Free Water Surface (FWS) System for the Treatment of Domestic Wastewater: A Comparative Study

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In this study, laboratory-scale continuous flow free water surface (FWS) constructed wetland systems were examined for their capacity to remove COD, BOD₅, total nitrogen, NH₄-N, NO₃⁻, NO₂⁻, total phosphorus and orthophosphate. The floating aquatic plant *Lemna minor* L. (Duckweed) was used and the system consisted of planted and unplanted reactors. The system was fed with weak and strong synthetic domestic wastewater. In the weak domestic wastewater treatment, the average removal efficiencies obtained from the evaluation of the system were 60.29 and 57.88 % for COD, 16.78 and 11.73 % for BOD, 31.09 and 13.1 % for total nitrogen, 1.92 and 23.2 % for NO₃⁻, 36.61 % and 17.53 % for total phosphorus and 36.4 and 16 % for orthophosphate in planted and unplanted reactors, respectively. The average NH₄-N concentration was 0.63 mg L⁻¹ in the influent and 0.92 and 0.62 mg L⁻¹ in the effluent from planted and unplanted reactors, respectively. The average NO₂⁻ concentration was 0.51 mg L⁻¹ in the influent and 0.56 and 0.96 mg L⁻¹ in the effluent from planted and unplanted reactors, respectively. In the strong domestic wastewater treatment, the average removal efficiencies obtained from the evaluation of the system were 91.42 and 87.67 % for COD, 79.09 and 69.92 % for BOD, 72 and 63.6 % for total nitrogen, 67.9 and 60.3 % for NH₄-N, 0.47 and 33.3 % for NO₃⁻, 98.28 and 98.76 % for NO₂⁻, 66.62 and 54.79 % for total phosphorus and, 61.82 and 51.7 % for orthophosphate in planted and unplanted reactors, respectively. The results showed that this system has a considerable capacity for treating strong domestic wastewater.

Keywords: Constructed wetland, Duckweed, Free water surface, Wastewater treatment, Ortho phosphate.

INTRODUCTION

Determining the general characteristics and formation of wastewater is necessary to solve the wastewater problem in Turkish cities with the lowest possible cost by using the convenient, available method. The constructed wetland system is a cost-effective natural alternative to conventional wastewater treatment plants. A constructed wetland is defined as an engineered system designed to simulate a natural wetland for waste treatment or other purposes.

A constructed wetland is considered to be a complex bioreactor. A number of physical, chemical and biological processes with microbial communities, emergent plants, soil and sediments accumulated in the lower layer occur in the systems^{1,2}.

The advantages of using the water plant *Lemna minor* L. are its high production rate, ease of manual harvesting from the surface, high protein content, low fiber content, ability to survive dry conditions, preferential ammonia uptake, ability to metabolize ammonia directly from the water and high protein content. All of these factors make *L. minor* as cost-effective for recycling as fertilizer and animal fodder. However,

L. minor grows only in the upper water surface layer where pollutant removal mainly occurs³.

L. minor species have shown characteristics that make duckweed-based systems (DBS) very attractive not only for wastewater treatment but also for nutrient recovery, which is due to the rapid multiplication of duckweed and the high protein content of its biomass (30 ± 49) % of dry weight^{2,4}.

However, in spite of the number of duckweed studies that have been reported, the system is still largely unknown from an engineering perspective. The majority of these duckweed studies were carried out using batch mode of operation consequently there is no clear information on optimal operating conditions for flow-through duckweed-based wastewater treatment systems. Therefore, the objective of the study was to evaluate the effectiveness of a wastewater treatment system that uses *L. minor* in free surface flow wetlands. To this end, strong and weak synthetic domestic wastewaters were applied to the system to examine COD, BOD₅, total nitrogen, NH₄-N, NO₃⁻, NO₂⁻, total phosphorus and orthophosphate (OP) removal. The results obtained will yield insights about the actual application of the system and it would be necessary to use the data given in the literature in the design.

