PBT was installed at the Cleanwater Educational research Facility (CERF) located at the Village of Minoa wastewater treatment plant.

The PBT system consists of a above ground PBT g) and a below ground recirculation tank (RT) a), manufactured from industrial available 48 in (1219 mm) diameter precast concrete sections. The 13 ft (3962 mm) high PBT was manufactured from a 48-in (1219 mm) diameter base with a height of 5 ft (1524 mm) including two precast concrete 48-inch (1219 mm) diameter riser sections with a height of 48-in (1219 mm) The RT was manufactures from a 48 in (1219 mm) diameter base with a height of 5 ft (1524 mm) including a precast flat sab cover with a thickness of 6 in (152 mm).

The PBT system including supporting infrastructure was installed by the Minoa Department of Public works (DPW) and CERF personnel according to local regulations.

The below ground RT a) has a total volume of 1,481 l (375 gal.) and contains 1,200 l (317 gal.) of liquid during operation.

The above ground PBT system tank g) has a total volume of 4,325 l (1142.5 gal.) and contains two sections of Bentwood CF-1900 Polyvinyl chloride (PVC) bacteria growth media f) used for Biological Oxygen Demand (BOD) and Chemical Oxygen Demand COD) reduction and nitrification. The growth media packing (GMP) is ultraviolet light (UV) protected and resistant to rot, fungi, bacteria decay, acids and alkalis commonly found in WW and has a surface area of 48 ft^2/ft^3 (157 m^2/m^3) [12].

The first GMP section is supported 1 ft. (304 mm) above the bottom of the PBT tank g) and has a height of 4 ft (1219 mm) and a specific surface area of 2,411.52 ft^2 (224.04 m^2). The second GMP section is supported 1 ft. (304 mm) above the first growth media section and has a height of 6 ft (1,828 mm) and a specific surface area of 3,617.28 ft^2 (336.05 m^2). The total specific surface area of the PBT GMP is 6,028.80 ft^2 (560.09 m^2). The one-foot gap between the GMP sections and the bottom of the PBT allows aeration through four 90-degree spaced air distributors k) manufactured from 1.5 in (38.1 mm) inside diameter Schedule 40 PVC pipes and fittings.

The liquid in the RT reservoir a) is pumped with a 1 hp (0.75 kW) submersible pump b) at a constant rate of 20 gal/min (75.7 l/min) through a

Schedule 40 (PVC) pipe c) with 1 in (25.4 mm) inside diameter into a 4 in (102 mm) and 1 ft (304 mm) high influent pan d) manufactured from Schedule 40 PVC pipe.

The pretreated MRW entering the TF Influent box is pumped directly at the entrance point with a 3 hp (2.25 kW) submersible pump i) at constant daily feed rate, adjusted with valve j) of 7571 l/d (2000 gal/d), 15,142 l/d (4,000 gal/d) , 30,284 l/d (8000 gal/d), 45,425 l/d (12,000 gal/d), 60,567 l/d (16,000 gal/d), and 90,850 l/d (24,000 gal/d) respectively into the influent pan d) through a Schedule 40 PVC pipe l) with 1.5 in (38.1 mm) inside diameter.

In the influent pan the WW and the recirculation liquid from the underground RT reservoir join and enter the distributer structure e). The distributer then trickles the recirculation liquid onto the GMP shown in Fig. 2. The GMP has alternating corrugated flow channels at a 60° angel allowing 720 vertical distributions per 1 ft (304 mm) [12]. As the liquid flows down through the channels of the GMP it is redistributed and spread throughout the whole GMP.

