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Development and performance assessment of a castor-based vertical flow constructed wetland system for utilization of landfill leachate

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ABSTRACT

Constructed wetlands are classified as one among the biological methods that use phytoremediation for polluted liquid treatment, which can remove, transform and degrade pollutants from wastewater using various wetland species. The present study furthers the exploration by the usage of cash crops, namely castor (*Ricinus communis*), rather than conventional wetland species (*Typha* and *Phragmites* etc.) in simultaneously treating the landfill leachate (LL) generated from municipal solid waste (MSW) as well as in utilizing the associated organic loadings for better growth of the plant itself (i.e., castor). This study involves optimization of the dilution factor of the leachate so as to cause optimal growth of the castor plant, starting from the seed-germination stage onto the field plantation stage. The treatment effectiveness of leachate using castor-based vertical flow constructed wetland system (VFCWs) was assessed for selected water quality parameters, which showed its variability in relation to the retention time. The study confirms not only the leachate toxicity tolerability but also the increased growth of the plant even up to 60% of aqueous leachate solution at the germination stage and up to 40% at pot culture studies as well. The present study, thereby, conforms to the potential usage of castor in treating the leachate and simultaneous growth-augmentation of the castor plant itself, which is known to be a potential cash crop (esp. for biodiesel).

Keywords: Constructed wetlands; Landfill leachate; Phytoremediation; Germination study; Pot culture; Castor plant

1. Introduction

Constructed wetland (CWs) is a wastewater treatment system that has the potential to reduce pollutants that will meet the criteria for water quality before discharging to the environment. It has the potential to treat a variety of wastewater by removing organics and heavy metals [1]. Six constructed wetlands, 120 L in volume with a depth of 40 cm, filled with gravel and planted with three-vegetation sugarcane reed and *Phragmites* fed with the effluent of a seasonal reservoir in Israel under two different retention times 2.5 and 5 d. The removal efficiencies were found to be 90.4% for total suspended solids (TSS) and 62.4% for chemical oxygen demand (COD) on average [2]. The effect of vegetation on removal efficiency of subsurface horizontal flow constructed wetland for nitrogen and phosphorus removal was studied from simulated plant nursery run-off water in New South Wales, Australia [3]. Their study revealed that the experimental lab planted with *Phragmites australis* removed greater than 96% total

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nitrogen (TN) and total phosphorus (TP) over 19 months, while the unplanted tub was inefficient with less removal of less than 16% total nitrogen and less than 45% phosphorus. They found that the plants were essential to a gravel-based wetland to achieve efficient nutrient removal with the effluent of TN and TP concentrations of less than 1 and 0.05 mg/L, respectively, with a 3.5-d retention time [4]. In another study, the treatment of landfill leachate by advanced oxidation processes (AOPs) was investigated in terms of percentage colour and COD removal [5].

Constructed wetlands can supply predictable water quality if they are properly designed and maintained. About 6,350 million m^3 of wastewater is being generated every year from 212 class I and 242 class II towns in India, of which only 36% in class I cities and 14% in class II towns are collected due to limited treatment facilities [6]. Leachate is a highly polluted heterogeneous liquid. The compositions of leachate are of organic matter such as COD (chemical oxygen demand) and TOC (total organic carbon); specific organic compounds, inorganic compounds and heavy metals [7,8]. The dumping of solid wastes in uncontrolled landfills can have a significant impact on the environment and human health. Due to the decomposition of organic matter, leachate derived from landfills or dumps comprises primarily dissolved organic compounds (DOC), largely in the form of fulvic acids. The solubility of metals in leachate is enhanced through complexion by dissolved organic matter. The ranges of organic compounds that may be found in groundwater are affected by landfill leachate.

Leachate treatment has become the need of the hour, as it is highly toxic. Several physicochemical and biological treatments are available for leachate treatment. But, most of them are uneconomical and energy-intensive. High-tech solutions applied for leachate treatment (i.e., reverse osmosis or ozonation) are expensive and unsuitable for many landfill sites. Constructed wetlands are appropriate alternatives to treat the leachate coming from wastewaters. Most of the studies used *Typha* and *Phragmites*, the two most popular water plants for the treatment of leachate (Table 1).