EXPERIMENTAL

Experimental set-up: A laboratory-scale wastewater treatment wetland was constructed and operated at the Uludag University Department of Environmental Engineering in Turkey. The system consists of two reactors: one in which *Lemna minor* L. was grown, and the other was without *L. minor* (control reactor). The reactors were formed with dimensions of 40 × 30 × 16 cm. The surface area of each reactor was 1200 cm². The water depth of the reactors was 6 cm. Light was supplied by a special lamp (OSRAM Day Light 18 W) during day times. The lamps were kept on during the 16 h daytime and were turned off by a timer for the remaining 8 h.

The treatment system operated with synthetic domestic wastewater⁵. The primary treatment was applied to weak domestic wastewater (COD-250 mg L⁻¹) and then strong domestic wastewater (COD-500 mg L⁻¹)⁶. The treatment system was built with a continuous flow. *L. minor* only grew at the reactor's surface and therefore did not disturb the flow regime and allowed optimal settling conditions. According to preliminary studies, the average hydraulic retention time (HRT) in each reactor was 3 days. Samples for water quality analysis were collected from the influent and effluent of the reactors at 3-day intervals.

Analytical methods: The pH, temperature, electrical conductivity (EC_{25 °C}), chemical oxygen demand (COD), five-days biochemical oxygen demand (BOD₅), total nitrogen (TN), ammonium-nitrogen (NH₄-N), nitrate (NO₃⁻), nitrite (NO₂⁻), total phosphorus (TP) and orthophosphate (OP) were determined in the influent and effluent of the reactors. The pH, temperature and EC were measured using a Consort multi-parameter analyzer (Consort, Belgium). The COD and BOD₅ analyses were performed according to standard methods⁷. Other analyses were conducted using measurement kits and analyzed using a Hach-Lange DR 5000 (Gmbh, Germany).

RESULTS AND DISCUSSION

In the weak domestic wastewater treatment, the pH values were 8.02 for the influent, 8.11 for the planted reactor and 8.28 for the unplanted reactor. For bacteriological removal of nutrients, the ideal pH values are over 6.6 for nitrification and

between 6.5 and 9.5 for denitrification⁸. The pH values measured in the system provide favorable conditions for nitrification and denitrification. In the strong wastewater treatment system, the pH values were 7.99 for the influent, 8.44 for the planted reactor and 8.29 for the unplanted reactor. Observed algal growth was thought to be an effective factor for measuring an effluent pH value that was higher than the influent value. Photosynthesis and respiration are both dependent on sunlight. Respiration events are very low compared to photosynthesis. The process on the surface of the system results in CO₂ consumption and O₂ production⁹. The increase of pH is the natural result of the administration of oxygen and the response to carbon dioxide removal from the system. As a result, algal growth in the free surface flow system leads to increases in pH. The system is open to the atmosphere, which is also a contributing factor in the activity of algae.

In the weak domestic wastewater treatment, for both planted and unplanted reactors, the temperature was 22.1 °C in the influent and 25.4 °C in the effluent. In the strong wastewater treatment, a temperature of 24.9 °C was observed in the influent and 26.4 °C in the effluent. Although there are still differing opinions on the temperature requirements for duckweed growth, the production of duckweed will decrease when the temperature is less than 17 °C or greater than 35 °C¹⁰. This system satisfies the optimum temperature conditions for the growth of *L. minor*.

In the weak domestic wastewater treatment, the EC values were 708 µS/cm for the influent, 1215 µS/cm for the planted reactor and 847 µS/cm for the unplanted reactor. In the strong wastewater treatment system, the EC values were 721 µS/cm for the influent, 1238 µS/cm for the planted reactor and 828 µS/cm for the unplanted reactor. The results of high electrical conductivity show that a wide range of mineral ions exists in wastewater¹¹.

