Article

Design of floating wetland for treatment of municipal wastewater and environmental assessment using emergy technique

Arfan Arshad[1], **Sikandar Ali**[1], **Shahbaz Nasir Khan**[2], **Muhammad Riaz**[1], **Sufyan Arshad**[3], **Ch. Arslan**[4], **Shafqat Noor**[1], **Muhammad Mohsin Waqas**[1]

[1]Department of Irrigation and Drainage, Faculty of Agricultural Engineering, University of Agriculture, Faisalabad, Pakistan

[2]Doctoral Research Assistant Bioproducts, Science and Engineering Laboratory, Washington State University, Tri-Cities, 2710, Crimson Way, Richland, Wa-99354, United States of America

[3]Department of Chemistry, University of Agriculture, Faisalabad, Pakistan

[4]Department of Structures and Environmental Engineering, University of Agriculture, Faisalabad, Pakistan

E-mail: arfanarshad52@gmail.com

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Abstract

The magnitude of wastewater has been increased due to rapid increase in population and industrialization in Faisalabad, Pakistan. Wastewater is being discharged directly into fresh water bodies without proper treatment due to insufficient treatment facilities which give rise to health problems. Wastewater treatment by chemical and thermal techniques is costly because these techniques rely on the use of chemicals and electricity. This study was planned to replace the chemical and thermal techniques with a floating wetland system which is an environmental protective technique for wastewater treatment. First order plug flow kinetic model was applied to calculate the surface area of wetland. This study also incorporates calculation of the emergy associated with the production of treated wastewater. From the whole calculations, it was observed that the total emergy of floating wetland 3.24×10^{17} sej/year is less as compared to conventional effluent treatment plant having emergy 5.71×10^{17} sej/year. The analysis indicates that use of floating wetland system can reduce cost as well as pressure on the local environment by providing option to reuse the wastewater after treatment. Results indicate that cost-benefit ratio was 0.88 which shows saving 3.7×10^{17} sej/year of surface water resources by using treated wastewater for agricultural production. Wastewater treatment by floating wetland system is environmental friendly, cost effective and energy efficient as compared to effluent treatment system. The study suggests that wetland system should be recommended for wastewater treatment in areas where large quantity of wastewater is generated from municipal sector.

Keywords first order plug flow kinetic model; floating wetland; retention period; hydraulic loading rate; emergy analysis.

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1 Introduction

Out of the available water resources, 97% of water is present in the oceans, 2% polar ice caps and 1% in fresh water lakes. Pakistan is facing serious water crisis due to gradual decrease in available surface water supplies which ultimately affect agricultural productivity across the country. Therefore, need of the time is to explore every possible resource for better management of water resources in all over the Pakistan. Wastewater treatment is one of the cheap and effective method to supplement irrigation water supplies. Faisalabad city has enormous number of industries which generate a massive amount of wastewater. Wastewater from municipal sector is being discharged into fresh water bodies like river and streams which deteriorates the quality of the surface water (Nayyef et al., 2012). Moreover, seepage from unlined wastewater channels in Faisalabad leads to contamination of groundwater. With the passage of time, water bodies have been considered as sites for disposal of domestic and industrial waste water which requires proper treatment (Bio-Wise, 2003; Aboulroos et al., 2006). Wastewater is the combination of water and unwanted products which come from domestic and industrial sectors. Treatment of wastewater before its disposal is very important because it adds nutrients, heavy metals and other contaminants to the fresh water bodies (Su et al., 2014). As wastewater includes enough amount of nutrients, therefore wastewater after proper treatment can also be used for bio-fertigation of agricultural crops. The use of wastewater for agricultural production is one of the alternate ways for irrigation (Khurana et al., 2012). Reuse of wastewater as bio-fertigation simultaneously solves the issues related to water shortage and wastewater disposal (Hargreaves et al., 2008).

Several techniques are being used for wastewater treatment across the world such as chemical precipitation, lime coagulation, ion exchange, aeration, chemical oxidation, electrolysis, ultra-filtration, and chlorination but all the techniques are expensive (Hargreaves et al., 2011; Mishra and Tripathi, 2016). Wastewater treatment by chemical methods generates the huge amount of slurry which increases the handling cost (Rakhshaee et al., 2009). Numerous natural systems like natural ponds and wetlands help to treat the wastewater in a controlled, environmentally protective and cost-effective way. These systems show high efficiency due to simple operation and maintenance (Rakhshaee et al., 2014). Constructed wetland is a well-established environmental protective technique for wastewater treatment. There are two basic types of constructed wetland system, one is surface flow constructed wetland and the second is subsurface flow constructed wetland system. These systems use soil and aquatic plants to remove contaminants from wastewater (Baskar et al., 2008; Borkar et al., 2011). In a constructed wetland system, several physical, chemical, biological and biochemical processes take part to remove the containments from wastewater (Hargreaves et al., 2008; Schroder et al., 2007; Sayadi et al., 2012; UN-Habitat, 2008).