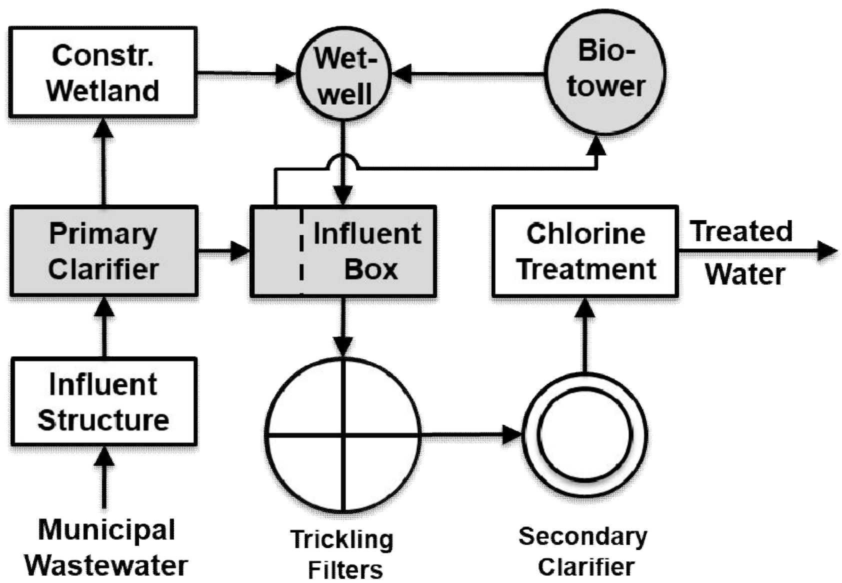

Fig. 1. Packed bio-tower Installation process flow sketch [22]

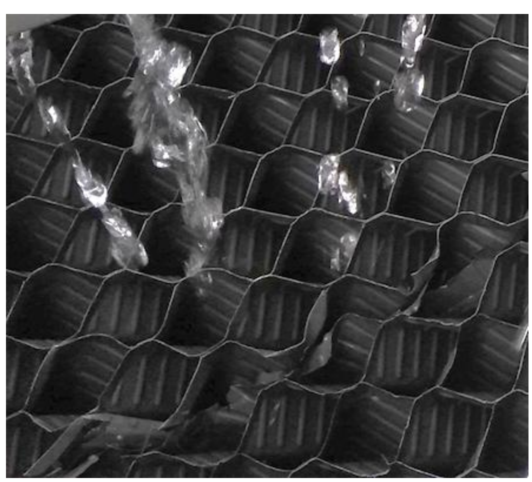

Fig. 2. Growth media packing [23]

After the liquid passes vertically the first 2 ft. (304 mm) of the 6 ft (1828 mm) media section it can be assumed that the liquid has been distributed equally throughout the whole GMP area. The remaining 4 ft. of the second GMP section and the entire 4 ft section of the first GMP section have then an equally WW distribution, assuming the WW has been distributed equally in the first top 2 ft section of the GMP. In addition, to the WW distribution, the CF-1900 growth media allows a uniform horizontal and vertical air flow distribution throughout the GMP provided by the 4 air distributors k), allowing optimal bacteria growth conditions by liquid and air supply [12]. As the WW exits the second GMP packing it is collected on the bottom of the PBT and then transferred back into the RT reservoir by gravity flow through a through a Schedule 40 PVC pipe h) with 4 in (101 mm) inside diameter. From the underground RT reservoir, the excess water is discharged by gravity flow through a through a Schedule 40 PVC pipe m) with 4 in (101 mm) inside diameter into an existing CW wet well structure at the same rate as the feed rate which is adjusted for pump i). The discharged liquid into the CW wet well is then transferred back to the TF IB structure together with the CW effluent water. A Schedule 40, 3 in (76) mm inside diameter PVC drainpipe n) allows to drain the PBT for routine maintenance and repairs. All PVC piping connections to the PBT concrete structure were done by using a Link-Seal® [24] that allows the attachment and sealing of pipes of any size through precast concrete holes.