Chemical oxygen demand (COD) and biochemical oxygen demand (BOD₅): Fig. 1 shows the removal efficiencies and COD concentrations in the influent and the effluent of the planted and unplanted reactors treated with weak and strong domestic wastewaters. The average COD concentrations were 250 mg L⁻¹ in the influent and 99 and 105 mg L⁻¹ in the effluent

Fig. 1. Removal efficiencies and COD concentrations in the planted and unplanted reactors treated with (a) weak domestic wastewater and (b) strong domestic wastewater

of the planted and unplanted reactors, respectively, for the weak domestic wastewater treatment, whereas concentrations of 500 mg L⁻¹ in the influent and 42 and 61 mg L⁻¹ in the effluent of the planted and unplanted reactors, respectively, were observed for the strong domestic wastewater treatment. The average COD removal efficiencies in the weak domestic wastewater treatment for the planted and unplanted reactors were 60.29 and 57.88 %, respectively. In the strong wastewater treatment, the removal efficiencies were higher. The removal efficiencies of the planted and unplanted reactors were 91.42 and 87.67 %, respectively. Mandy's experiment demonstrated that DWWT (Duckweed-based wastewater treatment) reactors can tolerate maximum influent COD concentrations from 300 to 500 mg/L¹³. These results overlapped with Mandy's experiment.

Fig. 2 shows the BOD₅ concentrations in the influent and effluent of the planted and unplanted reactors treated with weak and strong wastewaters. The average BOD concentrations were 119.28 mg L⁻¹ in the influent and 71.89 mg L⁻¹ and 78.82 mg L⁻¹ in the effluent of the planted and unplanted reactors respectively. For the weak domestic wastewater treatment, whereas the concentrations were 205 mg L⁻¹ in the influent and 42.85 and 61.66 mg L⁻¹ in the effluent of the planted and unplanted reactors, respectively, for the strong domestic wastewater treatment. The average BOD₅ removal efficiencies in the weak domestic wastewater treatment for the planted and unplanted reactors were 16.78 and 11.73 %, respectively. In the strong wastewater treatment, the removal efficiencies for the planted and unplanted reactors were 79.09 and 69.92 %, respectively.

Duckweed-covered systems can attain BOD and COD removal rates between 50 and 95 %^{2,12-14}. The role of duckweed in the removal of organic material has been the subject of controversy. Indirect effects, such as the provision of a surface and substrate for bacterial growth, change of the physico-chemical environment in the water, and the possibility of direct removal of small organic compounds by heterotrophic growth, were supposed^{15,16}. A dense cover of duckweed on the water surface has been suggested to inhibit both oxygen entering the water by diffusion from the air and photosynthetic production of oxygen by phytoplankton because of poor light penetration. It was stated that BOD removal could decrease in

ponds covered with duckweed because of the limited oxygen transfer into the water¹², however, it was found that the water column in a duckweed-covered sewage lagoon system with a low BOD load always remained aerobic¹⁷. Even shallow duckweed-covered batch-systems containing 100 % wastewater contained significantly more oxygen than the uncovered controls¹⁴. This most likely occurred because of oxygen leaking from the roots in these shallow containers, which maximized the ratio of duckweed surface area to wastewater volume.

Nutrient removal: High levels of N and P are known to cause the enrichment of our natural water bodies and cause eutrophication. Nutrients are generally (N, P) accumulated in the plant biomass and are removed through harvesting¹⁸. Nitrogen and P losses can be attributed to uptake by duckweed, its attached biofilm, the biofilm attached to the walls of the systems and sedimentation of particulate N and P¹⁴.

Total nitrogen (TN): Nitrogen (N) is a major component of municipal wastewater, stormwater runoff from urban and agricultural lands and wastewater from various types of industrial processes¹⁸. Various forms of nitrogen can exist in water, such as particulate and dissolved organic N, ammonium, nitrite and nitrate. These various forms can transform and serve as sources or end products for each other within the nitrogen cycle¹⁹. For this reason, only total nitrogen is considered in this study. Although various processes can affect the nitrogen components, denitrification is the only major net, high-term removal process for total nitrogen.