The present study was conducted to assess the ability of the vertical subsurface flow constructed wetland systems to treat the various proportions of landfill leachate (LL) and to evaluate the performances of the system planted with *Ricinus communis*. Furthermore, in this study, the physical and chemical parameters, including chemical oxygen demand (COD), TSS (ppm), conductivity (mS), salinity (ppm), chloride (mg/L) and nitrate (mg/L), were monitored, and the growth characteristics were also observed.

2. Materials and methods

2.1. Characteristics of landfill leachate

The leachate that was collected from the Srinivasapuram landfill area, which is the open waste piling area for the Thanjavur town region, at certain periods, was used in the present study (Table 2). The leachate used in our research was mixed with tap water to form a varying degree of dilution because studies reveal the need for dilution to control excess ammonia interfering the plant growth [23]. The leachate collected was kept in an airtight container in the refrigerator until use.

2.2. Experimental methods

The samples were collected from the outlet provided at the base throughout the study period. Physical and chemical parameters including pH, TSS (ppm), conductivity (mS),

Table 1
Summary of literature review of leachate treatment using CWs

Sl. no.	Type of plant	Wetland model	Leachate characterization (ppm)			Removal	References
			COD	TDS	TN		
1	*Typha angustifolia*	Horizontal subsurface flow	1,370	–	848	30%	[9]
2	*Phragmites australis*	Vertical flow	9,740	–	35.2	69%	[10]
3	*Typha domingensis*	–	2,301	607	627	86	[11]
4	*Phragmites australis*	Vertical flow	2,800	2,720	200	90	[12]
5	*Phragmites australis*	–	520		4.9	49	[13]
6	*Typha angustifolia*	Subsurface horizontal flow	8,000	500	4	94	[14]
7	*Typha latifolia*	Horizontal and vertical	4,700	2,800	75	36% in vertical and 60.9% in horizontal	[15]
8	*Echinochloa pyramidalis*	Vertical flow	5,000		500	92	[16]
9	*Solidago rigida*	Horizontal flow	781	186	212	97	[17]
10	*Phragmites australis* and *Typha latifolia*	Vertical flow	700		600	50%	[18]
11	*Typha latifolia*	–	3,220	32		50%	[19]
12	*Juncus effusus*	–	255			60%	[20]
13	*Iris pseudacorus* L.	Horizontal	722	530	120	90%	[21]
14	*Phragmites australis*	Vertical	255			65%	[22]

Table 2
Characteristics of landfill leachate collected from the landfill area

Parameters	Range	Average	SD
pH	6.89–7.51	7.28	1.3
TSS (ppm)	5,735–6,880	6,355	352
Conductivity (mS)	9.3–12.7	11.8	3
Salinity (ppm)	6,535–11,100	8,500	1,350
COD (mg/L)	1,700–2,800	2,550	250
Chloride (mg/L)	0.87–1.72	1.35	0.5
Bromide (mg/L)	3.4–11.83	8.5	2
Nitrate (mg/L)	135–180.28	158	25
Fluoride (mg/L)	12.6–16.31	14.35	4

salinity (ppm), COD (mg/L), chloride (mg/L), bromide (mg/L), nitrate (mg/L), and fluoride (mg/L) were monitored.

pH, conductivity and salinity were measured in a water analyzer kit (Make: Systronics, Model: 371). TSS was measured using the gravimetric method. COD analyses were performed using Colorimeter (Hach; DR 890). The 2 h digestion of the samples was conducted at 150°C in a COD digester (Hach; DR 8200). Chloride, bromide, nitrate and fluoride analyses were conducted using Multiparameter Benchtop Meter (Hach; HQ430d).

2.3. Germination studies

To investigate the effects of leachate on plants, three different proportions (namely 20%, 40% and 60%) were made, germination studies were carried out using conventional moisture paper, and their growth characteristics were compared with each other. The seeds of castor were germinated in sterilized Petri dishes with filter paper. The landfill leachate was added to each dish, and 15 healthy-looking seeds were evenly spread onto the surface of the filter paper. The control seeds were growing on an untreated nutrient medium under the same condition. The Petri dishes were covered by a glass cap to prevent loss due to evaporation. After 72 h, at the end of the test period, germination percentage and longest root seedlings were determined.