This study was planned to design a floating wetland system for treatment of municipal wastewater. Constructed floating wetland is an engineered system which makes use of the aquatic plants and natural processes to remove the contaminants from wastewater (Sandeep et al., 2005; Oladipupo et al., 2015). The floating wetland system works on the principle of phytoremediation in which aquatic plants extracts the contaminants through their roots from wastewater (Lasat, 2000; Pawan et al., 2015). This system works like natural method in which only a single plant can remove the multi-pollutants from wastewater. Many floating plants can be used in the wetland for removal of contaminants, but plant selection criteria depends on the climate conditions, nature of wastewater and nutrients to be removed. In this study emergy technique was also applied to compare a constructed floating wetland system with a conventional effluent treatment system. The main objectives of this study were (1) to evaluate all environmental work that sustains a treatment system; (2) to assess the environmental impacts of treatment systems, and (3) to document the economic analysis of treatment system.

2 Study Area and Methodology

2.1 Study area

This study was planned to construct a floating wetland system in Faisalabad city near University of Agriculture, Faisalabad, along the sub channel of Paharang drain (Fig. 1). Faisalabad city is situated in the Rechna Doab with total geographic area of 157 km^2. Faisalabad is located at latitude 31^o 26’, longitude 71^o 06’ with an average elevation of 184.4 m from mean sea level. In summer, the mean maximum and minimum temperature was recorded as 39 °C and 27 °C, respectively. In winter season it reaches at maximum temperature of 17 °C. The average annual rainfall is about 300 mm. In 19th Century British developed the Faisalabad as an Agricultural Market Town (Mandi Town). Faisalabad city is an industrial hub of Pakistan and well-known for its textile products. Paharang drain is the main drain which passes through the large industrial area of Faisalabad, carrying municipal wastewater and finally discharges to River Chenab. The average inflow of Paharang drain is about 3.7×105 m^3/day. Nosheen et al. (2000) reported that huge quantity of wastewater in the Paharang drain contributes from industrial sectors.

