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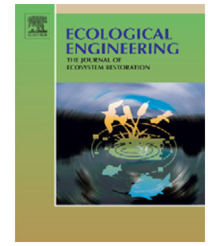

The efficiency of evapotranspiration of landfill leachate in the soil–plant system with willow *Salix amygdalina* L.

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ABSTRACT

The application of a specific species of willow—*Salix amygdalina* L., marked by high transpiration ability—is a cheap and effective method of landfill leachate disposal. A 2-year study examined the effectiveness of leachate evapotranspiration from soil–plant systems with willow species *S. amygdalina* L. Evapotranspiration from soil–plant systems planted with willow was from 1.28 up to 5.12 times higher than evaporation from soil surface barren of vegetation. This proves the usefulness of soil–plant systems with willow in landfill leachate treatment through vaporization. Evapotranspiration efficiency, as opposed to total amount of water added into the lysimeter, was not strong enough to vaporize all input of the landfill leachate in the lysimeters. This may indicate that the ground water requires isolation when soil systems remain under landfill leachate irrigation. Linear dependence between willow biomass growth and transpiration was observed to be significant ($p < 0.05$). Additionally, the research showed that the application of sewage sludge into the soil caused an increase in vaporization efficiency.

1. Introduction

In spite of different views on leachate treatment, many experts agree that an on-site treatment facility is needed, since it is easy to operate, and economical in terms of cost and energy (Bulc, 2006). Owing to low investment and maintenance costs, there has been a growing interest in applying plants in landfill leachate disposal (Ashbee and Fletcher, 1993). An on-site treatment using constructed wetlands (CW) is one of the low cost methods which has been widely practiced in a number of countries for many years. Its degree of success has varied but not exceeded 50% of removal efficiency of such pollutants as COD, BOD, and nitrogen (Cossu et al., 2001). Other studies have shown the importance of evapotranspiration during hot periods in natural wetlands and also in constructed wetlands (Chazarene et al., 2003). Evapotranspiration therefore might be used in soil–plant systems for landfill leachate treatment. It is of particular importance that leachate volume decreases as a result of soil–plant systems evapotranspiration (Dobson and Moffat, 1995). Such soil–plant systems are planted with macrophytes like willows, poplars and reeds, as these are the plants that are recommended by the USEPA (2000) for landfill leachate evapotranspiration.

The use of plants in landfill leachate evapotranspiration has been tested. Two willow species, *Salix alba* and *Salix nigra*, were used for landfill leachate disposal by Alker et al. (2003). The following evapotranspiration values: ranging from 8 to 9 mm/d, and 5 mm/d, obtained from the willow stands, were determined by Persson and Lindroth (1994), and Elowson (1999), respectively. Evapotranspiration from *Salix viminalis* L. and *Salix aquatica* Sm. stands, located at the municipal and industrial landfill sites, was significantly higher than an

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annual precipitation rate in Finland (Ettala, 1992). Transpiration of willow stands may be high enough to significantly affect the table level of ground water (Dulohery et al., 2000) and exceed annual precipitation (Persson, 1995). Research on young willow sprouts revealed that shortly after planting, evapotranspiration increased and caused vaporization of landfill leachate. Agopsowicz (1994) determined that evapotranspiration of 3-month willow sprouts was 1.6–1.8-times higher than an average precipitation rate in Poland, which is about 600 mm. Białowiec et al. (2003) confirmed that transpiration of 3-month old sprouts of *Salix amygdalina* L. resulted in evapotranspiraton ranging from 80 to 90%. Until now, research focused mainly on the use of different willow species for evapotranspiration of landfill leachate whose physical and chemical properties varied. In most cases, the researches were carried out during one vegetative period or even shorter. The use of soil–plant systems in landfill leachate disposal should be preceded by a selection of plant species and soil types. Agopsowicz (1994) tested tolerance of different willow species to pollutant concentration in landfill leachate. He determined species *S. amigdalina* L., *S. viminalis* L., and *S. purpurea* as the plants with the highest ability to evapotranspirate leachate and with high tolerance to pollutant concentrations in a soil solution. Hasselgren (1998) showed that by adding sewage sludge to soil, biomass yield may increase. It may be expected that willow—*S. amygdalina* L., within soil–plant systems, can evapotranspirate the whole bulk of incoming water, including landfill leachate. In view of the presented data it is possible to formulate the aim of this study—to determine landfill leachate evapotranspiration in soil–plant systems with *S. amygdalina* L. during two vegetation periods, as a function of a hydraulic loading rate (HLR) and sewage sludge fertilization.