2.4. Constructed wetland study (lab scale)

In the present study, rectangular lab scale wetland systems having dimensions of 75 (L) × 40 (W) × 30 (H) cm were used. These systems were operated under vertical flow conditions with three proportions of landfill leachate (i.e., 20%, 40% and 60%). The vertical flow reactors are constructed with an opening system at the base. The vertical flow constructed wetland (VFCWs) were fed with LL with the help of a peristaltic pump with a rate of 2 L. The hydraulic characteristics of the reactors are summarized in Table 3.

Castor was planted in all three reactors, which were supplied with three different proportions of leachate as mentioned above and labelled as R1, R2 and R3, and an unplanted control reactor was set up for each case to investigate the treatment effect imposed by the plants. The treated outlet water was collected through the opening present at the base of all reactors. Fig. 1 shows the overall methodology adopted and the characterizations studied of the CW reactors.

3. Results and discussion

3.1. Change in water quality parameters

The variation between influent and effluent in three proportions after treatment were given in Table 4, which shows influent and effluent changes in the pH, TSS (ppm), conductivity (mS), salinity (ppm), COD (mg/L), chloride (mg/L), bromide (mg/L), nitrate (mg/L) and fluoride (mg/L) in the leachate. It can be seen that the characteristics of the leachate were variable, and the coefficient of variations of all parameters was quite high.

3.2. Germination and plant growth studies

The root growth inhibition of castor seed was tested with LL of 20%, 40%, and 60%. The root length of germinated seeds was compared with the control (water). With increasing landfill leachate concentrations, the examined seeds showed higher inhibition in their germination (Fig. 2). Results are expressed as mean ± standard deviation.

Fig. 3 presents the effect of the landfill leachate on seed germination and root growth over two weeks. With increasing landfill leachate concentrations, the examined seeds showed higher growth inhibition. However, the sample 20% and 40% LL were not much toxic (exhibit stimulatory effects). The studies clearly show higher growth of castor seed, representatively by root length in leachate concentration of 20% and marginally low at a concentration of 40%, compared to control. However, with an increased concentration of leachate (at 40%), growth inhibition was observed. Hence, the usage of leachate concentration up to 40% is expected to show the best growth at germination.

The toxicity of leachate on seed germination may vary due to various factors and may induce both positive and negative responses in the plants [24–26]. In the present study, castor has been used and hence is expected to behave the same way in all replications (subject to natural

Table 3
Hydraulic characteristics of the reactors

Reactor type	Volume (in L)	OLR (kg COD/m^3 d)	HRT (d)	Q (L/d)
R1	4	0.0514	5	0.8
R2	4	0.0407	5	0.8
R3	4	0.236	5	0.8

Table 4
Average characteristics of different proportions of influent landfill leachate

Parameters	20%		40%		60%	
	Influent	Effluent	Influent	Effluent	Influent	Effluent
pH	8.47	7.2	8.54	8.15	7.43	7.22
TSS (ppm)	1,710	820	2,990	1,655	4,250	2,458
Conductivity (mS)	3.16	2.13	5.33	3.94	7.86	5.9
Salinity (ppm)	2,780	1,370	4,870	2,350	6,900	4,590
COD (mg/L)	257	135	814	560	1,475	855
Chloride (mg/L)	7.41	5.1	4.30	2.5	2.92	2.1
Bromide (mg/L)	0.091	0.078	0.181	0.178	0.48	0.32
Nitrate (mg/L)	32.41	22.5	48.36	33.6	80.49	69.25
Fluoride (mg/L)	0.466	0.31	0.402	0.39	0.347	0.26