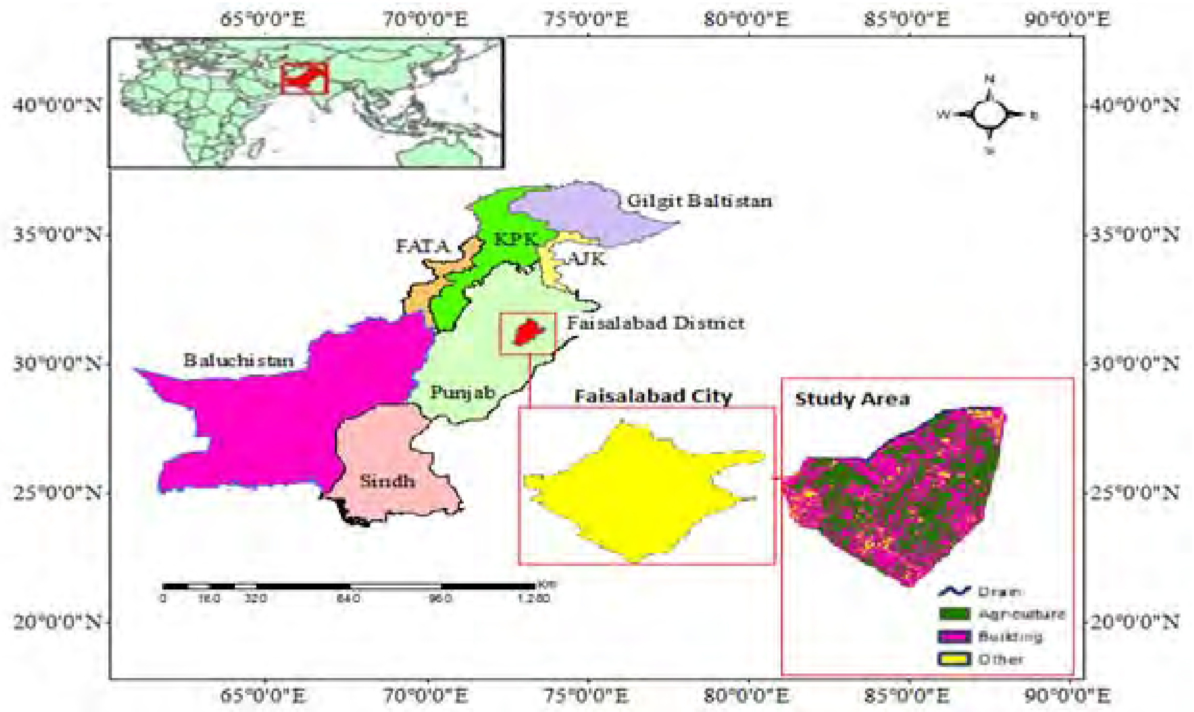

Fig. 1 Site map.

2.2 Description of conventional wastewater treatment system

Existing conventional wastewater treatment plant under this study located in Kohinoor Mill Limited (Pakistan). It collects the wastewater from different processing units of the industry. Wastewater after treatment is directly discharged into the wastewater channel. This treatment plant contains screening unit, Greece oil tanks, flow equalization tank, cooling tower flash chamber, primary clarifier, aeration tank, secondary clarifier and sludge holding tank (Fig. 2). The treatment efficiency of several units of this plant is very low due to high maintenance and chemicals cost which are used for treatment. Such types of problems can be solved if we replace conventional effluent treatment plant with natural/cost effective wetland treatment system (Fig. 3).

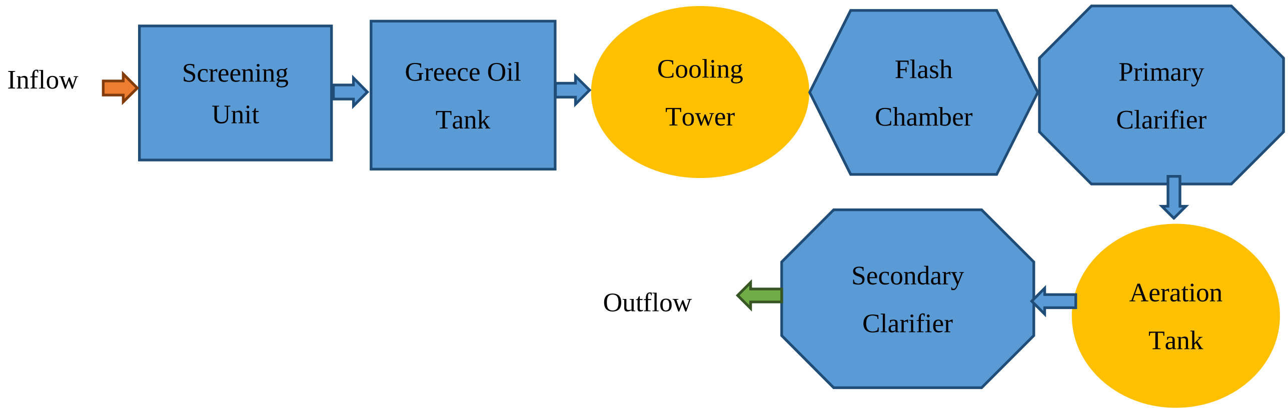

Fig. 2 Effluent treatment system (conventional treatment plant).

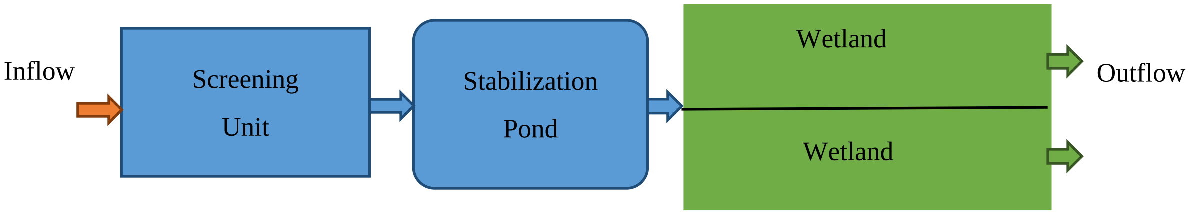

Fig. 3 Floating wetland system.