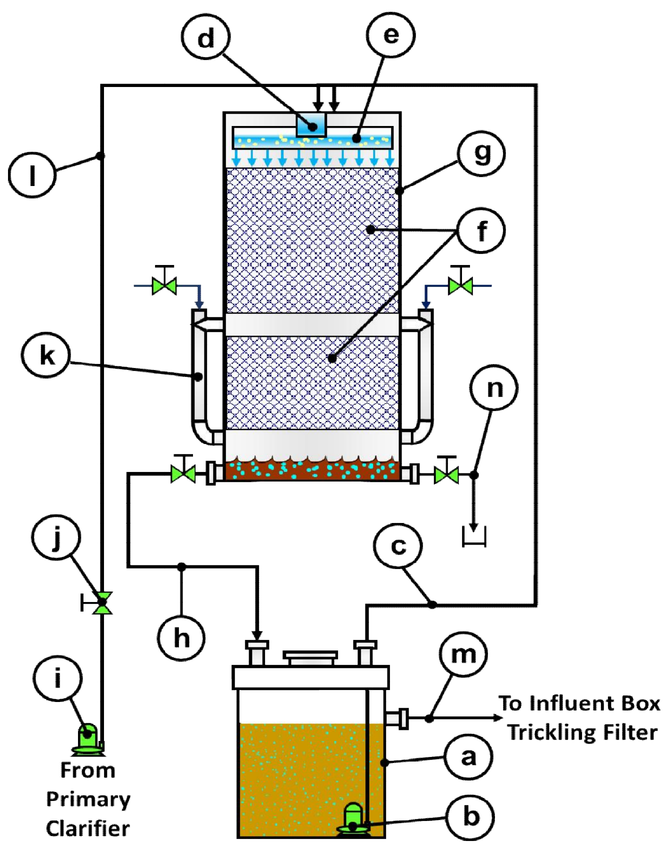

Fig. 3. Packed Bio-Tower Pilot Scale System: a) Reservoir, b) Pump, c) Recirculating Pipe, d) Influent Pan, e) Distributor f) Growth Media, g) Bio-tower Vessel, h) Return Pipe, i) Feed Pump, j) Flow Valve, k) Air Distributer, l) Feed Pipe, m) Discharge Pipe, n) Drain Port [25]

2.3 Packed Bio-tower Start-up

The PBT pilot system was started up using diluted liquid Cow Manure (CM) at approximately 6% solids content from a local farm. 14 l (3.70 gal) of CM was filled into the underground RT a) and diluted with 1000 l (264.2 gal) of pre-clarified MRS. The CM-MRS suspension is then pumped with is pumped with the submersible pump b) at a constant rate of 20 gal/min (75.7 l/min) through pipe c) into the influent pan d). The CM-MRS suspension then enters the distributer and trickles the liquid onto the Brentwood CF-1900 GMP f). As the liquid flows down through the first 2 ft (304 mm) of the top GMP, it is redistributed horizontal and vertical and spread throughout the entire GMP. This resulted in an equal distribution of the suspension through the remaining 4ft (1219 mm) of the top GMP section as well as the entire first (bottom) GMP section. As the suspension exits the second GMP packing it is collected on the bottom of the PBT and then transferred back into the RT reservoir by gravity flow through a through pipe h).

The PBT system continued to operate in this way for 3 weeks. Approximately 280l (74 gal) of the RT volume is added every other day with pre-clarified MRS from the PC using pump i). The discharged RT volume is transferred with pipe m) per gravity flow into the CW wet well. After the 3-week inoculation phase, the initial testing started with a feed rate of 7571 l/day (2,000 gal/day) of pre-clarified MRS.

2.4 Testing and Recording

500 ml Nalgene bottles were used to collect the influent MRS influent and effluent samples. The samples were stored in a cold room at 4.0°C (39.2°F) before, during and between testing.

A HACH DR900 Spectrophotometer and a HACH DRB200 Reactor was used for analyzing the exact concentration of Chemical Oxygen Demand (COD), and Ammonia Nitrogen (NH3-N. The analyzation of the collected samples followed HACH Method 8000 [26] for COD using HACH COD TNT plus Vial Test (3-50.0 mg/L), and HACH Method 10031 [27] for NH3-N using HACH-TNT Reagent Set (0.4-50.0 mg/L).