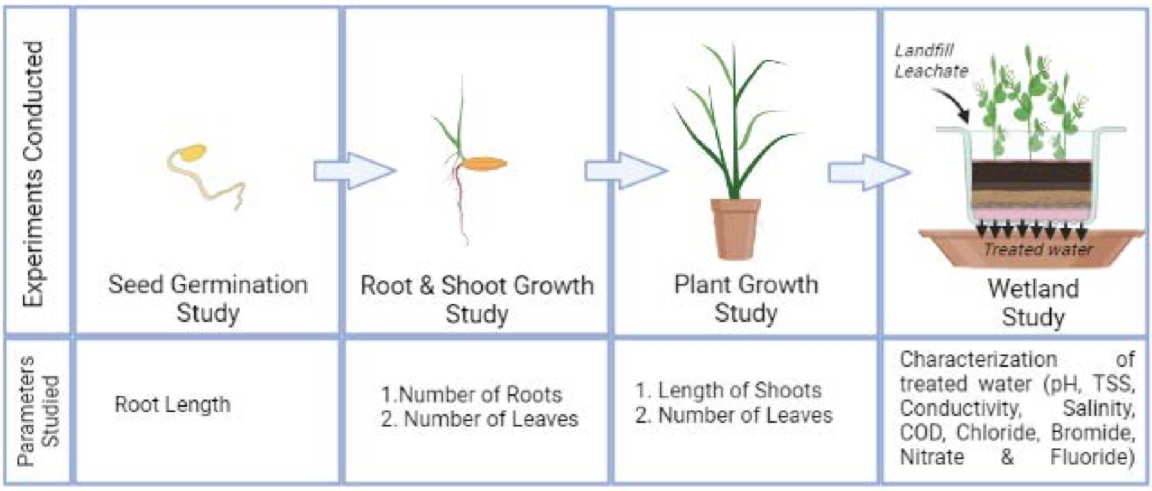

Fig. 1. Detailed methodology used in the constructed wetland systems.

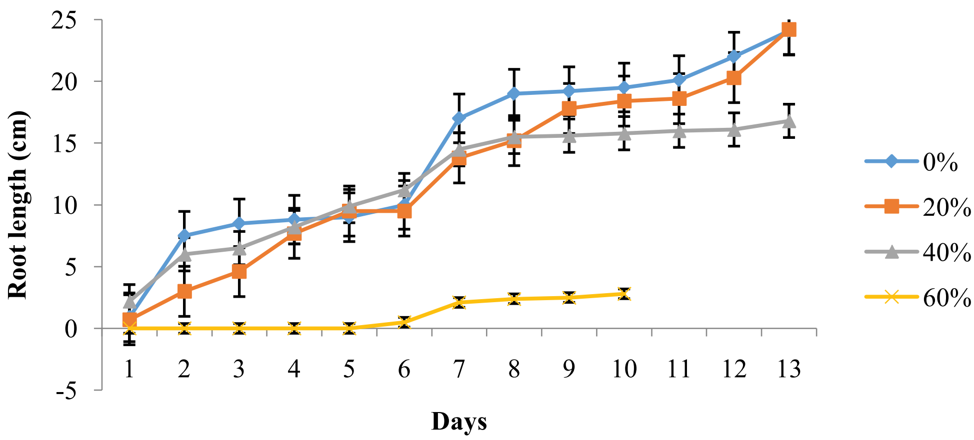

Fig. 2. Effect of the landfill leachate on root growth.

and environmental random variation). Hence, the variation of shoot growth may be attributed to the effect of leachate concentration alone. As indicated in Fig. 4, the shoot length seemed to show maximum growth at 20%, with marginally lesser at 40%. At 60% dilution, the plants stopped growth. Hence, even for shoot growth, a maximum of 40% of dilution of LL is recommended based on the shoot growth pattern.