2.3 Floating wetland system: an overview

Constructed floating wetland is an engineered system which makes use of the aquatic plants and natural processes to remove the contaminants from wastewater (Sandeep et al., 2005). Treatment of wastewater in floating wetland system occurs by physical, biological and chemical process. In physical process, plants hinder the path of water and decrease its velocity which creates a better situation for sedimentation of heavy particles and suspended solids. In chemical process, plants treat the wastewater by killing the pathogens through antibiotic substances which generates from the root of the plants. Biological treatment of wastewater in wetland occurs with six biological processes which are photosynthesis, respiration, fermentation, nitrification, denitrification, and phosphorus removal. Wetland system works on the principle of phytoremediation in which aquatic plants uptake contaminants from wastewater through their roots (Lasat, 2000; Pawan et al., 2015). Removal rate of contaminants from wastewater depends on numerous biochemical processes in plants, i.e., phytoextraction, phytostabilization, and phyto–volatilation (Chibuike et al., 2014). Free floating and submerged plants have capability to remove contaminants from wastewater (Kivaisi, 2001). Due to high capability for nutrient removal from wastewater, water lettuce plant has been used in many studies. These plants have been reported to double their biomass in 6 days.

Water lettuce plant: The water lettuce has been used in many studies for removal of contaminants from wastewater. Treatment of wastewater in the floating wetland with water lettuce plants is well reported by many researchers (Pawan et al., 2015; Piyush et al., 2012; Miretzky et al., 2004; Espinoza et al., 2005; Maine et al., 2004). These plants uptake heavy metals such as As, Cr, Pb, Ag, Cd, Cu, Hg, Ni and Zn from wastewater (Miretzky et al., 2004). The water lettuce plant removes heavy metals from wastewater in two steps. The first step involves the adsorption, chelation, and ion exchange. In adsorption, the magnitude of heavy metals uptake is variable for different species of Plant. The second stage comprises of heavy metal precipitation induced by the roots of water lettuce plant (Tripathi et al., 2010). Water lettuce plants are the natural super accumulator of heavy metals and these plants also treat the wastewater by rhizofiltration process (Ranjana et al., 2012).

2.4 Design criteria for floating wetland

First order plug flow kinetic model was applied to calculate the surface area of wetland as already applied by different researchers (Reed et al., 1995; Kadlec and Knight, 1996a, b). In this study, Reed method was used to calculate the area of floating wetland, inflow concentration, influent/effluent Biochemical Oxygen Demand (BOD) concentration, temperature constant, porosity and water depth were selected as design parameters.

$$A = \frac{\mathrm{Q}\ln\left(\frac{\mathrm{Ci}}{\mathrm{Co}}\right)}{\mathrm{KT}\times\mathrm{d}\times\mathrm{nv}} \quad (1)$$

$$\mathrm{KT} = \mathrm{K20}\times\Theta^{\,(\mathrm{Tw}-20)} \quad (2)$$

where A is the surface area of wetland (m^2), Q is the quantity of inflow (m^3/day), Ci the influent concentration of BOD (mg/l), Co is the effluent concentration of BOD (mg/l), d is the depth of water (m), nv is porosity which is related to that part of wetland which is not occupied by plants, K_T is the temperature constant (day^{-1}), K_{20} is the temperature constant at temperature 20°C (day^{-1}), Tw is the temperature of wetland (°C) and Θ is the temperature coefficient for rate constant and its value depends on nature of pollutants to be removed. The values of K_{20} and Θ depends on the nature of pollutants. If we consider the BOD removal then K_{20} = 0.678 day^{-1} and the value of temperature coefficient is 1.06 while for NH_4^+ removal K_{20} = 0.218 day^{-1} and Θ= 1.048. The time to retain the wastewater and hydraulic loading rate in floating wetland can be calculated by using equation (3) & (4) respectively.

$$t = \frac{\mathrm{A}\times\mathrm{d}\times\mathrm{nv}}{\mathrm{Q}} \quad (3)$$

$$\mathrm{HLR} = \mathrm{Q/A} \quad (4)$$

where t is the time to retain wastewater in the wetland (day), A is the area of wetland (m^2); d represents the depth of water in the wetland (0.5m in this study); n is the porosity (typically 75%), Q is the average inflow (m^3/d) and HLR is the hydraulic loading rate (cm/day or m/day).BOD removal efficiency of the whole system is calculated by formula (5) and the results are in (Table 2).