3. RESULTS AND DISCUSSION

Fig. 4 shows that PBT pilot system feed with MRS at a temperature of 15°C (59.0°F) at a flow rate of 7,571; 15,142; 30,285; 45,925; 60,567; 90,850 l/d (2,000; 4,000; 8,000; 12,000, 16,000; 24,000 gal/min) is able to reduce the Chemical Oxygen Demand (COD) and Nitrogen Ammonia (NH3-N) concentration based on influent MRS flow and the associated Retention Time (Rt) of 230, 115, 57, 38, and 19 min in the reservoir respectively. MRS influent and effluent samples for analyses were taken 2 days after the PBT pilot system flow rate was changed allowing the system to stabilize. MRS influent numbers in Fig. 2 shown different values for the COD and NH3-N due to the daily fluctuation of the incoming MRS at the WWTP at the day of collection [19,20,21].

After the 3 week inoculation phase the PBT was fed with MRS at a flow rate of 7,571 l/d (2,000 gal/d) and a Rt of 230 min, COD concentration dropped from 137.0 mg/l to 50.0 mg/l and NH3-N dropped from 21.9 mg/l to 0.4 mg/l which represents a reduction of 63.4% and 98.3% respectively. The average outside temperature was between 17.8°C (64.0°F) and 23.3°C (74.0°F).

The flow rate of the PBT pilot system was changed to 15,142 l/d (4,000 gal/min) after it operated 6 days at a flow rate of 7,571 l/d (2,000 gal/d). Under the new flow rate the COD and NH3-N concentration dropped 69.2% and 96.1% respectively at a Rt of 115 min., which represents a decrease in COD from 87.0 mg/l to 26.7 mg/l and a NH3-N decrease from 18.6 mg/l to 0.7 mg/l. The average outside temperature was between 10.6°C (51.0°F) and 21.7°C (71.0°F).

The PBT pilot system flow rate was adjusted to 30,285 l/d (8000 gal/d) and a corresponding Rt of 57 min after the system ran for another 6 days. the COD concentration dropped from 115.0 mg/l to 42.0 mg/l representing a 63.5 % reduction. The NH3-N concentration dropped from 30.2 mg/l to 1.8 mg/l representing a 94.0% reduction. The average outside temperature was between 12.8°C (55.0°F) and 18.9°C (66.0°F) during operation.

At 45,925 l/d (12,000 gal/d) of WW flow corresponding to a Rt of 38 min., a reduction of COD concentration from 140.0 mg/l to 37.0 mg/l was measured, representing a 73.6 % reduction. The NH_3-N concentration dropped from 28.8 mg/l to 0.2 mg/l representing a 99.3% reduction. The outside temperature during operation was between 8.9°C (48.0°F) and 23.9°C (75.0°F).

An WW influent flow of 60,567 l/d (16,000 gal/d) with a Rt of 29 min. showed a reduction of COD and NH_3-N concentration from 125.0 mg/l to 19.0 mg/l and 22.6 mg/l to 1.1 mg/l representing a 84.8 % and 95.1 % reduction respectively. The outside operation temperature was between 8.9°C (48.0°F) and 21.7°C (71.0°F).