2. Materials and methods

2.1. *Landfill leachate characteristics*

A municipal landfill in Wola Pawlowska near Ciechanów in Poland was the source of leachate used in the experiment. The landfill has been operating since June 1994. Total landfill area is 12 ha; landfill section is 3.5 ha. Average pollutants' concentrations in leachate were estimated on the basis of 48 leachate samples. Mean COD concentration was about 1425.4 mg O_2/dm^3, comprised in 37.2% of soluble compounds concentration. BOD_5/COD ratio was 0.17. Electrolytic conductivity value was approximately 12.3 mS/cm. Average ammonium value in the leachate was 591.9 mg NH_4/dm^3, which was comprised in about 76% of Kjeldahl nitrogen. Orthophosphate concentration was 3.6 mg P-PO_4/dm^3.

2.2. *System design and control*

The experiment was conducted in laboratory scale using lysimeter method (Agopsowicz et al., 2001). A 1 m high lysimeter of 0.6 m in diameter and 0.28 m^3 in volume was a model of a soil profile (soil–plant system). A piezometer constructed of PCV tubes, each of which 5 cm in diameter, was put into the lysimeter for ground water sampling, adding and level control. The piezometer was closed from the top and filtered from the bottom in a gravel layer. The gravel layer, whose particle's diameter ranged from 10 to 20 mm, allowed drainage of percolating water. In order to compensate the temperature inside the lysimeter and in the soil, the lysimeter was placed in the ground. Fig. 1 shows lysimeter's construction and experimental configuration.

The experiment was conducted during two vegetation periods, as an example of willow's short rotation plantations (SRP). Evapotranspiration of landfill leachate in soil–plant system with *S. amygdalina* L. was examined as a function of:

- soil type—sand (S) and sand with a dose of 450 Mg d.m./ha of sewage sludge (C);
- leachate hydraulic loading rate—1, 3 and 5 mm/d.

Each variant of the experiment was repeated three times.

The applied sewage sludge was comprised of 57.8% moisture, 76.5% d.m. the organic matter content, 1.21% d.m. of Kjeldahl nitrogen content and its reaction in 1 N KCl remained at the level of 6.82 pH.

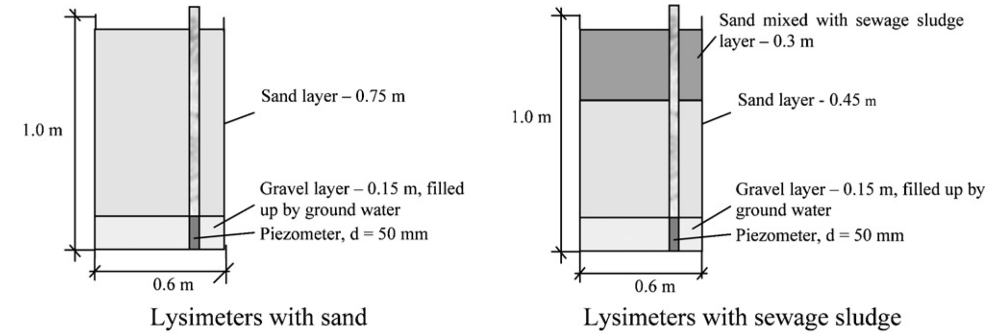
A 0.3 m deep layer of a sewage sludge–sand mixture was settled at the top of the lysimeter. Sand soil and sand-and-sewage sludge soil varied in terms of physical and chemical properties. The content of the analyzed parameters in sand-and-sewage sludge soil was about 10 times higher than in sand soil, whereas sand soil pH was about 0.9 units higher than sand-and-sewage soil pH (Table 1).