$$\text{Removal Efficiency} = \left\{1-\frac{\mathrm{Ce}}{\mathrm{Co}}\right\}\times 100\% \quad (5)$$

The basic design parameters include the area of wetland, loading rate, retention time, plant type, and temperature. Each parameter has its own significance in this system. Plants physically hold up the pathway of wastewater enhancing sedimentation of suspended solids. Wetland temperature is an important design parameter because BOD and various other contaminant removal depend on temperature. Aquatic plants are major hyper accumulator for pollutant removal and their growth rate also depends on the temperature. As the plants avail suitable temperature they grow more quickly and absorb more contaminants from wastewater. The meteorological data for sizing the wastewater treatment plant was collected from Agro-Met Bulletin, Agricultural Metrological Cell, Department of Crop Psychology, University of Agriculture Faisalabad.

Table 1 Data used for sizing the wastewater treatment plant.

Parameters	Value	Unit
Average daily inflow (Q)	2000	m^3/day
Average BOD of influent	240	mg/l
Required BOD	60	mg/l

3 Results and Discussion

3.1 Calculation of wetland design parameters

In our study, following parameters were used for sizing of floating wetland (Table 1),

Q = 2000 m^3/day C_i= 240 mg/l C_0=60 mg/l

d = 0.5m nv = 75% T_w=11.7 ^oC

$K_T=K_{20}\times \Theta^{(T_w-20)}$

$K_T=0.687\times (1.06)^{(11.7-20)} = 0.4180$ /day

$$A = \frac{Q\ln\left(\frac{Ci}{Co}\right)}{KT\times d\times nv} = \frac{2000\ln\left(\frac{240}{60}\right)}{0.418\times 0.5\times 0.75} = 17687.37\ m^2$$

The time taken to retain the water in the channel was calculated as following,

$$t = \frac{A\times d\times nv}{Q} = \frac{17687.37\times 0.5\times 0.75}{2000} = \text{approx. 4 days}$$

The hydraulic loading rate was calculated as following. Hydraulic Loading Rate (HLR) is the measure of volumetric application of wastewater in wetland and it is calculated as following.

HLR= Q/A= 2000/17687.37= approx. 11cm/day

Geometry of floating wetland system: in this study, floating wetland consists of multi cells working in a parallel way to retain the water in balance as seasonal variation occurs. During the hot climate, when more water evaporates, it can be balanced by taking an individual channel and retention time can be reduced. In Multi flow cells maintenance of the system also easier, i.e. if one unit is under maintenance at the same time all other units can work properly. The wetland cell structure is very important in basin design due to its effects on flow hindrance and hydraulic circuiting. Mitsch and Gosselink (2007) recommended the minimum Length to width ratio (aspect ratio) of 2:1 to 3:1 for surface-flow wetland. Longer the flow path, the greater will be the resistance and high aspect ratio increases the time to retain wastewater in wetland which ultimately leads to overflow problems due to regular accumulation of plants mess. Length to width ratio for this study was assumed 3:1. Based on the area of wetland, the total scale of wetland was designed to be 230 m in length and 76.87 m in width (Fig. 4).

Table 2 Effluent BOD concentration in the floating wetland.

Month	Avg. normal temp. (^0C)	Influent BOD (mg/l)	Retention time (day)	Effluent BOD (mg/l)	Removal efficiency %
Jan	11.7	240	4	61	74
Feb	16.5	240	4	55	77
Mar	19.0	240	4	50	79
Apr	27.0	240	4	32	87
May	31.8	240	4	15	94
Jun	31.8	240	4	15	94
Jul	31.0	240	4	18	92
Aug	31.3	240	4	17	93
Sep	29.9	240	4	22	91
Oct	25.4	240	4	36	85
Nov	19.6	240	4	49	80
Dec	14.5	240	4	57	76