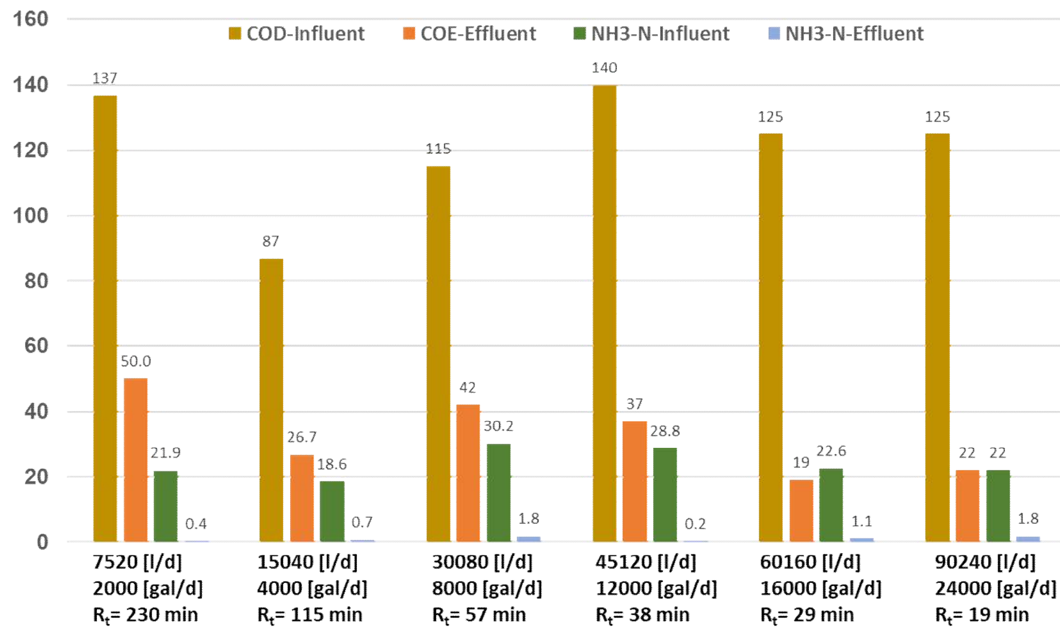

Fig. 4. Packed Bio-Tower Pilot Scale System COD, NH3-N results based on flow and retention time

A flow rate was adjusted to 90,850 l/d 24,000 gal/d) and a Rt of 19 min for the PBT pilot system. The COD concentration dropped from 125.0 mg/l to 22.0 mg/l representing an 82.4% reduction. The NH_3-N concentration dropped from 22.0 mg/l to 1.8 mg/l representing a 91.8% reduction. The average outside temperature was between -3.3°C (26.0°F) and 7.2°C (45.0°F).

Also, as the flow rate was increased, the COD percentage reduction increased from 63.4% for a flow of 7,571 l/d (2,000 gal/d) to 84.8% and 82.4% for flow rates of 60,567 l/d (16,000 gal/d) and 90,850 l/d 24,000 gal/d) respectively. This can be explained with a still increasing bacteria population during the experimental even when the temperatures dropped below 0°C (32°F) while the MRS temperature was at 15.0°C (59.0°F).

NH_3-N reduction was found to be between 98.3% for a flow of 7,571 l/d (2,000 gal/d) and 99.3% for flow rates of 45,925 l/d (12,000 gal/d). At higher flow rated of 60,567 l/d (16,000 gal/d) and 90,850 l/d (24,000 gal/d) the NH_3-N reduction decreased to 95.1% and 91.8% respectively. This can be explained with temperatures as low as 8.9°C (48.0°F) and -3.3°C (26.0°F) during the testing phase, while the MRS temperature was at 15.0°C (59.0°F).

4. CONCLUSION

This study shows that the developed and designed packed bio tower pilot scale system consisting of 1209 mm (4 ft.) diameter and 3962 mm (13 ft.) high bio tower and a 1,481 l (375 gal.) recirculation reservoir, containing Bentwood CF-1900 growth media with a total surface area of 6,028.80 ft² (560.09 m²) and a fixed recirculation rate of 75.7 l/min (20 gal/min) is able to reduce municipal residential sewage with an influent temperature of 15°C (59.0°F). The influent COD value reduction achieved is between 63.4% and 84.8%, whereas the COD influent value varied between 87 mg/l and 140 mg/l. The influent NH_3-N reduction achieved was between 99.8% and 91.8% whereas the influent NH_3-N value was between 28.8 mg/l and 18.6 mg/l at a flow rate between 7,571 l/d (2000 gal/d) and 90,850 l/d (24,000 gal/d).

During outside temperatures below 0°C (32°F) a COD and NH_3-N reduction of 82.4% and 91.8% respectively.

Future study should be focus on higher recirculation and flow rates and upscale of the packed bio-tower system to generate dischargeable treated water or treated water for irrigation purposes based on local and state regulations.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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