Wooden sprouts of the parent willow were cut to a length of 200–250 mm and to a diameter of 20–25 mm. Willow cuttings were planted with a density of 7 plants m^{-2}, according to Sennerby-Forsse (1986). At the end of the vegetation period, harvested above-ground parts of the plant were dried and weighed for biomass growth evaluation (g d.m./m^2).

The lysimeters were located under a foil roof which had been firmly insulated. There was no natural rainfall or natural ground water inflow into the lysimeters. All the lysimeters, i.e. those with willow as well as those plantless (control), were watered in the following ways: with landfill leachate according to the assessed HLR (once per week); by simulation of rainfall (distilled water) (once per week); and incoming clean ground water (distilled water) according to meteorological data (GUS, 2000) (once per month). Watering was performed by pouring out water into the lysimeters. The amount of leachate and water input was measured by weighing. Once per month free drainage water that had gathered inside the lysimeter was pumped out through the gravel layer and the piezometer using a peristaltic pump, prior to weighing. Having been measured, water masses (kg) were converted into (mm) units.

Table 1 – Physical and chemical properties of the soil used in the experiment

Parameter	Sand	Soil type sand with sewage sludge
Reaction in 1 N KCl (pH)	8.2	7.3
Organic matter (% d.m.)	0.22	2.73
Kjeldahl nitrogen (% d.m.)	0.003	0.22
Phosphorus (mg P_2O_5 100 g^{-1} soil)	3.6	49.6
Salinity (g Cl^- dm^{-3} soil)	0.1	0.8



		Plant species			
		Willow – *Salix amygdalina* L.		No plants – control lysimeters	
The leachate hydraulic loading rate	1 mm/d	WS1	WC1	S1	C1
	3 mm/d	WS3	WC3	S3	C3
	5 mm/d	WS5	WC5	S5	C5
		Sand	Sand with sewage sludge	Sand	Sand with sewage sludge
		Soil type			

Fig. 1 – The construction of lysimeters and the experiment configuration.

2.3. *Treatment efficiency parameters*

Water balance was estimated according to Grip et al. (1984):

$$E = Q_h - Q_e \quad (1)$$

where E is the evapotranspiration (mm), Q_e the amount of water pumped out from the lysimeter (mm), and Q_h is the total amount of water added into the lysimeter (mm).

$$Q_h = Q_l + Q_p + Q_s \quad (2)$$

where Q_l is the amount of added landfill leachate (mm), Q_p the amount of precipitation (mm), and Q_s the amount of added ground water (mm).

In the lysimeters with plants, E stood for evapotranspiration, whereas in plantless lysimeters (control lysimeters) (E_v) was estimated as evaporation. Transpiration (T) was calculated from the following equation:

$$T = E - E_v \quad (3)$$

On the basis of the total amount of water which had been vaporized in soil–plant systems the following ratios of vaporization efficiency were calculated: ratio of total evapotranspiration to total amount of added water into the lysimeter (E/Q_h), ratio of total transpiration to total evapotranspiration (T/E), and ratio of total evapotranspiration to total evaporation (E/E_v). Ratio E/Q_h shows evapotranspiration efficiency in comparison to the amount of supplied water. Ratio T/E points out to the degree of participation of plants in evapotranspiration, and ratio E/E_v shows how many times evapotranspiration from soil–plant systems is higher than that from soil surface barren of vegetation. The ratios were used to estimate landfill leachate vaporization efficiency. In addition, a relation between biomass growth and total transpiration was estimated. For this purpose, linear correlation and regression coefficients were determined at the significance level ($p < 0.05$).

3. Results

The experiment showed that plant's use in landfill leachate disposal caused an increase of evapotranspiration efficiency as compared to evaporation from uncovered soil. Evapotranspiration values in systems WC and WS were higher than evaporation values and ranged from 149.69 to 545.80 and from 183.11 to 411.77 mm, respectively. In the 1st and the 2nd year, evaporation from the sand with sewage sludge (C) ranged from 110.32 to 206.59 mm and was higher than that from the sand soil results (S) (from 73.84 to 152.48 mm). Evaporation in the 2nd year was higher than that in the 1st year (Fig. 2). It was determined that evapotranspiration from soil–plant systems with sand-and-sewage sludge was higher than that from the systems with sand soil throughout the 2 years of the experiment. Calculated transpiration ranged from 35.48 to 339.79 mm, and was the highest in system WC1 in the 2nd year (Fig. 2).