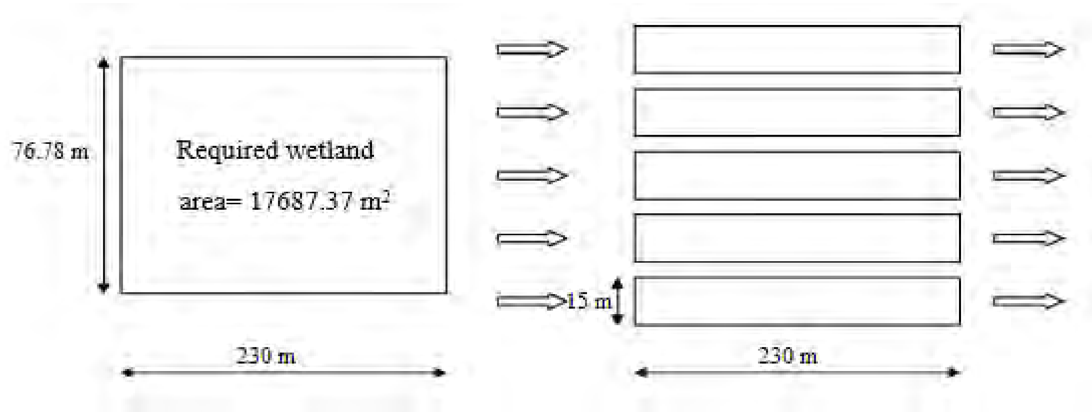

Fig. 4 Layout of floating wetland treatment system.

3.2 Environmental impact analysis of wastewater treatment systems

Wastewater treatment systems affect the environment in different ways. Environmental degradation occurs with several phenomenon's but the main problem amongst is the disposal of untreated wastewater to fresh water channels. Therefore, need is to consider the impact of all the resources which are used to treat the wastewater. Bengtsson et al. (1997) analyzed all the resources which were used to treat the wastewater and they also focused on emissions from construction and operation of the system. Weighting technique can be applied to estimate the energy consume during treatment of wastewater as well as to address the environmental impacts of treatment systems (Ødegaard, 1995). The environmental impacts of different wastewater treatment methods can be analyzed by applying life cycle assessment (LCA) technique (Pradipet al., 2013; Al-Dosary et al., 2015; Giovanni et al., 2016). But there is one drawback that these studies largely deal with the direct use of energy and other resources. But there is need to incorporate indirect resources which involve human labor and assessment of environmental work for generation of those resources. In this study all the direct and indirect resources were computed by using emergy technique.

3.2.1 Emergy analysis

Emergy is a form of energy that is used in direct and indirect transformations required to make a product. Emergy is a combination of all the energy used to make a product in one kind of energy. In emergy analysis, total emergy required for making a product is assigned to all of its by-products and all types of energies, materials and human services are quantified in common unit of solar emergy. Solar emergy is measured in unit of solar emjoules (sej) and it is the product of the transformity parameters and the energy available for the resource. The transformity is the amount of solar emergy required to make 1J of a resource. The methodology for emergy evaluations has been described by different researchers (Ulgiati et al., 2001). Emergy technique is suitable for comparison of different wastewater treatment techniques (Shao et al., 2017). All the direct and indirect resources which were used in whole the treatment system are shown in system diagram (Fig. 5). The main purpose of the system diagram was to conduct an inventory of processes and flows which were involved in the treatment system. Conventional or effluent treatment plant requires inputs of imported chemicals and other man-made factors, while the wetland system depends on natural energies.