Fig. 3 shows the removal efficiencies and total nitrogen concentrations in the influent and effluent of the planted and unplanted reactors treated with weak and strong domestic wastewaters. The average total nitrogen concentrations were 22 mg L⁻¹ in the influent and 15.1 and 19.1 mg L⁻¹ in the effluent of the planted and unplanted reactors, respectively, for the weak domestic wastewater treatment, whereas they were 49.85 mg L⁻¹ in the influent and 15.16 and 19.1 mg L⁻¹ in the effluent of the planted and unplanted reactors, respectively, for the strong domestic wastewater treatment. The average total nitrogen removal efficiencies in the weak domestic wastewater treatment for the planted and unplanted reactors were 31.09 and 13.1 %, respectively. In the strong wastewater treatment, the removal

Fig. 2. Removal efficiencies and BOD concentrations in the planted and unplanted reactors treated with (a) weak domestic wastewater and (b) strong domestic wastewater

Fig. 3. Removal efficiencies and total nitrogen concentrations in the planted and unplanted reactors treated with (a) weak domestic wastewater and (b) strong domestic wastewater

efficiencies were higher; the planted and unplanted reactors were 72 and 63.6 %, respectively.

Substantial removal of N may occur through the settling of N-containing particulate matter in the wetland inflow. In addition, because N is an essential plant nutrient, it can be removed through the uptake of ammonium or nitrate by plants and stored in an organic form in the wetland vegetation²⁰. Because nitrogen removal is affected by such factors as hydraulic loading rate, nitrogen/carbon ratio and short retention time, the amount of removal may vary²¹. The *L. minor* used in the system is naturally rich in nitrogen and phosphorus. Therefore, it is limited in adsorbing additional nitrogen and phosphorus¹⁰. The results obtained showed that weak domestic wastewater applications remain limited, whereas the strong domestic wastewater application appears to be capable of efficient removal.

Ammonia nitrogen (NH₄-N): Ammonium ions (NH₄) are the most available nitrogen source, and duckweed can continue to grow even with low levels of nitrogen, depending on the temperature. However, the level of ammoniain the water proportionally influences the amount of crude protein in plants. Toxic effects on the duckweed can occur when the amount of

nitrogen in the water reaches value over the optimal levels. Duckweed may be a good biological filter when a sufficient intensity is held in²².

Nitrogen in the an aerobic effluent is mainly present as ammonium. This is an advantage because duckweed shows a preferential uptake of ammonium over other sources of nitrogen¹⁴. Despite being the preferred source of N for duckweed plants, ammonium may become one of the parameters that inhibit the growth of duckweed in wastewater^{2,4}.

The average NH₄-N concentrations in the weak domestic wastewater treatment were 0.63 mg L⁻¹ in the influent and 0.92 and 0.62 mg L⁻¹ in the effluent of the planted and unplanted reactors, respectively (Fig. 4).

Similar to organic matter removal, algae are also effective at nutrient removal. Some of the nitrogen is removed from the environment by the nitrification-denitrification mechanism and some of it is removed by the algal cells. The increase of the nitrate concentration in the control reactor depends on the development of algae, while the ammonium concentrations decrease.

The average NH₄-N concentrations were 6.18 mg L⁻¹ in the influent and 1.96 and 2.48 mg L⁻¹ in the effluent of the

Fig. 4. Removal efficiencies and NH₄-N concentrations in the planted and unplanted reactors treated with (a) weak domestic wastewater and (b) strong domestic wastewater

planted and unplanted reactors, respectively, for the strong domestic wastewater treatment. The average $\text{NH}_4\text{-N}$ removal efficiencies for the planted and unplanted reactors were 67.9 and 60.3 %, respectively (Fig. 4).