The effect of willow on evapotranspiration efficiency was estimated. Ratios: E/Q_h, T/E and E/E_v have been calculated (Table 2). A comparison of the amount of water added into the lysimeters with evapotranspiration values shows that total amount of water added into the lysimeter was higher (Q_h) than evapotranspiration (E) in all experimental variants in both vegetation periods. Similarly, in all experimental variants

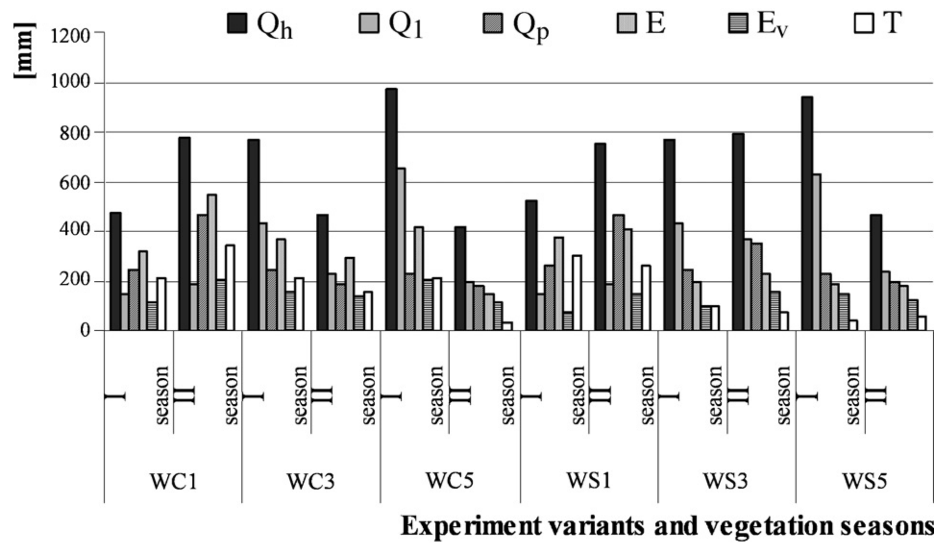


Fig. 2 – A comparison of the amount of water dozed into the lysimeters with the vaporization values. The description of the abbreviations is presented in Fig. 1.

Table 2 – The values of ratios T/E, E/E_v and E/Q_h in the soil–plant systems

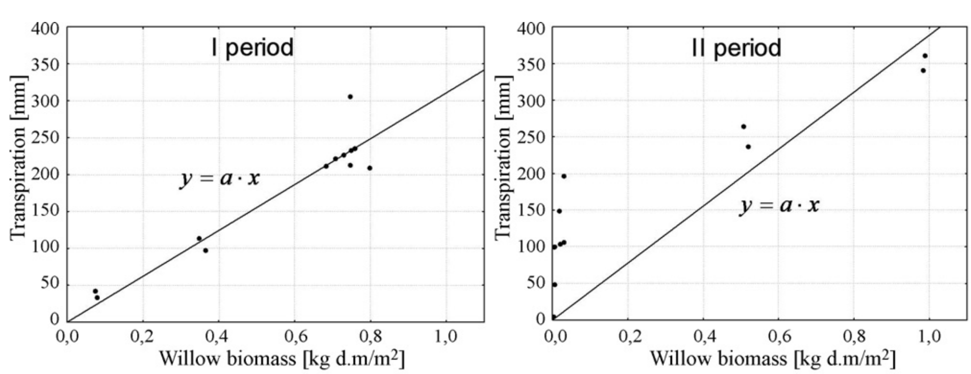
The ratio	WC1 C1	WC3 C3	WC5 C5	WS1 S1	WS3 S3	WS5 S5
I vegetation period						
T/E	0.65	0.57	0.51	0.80	0.49	0.22
E/E_v	2.89	2.33	2.02	5.12	1.97	1.28
E/Q_h	0.67	0.48	0.43	0.72	0.26	0.20
	0.23	*0.21*	*0.22*	*0.16*	*0.13*	*0.14*
II vegetation period						
T/E	0.62	0.53	0.24	0.64	0.32	0.32
E/E_v	2.65	2.11	1.31	2.78	1.48	1.47
E/Q_h	0.71	0.62	0.36	0.55	0.28	0.40
	0.27	*0.25*	*0.28*	*0.20*	*0.21*	*0.26*