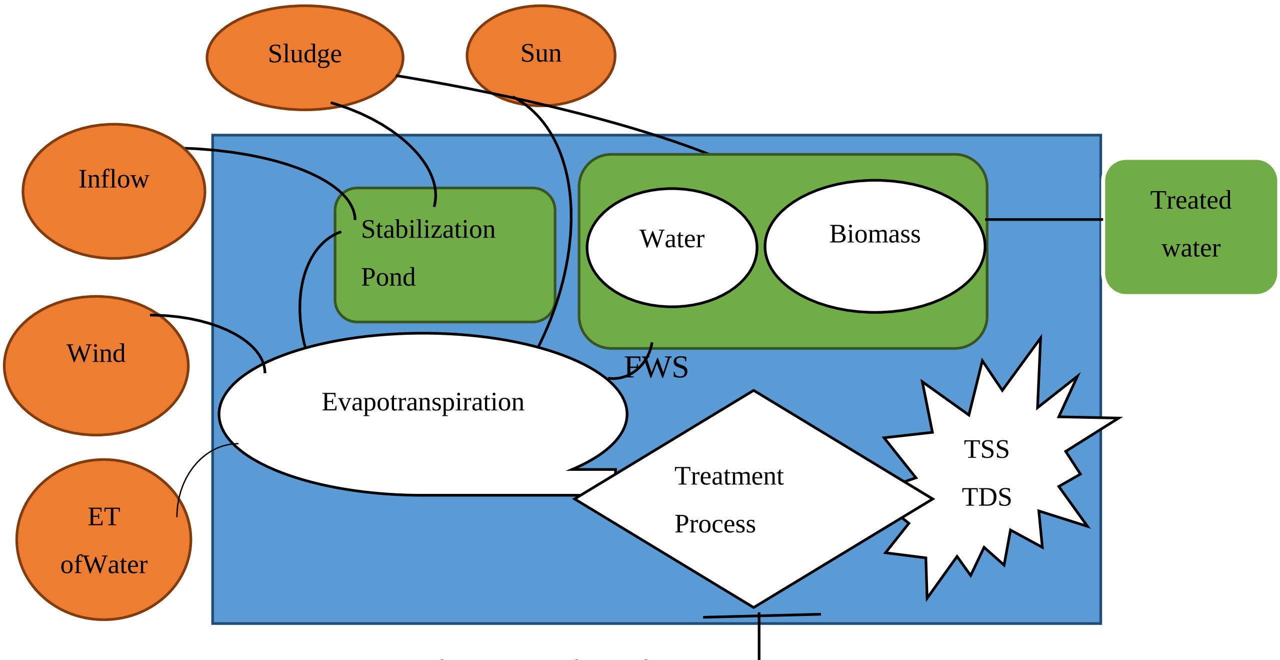

Fig. 5 Emergy flow diagram for the floating treatment wetland system.

3.2.2 Emergy calculation of floating wetland treatment system

Nelson et al. (2001) applied emergy technique to quantify the resources used to treat the wastewater treatment in wetlands. In this study different input parameters were considered for floating wetland such as sunlight, evapotranspiration, rain, construction cost to build a wetland, etc. (Table 4). Every input is multiplied with its own transformity parameter to get the emergy of that resource. From the whole calculations, it was observed that the total emergy of floating wetland 0.467×10^{17} sej/year is less as compared to conventional effluent treatment plant having emergy 2.92×10^{17} sej/year (Table 3). The results show that floating wetland system has minor environmental cost as compared to conventional effluent treatment plant. The higher emergy of conventional effluent treatment plant is due to the electricity consumption in cooling tower, primary and secondary clarifier in the treatment system. The total emergy required to treat the wastewater in floating wetland was 0.467×10^{17} sej/year, which indicates the environmental cost of the floating wetland system to treat 7.3×10^{11} g of waste water. The transformity parameter for surface water is 5.12×10^{5} sej/g. If we take the equivalent volume of surface water then emergy for surface water is 7.3×10^{11} g × 5.12×10^{5} sej/g = 3.7×10^{17} sej, while for the treated water the emergy is 0.467×10^{17} sej. This represents that a farmer can get benefit from the environment by saving the 7.3×10^{11}g of surface water. The total emergy for purified water, which is 4.16×10^{17} sej, equal to the sum of surface water and emergy of treated wastewater. If we discharge the treated wastewater into rivers or canals, then there is environmental cost of 0.467×10^{17} sej.

3.2.3 Cost-Benefit analysis

Cost-Benefit Analysis (CBA) is a comparatively simple and common technique for making decisions and evaluating the environmental impacts. This technique is based on the "inclination-to-pay" principle, which describes that the values of environmental systems closely depend on human opinions. The capital cost of the wetland system was estimated as 0.467×10^{17} sej/year while the conventional treatment system costs 2.92×10^{17} sej/year for treating the same amount of wastewater. The capital cost of the wetland system is low due to the additional positive effects of wetland maintenance and lower input cost. The cost- benefit ratio was 0.88(3.7×10^{17} sej / 4.16×10^{17} sej) which shows saving 3.7×10^{17} sej/year (4.16×10^{17} sej/year–0.467×10^{17} sej/year = 3.7×10^{17} sej/year) of fresh water resources by using treated wastewater for agricultural production.

The economic analysis shows that the wetland system is more environmental friendly and cost-effective than the effluent treatment system.

Table 3 Emergy Analysis of traditional treatment plant.

Items	Raw unit per year	Transformity sej/unit	Solar emergy (1017 sej/year)
Electricity [a]	7.8×10^{11} J	1.43×10^{05}	1.12 sej
Maintenance cost [b]	6.02×1006 PKR	1.21×10^{10}	0.72 sej
Building price [c]	9.00×1006 PKR	1.21×10^{10}	1.08 sej
Total emergent			2.92 sej
Treated wastewater [d]	7.30×1011 g	4×10^{05}	2.92 sej

[a]Electricity= 600×365 kwh = 219000 kwh = 7.8×10^{11} J/year. The transformity for electricity is 1.43×10^{5} sej/J (Siracusa et al., 2006).