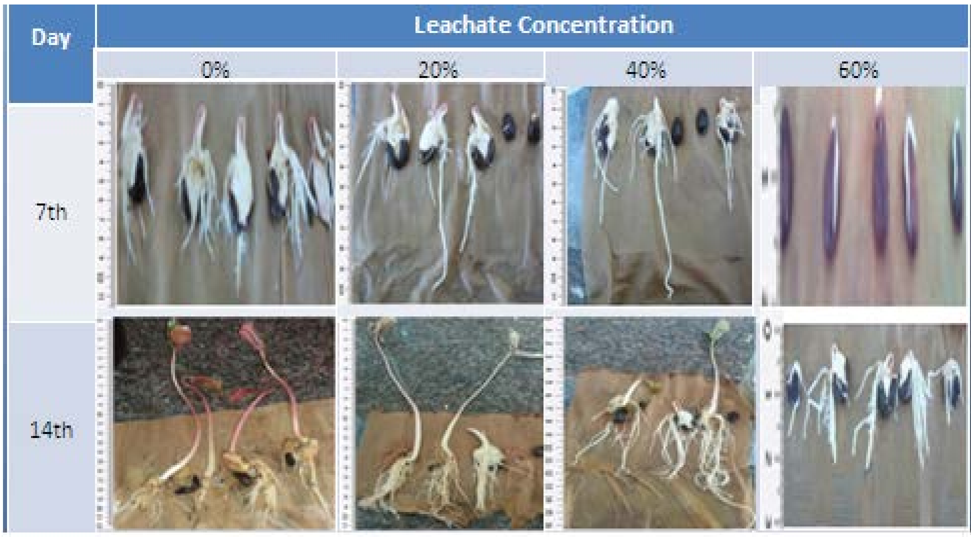

Fig. 3. Effect of the landfill leachate on seed germination.

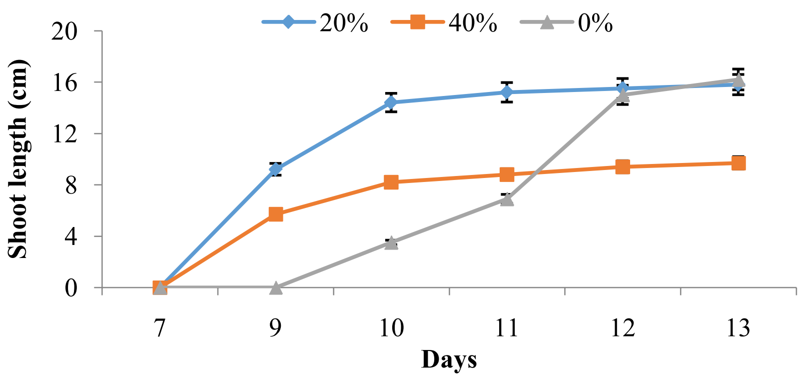

Fig. 4. Effect of the landfill leachate on shoot growth.

3.3. Removal of COD

In the study, the initial COD concentration of various proportions of landfill leachate was studied over a period with the VFCW. The influent concentration was 257, 814, and 1,475 mg/L, respectively, for the three different proportions and corresponding effluent concentrations were compared for their removal ability. For COD, the effluent concentration was insignificantly different with regard to proportions. During the study, the average COD removal in the *Ricinus communis* and Control was obtained as 65% and 49%, respectively (Fig. 5). The VFCW system planted with castor provided higher COD removal rates than the control, which can be compared with similar studies [27–29]. Wojciechowska [30] reported that treating wastewater with constructed wetlands has potential advantages over the conventional treatment processes.

3.4. Removal of total suspended solids

The input TSS concentration varied between 1,710 and 4,250 mg/L. The TSS output concentrations were in the range of 965–1,160 mg/L, 2,452–2,680 mg/L, and 2,756–3,800 mg/L in their corresponding proportions of leachate when compared with the control. The TSS removal in VFCW is probably the result of physical processes such as sedimentation and filtration [31]. As summarized by Vymazal [32], the reductions are usually within the wide ranges specified in previous studies for similar CW systems. Unlike COD, TSS showed lesser effectiveness for LL than normal (Fig. 6). Hence, up to 40%, the TSS variation has been found positive. At higher concentrations, it is found to be negative.

3.5. Removal of nitrate

Nitrate concentration in the influent varied between 34 and 80 mg/L depending on the changes in the leachate concentration. The average effluent concentration was 42.27 ± 9.8 mg/L in planted and 62.5 ± 8 mg/L in control. The overall removal rates achieved were 62% based on the average removals throughout the study period (Fig. 7). In fact, studies indicate that, up to 40% dilution, there is a reportable reduction in nitrate concentration. The nitrate removal was, by and large, better in LL-based wetland than the control, yet like TSS.