Nitrate and nitrite (NO_3^- and NO_2^-): Fig. 5 and 6 show the removal efficiencies and NO_3^- and NO_2^- concentrations in the influent and effluent of the planted and unplanted reactors treated with weak and strong wastewaters. The average NO_3^- concentrations were 0.51 mg L^{-1} in the influent and 0.49 and 0.31 mg L^{-1} in the effluent of the planted and unplanted reactors, respectively, for the weak domestic wastewater treatment and 0.90 mg L^{-1} in the influent and 0.47 and 0.60 mg L^{-1} in the effluent of the planted and unplanted reactors, respectively, for the strong domestic wastewater treatment. The average NO_3^- removal efficiencies in the weak domestic wastewater treatment were 1.92 and 23.2 % for the planted and unplanted reactors, respectively. In the strong wastewater treatment, the removal efficiencies were higher; 47 and 33.3 % for the planted and unplanted reactors, respectively. The average NO_2^- concentrations were 0.51 mg L^{-1} in the influent and 0.56 and 0.96 mg L^{-1} in the effluent of the planted and unplanted reactors, respectively, for the weak domestic wastewater treatment, whereas

they were 0.8 mg L^{-1} in the influent and 0.02 and 0.006 mg L^{-1} in the effluent of the planted and unplanted reactors, respectively, for the strong domestic wastewater treatment.

Nitrate formed as a result of nitrification is spent on the transition denitrification and the plant body²³. Duckweed is effective at nitrogen removal. In the unplanted reactor, a decrease was observed after the initial increase of nitrate concentration. This result is explained by denitrification.

Total phosphorus (TP): Phosphorus (P), like N, is a major plant nutrient; hence, the addition of P to the environment often contributes to the eutrophication of lakes. Phosphorus removal from aquatic macrophyte systems is caused by plant uptake, microbial immobilization into detritus plant tissue, retention by underlying sediments and precipitation in the water column²⁴. Phosphorus in wastewater may be present as *orthophosphate*, *polyphosphate* or *orthophosphate*²⁵, which is affected by biotransformation, sorption, settling, sedimentation, mineralization and hydrolysis¹⁹.

The rate of phosphorus removal is site-specific and depends on the wastewater characteristics, type of aquatic plant, harvest frequency and climate. The typical removal rate varies between 30-50 %²⁶. Phosphorus in water may be removed by mechanisms

Fig. 5. Removal efficiencies and NO_3^- concentrations in the planted and unplanted reactors treated with (a) weak domestic wastewater and (b) strong domestic wastewater

Fig. 6. Removal efficiencies and NO_2^- concentrations in the planted and unplanted reactors treated with (a) weak domestic wastewater and (b) strong domestic wastewater

such as use in plant metabolism, adsorption on the particles and organic materials. Duckweeds use phosphorus as required for its growth. Vegetative use in the free surface flow planted reactor, which occurs in addition to other mechanisms, indicates more phosphorus removal than the unplanted reactor.

The average total phosphorus concentrations were 4.22 mg L⁻¹ in the influent and 2.67 and 3.48 mg L⁻¹ in the effluent of the planted and unplanted reactors, respectively, for the weak domestic wastewater treatment, whereas they were 8.03 mg L⁻¹ in the influent and 2.68 and 3.63 mg L⁻¹ in the effluent of the planted and unplanted reactors, respectively, for the strong domestic wastewater treatment. The average total phosphorus removal efficiencies in the weak domestic wastewater treatment for the planted and unplanted reactors were 36.61 and 17.53 %, respectively. In the strong wastewater treatment, the removal efficiencies were 66.62 and 54.79 % for the planted and unplanted reactors, respectively (Fig. 7).

It was stated that *Ceratophyllum sp.* and *Lemna sp.* are the plants that uptake the most nutrients and the greatest concentrations of phosphorus are concentrated in the roots and rhizome parts of these plants²⁷. It was reported that *L. minor* removes over 20 % of phosphorus and is easy to harvest²⁸. In Turkey, studies on *L. minor* and phosphorus removal have

shown varying treatment efficiencies: 3–78 % by Zeren *et al.*²⁹; 27–63 % by³¹; 11 %, yield up to 90, by Sarialioglu²⁶. In agreement between the results of the aforementioned studies and this study, the most appropriate type of treatment was found to be *L. minor* in terms of efficiency.