[b]Maintenance costs of effluent treatment system is 6.02×10^{6} PKR. It includes cost of chemical inputs, fuel used in working process, services and sludge disposal. The transformity for maintenance is 1.21×10^{10} sej/PKR (Siracusa et al., 2006).

[c]Building Price = 9.00×10^{6} PKR/year and transformity for building price is 1.21×10^{10}(Siracusa et al., 2006).

[d]Treated wastewater = Q =8 3.33 m^3/h × 8760 h/year × 1000.000 g/m^3 = 7.30×10^{11}g/year. The solar emergy for one unit of the treated wastewater is 4 $\times10^{5}$ sej/g (Siracusa et al., 2006).

Table 4 Emergy analysis of the floating wetland treatment system.

Items	Raw unit per year (J, g)	Transformity sej/unit	Solar emergy (10^{17} sej/year)
Sun light [a]	2.23×10^{13} j	1	0.00023 sej
Rain [b]	3.80×10^{10} j	18199	0.0069 sej
Evapotranspiration [c]	3.18×10^{9} j	1.80×10^{4}	0.0005 sej
Wind Kinetics [d]	1.59×10^{9} j	1496	0.00023 sej
Construction cost [e]	3.90×10^{6} g	1.20×10^{10}	0.46 sej
Bricks	3.7×10^{6} g		
Concrete	1.95×10^{5} g		
Total emergy			0.467 sej
Treated waste water [f]	7.30×10^{11} g	0.6×10^{5}	0.467 sej

[a]Sunlight = Mid-range radiations × sun time × surface area = 2.23×10^{13} J/year. The transformity for the sunlight is 1 sej/j (Odum, 1996).

[b]Rain = Total area × precipitation × density of water × free energy of Gibbs = 17687.37 m² × 0.4373 m $\times10^{6}$ g/m^3 × 4.94 J/g = 3.8×10^{10} J/year. The transformity for the rain is 18199 sej/j (Odum, 1996; Siracusa et al., 2006).

[c]Evaporation = ET × A × density × free energy Gibbs = 0.036 m/Anne × 17687.37 m^2 ×1000000 g/m^3 × 4.9j/g = 3.18 $\times10^{9}$. The transformity for the evapotranspiration is 1.8×10^{04} sej/j (Siracusa et al., 2006).

[d]Wind kinetic = r × c × (vg) 3A, where r is the density of air (1.23 kg/m^3), c is the drag coefficient (1E-3), where v is the average velocity of wind (1.25 m/s), where vg is the geostrophic wind (10/6v) and A is the area of floating wetland (17687.37 m^2). Wind kinetic = 1.23 kg/m^3 × 0.001 × (10/ (6 × 1.25 m/sec)) ^{3} × 17687.37 m^2 × 31536000 sec/year= 1.5×10^{9} j/year. Transformity for the wind kinetics is 1496 sej/j (Odum, 1996; Siracusa et al., 2006).

[e]Construction price for wetland = 3.90×10^6 g/year. Bricks = 3.70×10^6g and concrete = 1.95×10^5 g, total cost for wetland would be 3.90×10^6 g/year. The transformity for construction price of wetland is 4.68×10^{16} sej/g (Siracusa et al., 2006).
[f]Treated wastewater = 83.33 m^3/h × 8760 h/year × 1000 g/m^3 = 7.3×10^{11}g/year. The solar emergy per unit of the treated wastewater is 0.6×10^5sej/g.

4 Conclusion

In this water scarce situation of Pakistan, there is need to properly harvest water by all means for sustainable agricultural production. Irrigation water supplies can be supplemented by treated wastewater for crops. Sustainability arises in the case of floating wetland system, as the treated wastewater can be used for irrigation purposes in a region that undergoes a high threat of water pollution and water shortage. In this study, the emergetic technique associated with the energetic technique helps to compare two types of wastewater treatment systems. The study shows that the floating wetland system is cost effective and energy efficient than the industrial effluent treatment plant and wetland system also provides additional environmental benefits. The low cost-benefit ratio shows that if we replace effluent treatment system with floating wetland, then the emergy cost will significantly drops. The analysis indicates that if we use treated wastewater for irrigation purposes then we can save a significant amount of fresh water supplies. It is recommended that wetland system should be adapted to convert wastewater into opportunity in cities where huge magnitude of wastewater is generated.

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