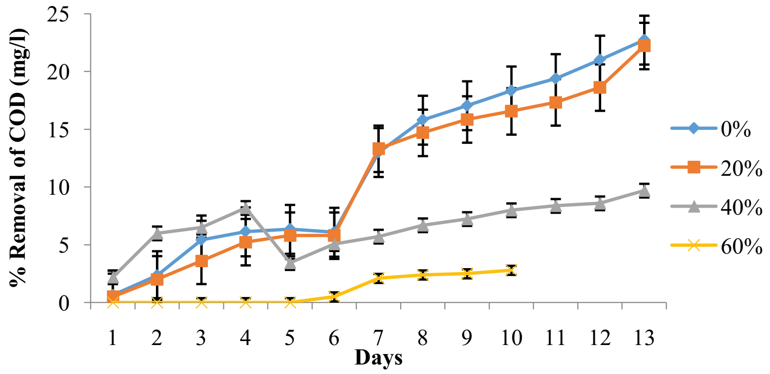

Fig. 5. Effect of COD removal.

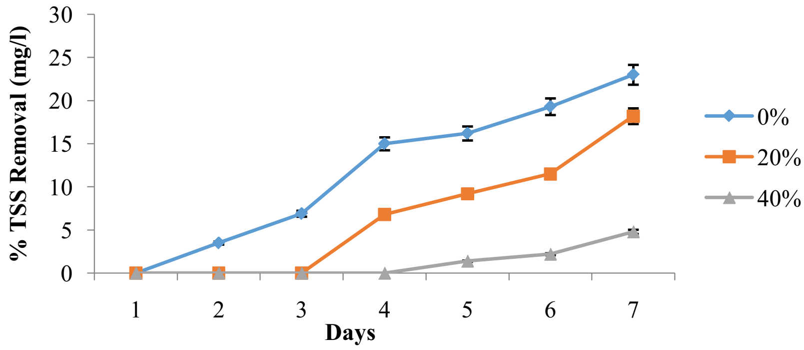

Fig. 6. Effect of TSS removal.

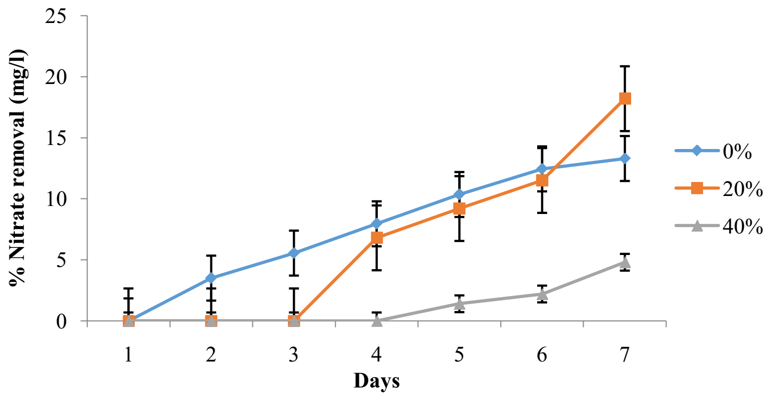

Fig. 7. Effect of nitrate removal.

4. Conclusion

The mature landfill leachate has low biodegradability due to the presence of refractory organics and high ammonia concentration, which makes its treatment difficult by a conventional process. In this study, *Ricinus communis* planted and one unplanted-control system was used to treat the landfill leachate. The planted reactors exhibited higher removal capacity than the unplanted system, which showed higher COD removal efficiencies than the control. The leachate should be diluted to the appropriate concentration in order to avoid scorching plants and saplings, and the studies indicated that the dilution should be not more than 40% to have better growth of the plants' studies as well as better treatment of wastewater (esp. with respect to COD, TSS and nitrate). The significantly high concentrations of COD and TSS need to be addressed in order to minimize possible short- and long-term stresses on the crop and environment.

It is suggested further analysis of possible organic contaminants, pathogenic microorganisms and other toxic substances in leachate as well as document their impact on the environment. The present research was conducted to evaluate the phytoremediation potential of the plant. With the results, it can be assumed that castor shows the most adaptable reaction to landfill leachate at all concentrations. Based on the above-mentioned results, it can be concluded that the castor plant has a great potential to treat LL and could be used in phytoremediation technology.

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