The results obtained from the plantless lysimeters are in italics. The description of the abbreviations is presented in Fig. 1.

evaporation (E_v) did not exceed Q_h values (Table 2). Ratio E/Q_h values were the highest ranging from 0.67 to 0.71 in soil–plant systems with willow growing in sand with sewage sludge soil and sand soil, 0.72 with a low leachate hydraulic loading rate 1 mm/d (Table 2).

In vegetation period I, in the systems with willow growing on sand with sewage sludge soil, with HLR 1 to 5 mm/d, and also with willow growing on sand soil with HLR 1 mm/d, the values of the ratio T/E exceeded 0.5. The highest value of T/E 0.80 was in system WS1 (Table 2).

The impact of biomass growth on transpiration was analyzed. A comparison between biomass growth and transpiration indicated a high significant ($p < 0.05$) linear correlation (Fig. 3). In soil–plant systems with willow, an increase of biomass growth by 1 kg d.m./m^2 caused an increase of total transpiration by 310.6 mm/a in the 1st year of the experiment, and by 388.6 mm/a in the 2nd year.



	a	r(x,y)	r²	p
I – period	310.6	0.949	0.901	0.00000
II - period	388.6	0.537	0.288	0.00005

Fig. 3 – The dependence between willow biomass growth and total transpiration in two vegetation periods (I; II) with statistical parameters of correlation analyses on the significance level ($p < 0.05$), where $r_{(x,y)}$: correlation coefficient, r^2: determination coefficient, a: regression coefficient, p: computed probability.

4. Discussion

The measured efficiency of landfill leachate evapotranspiration mostly depended on the physical and chemical properties of landfill leachate and the applied plants species. In this experiment evapotranspiration results ranged from 149.69 to 545.80 mm. Research conducted by Hasselgren (1992) on landfill leachate disposal using willow *S. viminalis* L., *Salix dasyclados* determined that maximum evapotranspiration was between 1200 and 1500 mm. Watzinger et al. (2003) indicated lower values of evapotranspiration in the lysimeters with willow *S. viminalis* L. irrigated with landfill leachate than in the lysimeters irrigated with tap water, where the values reached 1088 mm. In the presented experiment evapotranspiration results were lower, yet they were obtained from leachate with a higher concentration of pollutants—almost 10 times in comparison to the results of Hasselgren (1992) and about 2 times in comparison to the results of Watzinger et al. (2003). This shows that landfill leachate evapotranspiration efficiency depends on physical and chemical properties of landfill leachate, especially on its negative influence on plants. The presence of dissolved compounds in water may affect evapotranspiration in two ways: (i) It may pose toxic threats to plants. As Fig. 3 and Table 2 show, biomass growth was inhibited especially during period II, and the participation of transpiration in evapotranspiration was low. The influence of landfill leachate on plants may be explained more explicitly by comparing the values of the transpiration efficiency coefficient (β^{-1}—ratio of biomass to transpiration) (g d.m./mm). A typical transpiration coefficient for willow is in the range 1.9–4.9 g d.m./mm (Eckersten and Ericsson, 1989; Kowalik and Eckersten, 1989). When toxic compounds are available to plants, the value of β^{-1} decreases Thompson et al., 1998). In this study the values of β^{-1} were in the range 0.13–3.84 g d.m./mm, but during period II in variants WC3, WC5, WS3 and WS5 they ranged between low values 0.12 and 0.45 g d.m./mm (Białowiec, 2005). This indicates toxic influence of leachate on plants, which may cause decrease of evapotranspiration. (ii) It may decrease the difference between soil water tension and soil water tension at air entry, and hence decrease evaporation (Persson, 1995).