Orthophosphate (OP): Orthophosphate is the most easily removed of the three types of phosphorus. Orthophosphate is the predominant inorganic form of P in surface waters. It's readily accumulates in wetland vegetation and soils as the result of biological uptake and chemical bonding²⁰. The main orthophosphate removal mechanism in DWWT is plant uptake.

Fig. 8 shows the removal efficiencies and orthophosphate concentrations in the influent and effluent of the planted and unplanted reactors treated with weak and strong domestic wastewaters. The average orthophosphate concentrations were 2.5 mg L⁻¹ in the influent and 1.59 and 2.46 mg L⁻¹ in the effluent of the planted and unplanted reactors, respectively, for the weak domestic wastewater treatment, whereas they were 7.02 mg L⁻¹ for the influent and 2.68 and 3.39 mg L⁻¹ in the effluent of the planted and unplanted reactors, respectively, for the strong domestic wastewater treatment³⁰. The average orthophosphate removal efficiencies in the weak domestic wastewater treatment for the planted and unplanted reactors

Fig. 7. Removal efficiencies and total phosphorus concentrations in the planted and unplanted reactors treated with (a) weak domestic wastewater and (b) strong domestic wastewater

Fig. 8. Removal efficiencies and orthophosphate concentrations in the planted and unplanted reactors treated with (a) weak domestic wastewater and (b) strong domestic wastewater

were 36.4 and 16 %, respectively. In the strong wastewater treatment, the removal efficiencies were higher; 61.82 and 51.7 % for the planted and unplanted reactors, respectively.

Orthophosphate is the dominant form of phosphorus in surface waters. This form of phosphorus accumulates in wetland plants and finds biological purpose in soil and chemical bonds. Low pH wetlands consist of iron and aluminum phosphate minerals and in response, high pH wetlands with calcium phosphate minerals have occurred. This is the basic phosphorus removal mechanism in wetlands³¹.

The orthophosphate removal efficiencies of the experimental study compare well with other experimental studies³²⁻³⁴.

Conclusion

It was observed that the measured effluent temperatures are suitable for the development of *L. minor*. During the study period, the pH values of the system provided favorable conditions for nitrification and denitrification processes. In this study, based on the data obtained from the free surface flow reactor system, the comparison of the planted and unplanted reactors showed *L. minor's* effective role in the removal of total nitrogen in parallel with the literature. More efficient NH₄-N removal was obtained in the strong wastewater application than in the weak wastewater application. In addition, high nitrate and nitrite removal was observed in the strong wastewater application. In the control reactor, the nitrate concentration first decreases and then increased. This situation is explained by the denitrification process. The nitrate and nitrite increases in the control reactor show the development of algae and as a result, nitrogen, nitrate and ammonium assimilation was begun. Duckweeds use phosphorus for their growth. In addition to other mechanisms, the vegetative use occurring in the free surface flow system caused more phosphorus removal in the planted reactor for weak and strong wastewater applications. As seen in this study, orthophosphate removal was effective in the planted reactor. The orthophosphate removal mechanism suggests that the formation of calcium phosphate minerals occurred.

When data obtained from the application of a strong domestic wastewater on free surface flow system evaluated with "Turkey Water Pollution Control Regulation" which brought to the discharge of natural treatment systems; BOD, COD, TSS and pH values provides the discharge standards.

In parallel with the literature, in weak domestic wastewater applications, the achievement of low BOD removal in the water can be explained by the limited oxygen transfer. The calculated removal efficiencies were consistent during the experimental period. With regards to the removal efficiencies, the free water surface system was applicable when it was used to treat strong domestic wastewater.

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