It was observed that evaporation from the soil surface uncovered with plants was not as efficient as the amount of water dozed into the lysimeters. This may indicate that evaporation may be used only for landfill leachate evaporation during its recirculation at the top of a waste heap which needs to be isolated from the ground water. The dark color of the sand added with sewage sludge, resulting from organic matter content, may be responsible for higher evaporation from this sand in comparison to pure sand. The dark color of the soil had an influence on the increase in soil temperature, which improved evaporation. Water retention and capillary suction was higher in organic soil. The increase of evaporation from a landfill site during landfill leachate recirculation could be achieved by sewage sludge disposal at the top of the waste heap.

The values of E/Q_h ratio in all experimental variants were below 1.0. This proves that not all water, including landfill leachate being irrigated within soil–plant systems with willow, had evapotranspirated. This indicates potential migration of pollutants from leachate into ground water. Białowiec et al. (2004) determined a risk of ground water pollution while disposing landfill leachate in soil–plant systems deprived of isolation layers. High concentrations of pollutants such as nitrates, in particular, were observed in the range from 70.9 to 164.1 mg N-NO_3/dm^3 and nitrites in the range from 0.19 to 46.58 mg N-NO_2/dm^3. Tyrrel et al. (2002) confirmed that phytoremediation of landfill leachate through land application may indicate a risk of ground water contamination and soil degradation. Therefore, in order to protect ground waters, Smith et al. (1999) suggested either applying landfill leachate to impermeable soils or irrigating soil–plant systems inside the landfill site at the top of the waste heap. The increase of transpiration, i.e. the increase of plants' participation in evapotranspiration, leads to an increase in evapotranspiration efficiency in soil–plant systems as compared to evaporation from the plantless soil surface. Białowiec (2005) assumed that the participation of plants in evapotranspiration will be significant when T/E is higher than 0.5 and E/E_v equals 1.83, i.e. when transpiration is higher than evaporation. Willows growing on sand with sewage sludge, with HLR 1 to 5 mm/d, and also growing on sand soil with HLR 1 mm/d, had a significant influence on evapotranspiration efficiency in period I, especially in system WP1 because of high involvement of transpiration in evapotranspiration. In vegetation period I, in the systems with willow growing on the sand soil, with HLR 3–5 mm/d, the values ratio T/E did not exceed 0.5 value (Table 2). This proves the advantage of evaporation in evapotranspiration. The values of E/E_v ratio exceeding 1.83 were found in the experimental variants in which the values of T/E ratio were higher then 0.5 (Table 2). That confirms the plants' significant involvement in evapotranspiration in the soil–plant system where the calculated limited values of the T/E and the E/E_v ratios were exceeded. Analogous but slightly lower influence was also observed in the soil–plant systems with a low biomass yield and even with willow necrosis in vegetation period II (WC3, WC5, WS3, WS5).

Białowiec et al. (2003) observed higher values of T/E and E/E_v ratios while examining the ability of landfill leachate evapotranspiration from young willow shoots—*S. amygdalina* L., which were in the range from 0.72 to 0.93 and from 3.7 to 14.4, respectively. Those results were obtained using a landfill leachate whose concentration of components was lower than that in this research. It is expected that the involvement of plants in evapotranspiration will increase while treating less polluted landfill leachates.

5. Conclusions

The application of willows increased evapotranspiration efficiency by 1.28–5.12 times as compared to evaporation efficiency from the plantless soil surface. The involvement of plants in evapotranspiration from soil–plant systems with the leachate hydraulic loading rate of 1 mm/d was significant and was in the range of 62–80%.

The willow species *S. amygdalina* L. may be used for landfill leachate evapotranspiration with HLR 1 mm/d, and even with HLR 3 mm/d, providing that sewage sludge is added to the soil prior to use.

There exists a risk of ground water contamination while applying landfill leachate to soil–plant systems located in an area which is deprived of isolation layers.

A linear correlation between biomass growth and transpiration may prove that plants with high biomass growth should be selected while designing soil–plant systems to be used for landfill leachate disposal on a technical scale. An increase in the plants' biomass growth can be obtained by good management and fertilization, for instance by sewage sludge addition.

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