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Duckweed does not improve the efficiency of municipal wastewater treatment in lemna system plants

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Abstract: This study investigated the operation of three full-scale Lemna System surface flow municipal wastewater treatment plants, built according to the Lemna Corporation design. These plants consist of two ponds, the first aerated and the second for duckweed, with a barrier grid in the latter to ensure uniform plant distribution across its area. According to designers duckweed improves the efficiency of wastewater treatment. The three treatment plants are situated in central Poland and they differ in the occurrence of duckweed, two of them, located in Raków and Bąkowiec, operate without duckweed. and the third in Falęcin Stary, *Lemna minor* covers ca. 90% of second pond surface. The efficiency of Lemna System wastewater treatment was found not to differ between the plants with and without duckweed. The aerated pond played the main role in reduction of pollutants in the investigated Lemna Systems.

Introduction

In Poland constructed wetlands are mainly applied to the treatment of household sewage (Obarska-Pempkowiak et al. 2010, Pawęska and Kuczewski 2013). To a limited extent they are also used in treating the specific kinds of wastewater i.e. stormwaters (Bergier 2011), landfill leachate (Wójcik 2010) as well as in the utilisation of sewage sludges (Hardej and Ozimek 2002). In Poland constructed wetlands installed are most often those with a subsurface flow and emergent macrophytes, as well as those with surface flow and pleustonic plants (Ozimek and Czupryński 2003a). The use of pleustonic plants (duckweed) in wastewater systems dates back to the 1970s (Culley and Epps 1973, Wolverton and McDonald 1976). Floating duckweeds were originally recommended for wastewater treatment in developing countries with a warm climate (Culley 1973), then subsequently for colder regions (Ngo 1987, Poole 1996). Lemnaceae are widely distributed and have succeeded in colonizing nearly all regions of the world except areas with a cold summer climate (Landolt 1982). The ability of duckweed to treat wastewater has been attributed to its rapid growth rate and high capacity for nutrient removal by direct uptake from its environment (Cheng et al. 2002, Körner et al. 2003 Ozengin and Elmaci 2007). In regions with a temperate climate, *Lemna gibba* L. and *Lemna minor* L. are the most popular species in constructed wetlands (Ozimek 1996). The utility of duckweed in wastewater treatment plants has been demonstrated mainly in laboratory and outdoor experiments (Oron et al. 1987, Öbek and Hasar 2002, Shammout et al. 2008) and by the operation of pilot plants, often for a limited period of time (Ran et al. 2004, Zimmo et al. 2004, Jena et al. 2010, Priya et. al. 2012). Vymazal (2001) highlighted the lack of information on the treatment efficiency of full-scale operational versions of the duckweed-based system. Full-scale wastewater treatment plants, with duckweed have been used mainly in warmer regions of the world, e.g. Taiwan, China, Bangladesh, India and Bolivia (Shammout et al. 2008, Gijzen and Veenstra 2000). In Europe, full-scale Lemna System wastewater treatment plants (operated throughout the year) have been constructed mainly in Poland (Ozimek and Czupryński 2003b, Citres et al. 2006). This system was recommended by its designers as inexpensive, easy to operate and efficient in wastewater treatment. Duckweeds treat wastewater directly through nutrient uptake and accumulation in their tissue, and indirectly by creating an environment for nitrifying and denitrifying bacteria through stratification of oxygen in the water column. In addition, the plants can eliminate smelts, algae by shading, and mosquitoes by forming a physical barrier to their larvae (Poole 1996). In Poland, the first original full technical scale Lemna System designed by the Lemna Corporation was built in 1992. Lemna System consists of two ponds: a primary mechanically aerated pond and secondary duckweed pond. In Poland in the 1990s 40 Lemna Systems were operated, ten years later some of them changed technology because of the problem with duckweed.

Our observations have led to the working hypothesis that the presence of duckweed does not in fact raise the effectiveness of wastewater treatment by Lemna System, but generates unnecessary ballast. In order to verify this hypothesis we have compared the efficiency of the reduction of suspended solids, biochemical oxygen demand, chemical oxygen demand, nitrogen and phosphorus in wastewater occurring in three full-scale Lemna Systems situated in central Poland, one with duckweed and two without.

Area

This study examined three Lemna System wastewater treatment plants, built according to the Lemna Corporation design. They are located in three villages in central Poland: Falęcin Stary, Raków and Bąkowiec. The plants were built in 1993 in order to treat municipal wastewater. Each plant consists of two ponds joined in series: the first an aerated pond (AP) with baffles to improve the hydraulics, and the second a Lemna pond (LP) with a floating barrier grid to prevent clustering of the duckweed. The characteristics of the three Lemna System wastewater treatment plants are summarized in Table 1.

Material and methods

Investigations were carried out monthly from March 2010 to December 2010. In 2011 due to reconstruction work on the Lemna System in Falęcin Stary in September 2011, the sampling period ended in August. The water temperature and area covered by duckweed were monitored every third day. The species composition and biomass of plants were determined monthly. A "Czerbak"-type sampler (Czernik and Rybak 1995) was used to collect plant biomass. Back in the laboratory, the collected plants were washed and dried at 105°C for 24 hours. Plant dry mass, the nitrogen and phosphorus contents were analyzed according to Standard Methods (2005).

Samples of wastewater were collected at 3 sites in each Lemna System: 1 – inlet to AP, 2 – inlet to LP and 3 – outlet from LP. During each sampling session the dissolved oxygen content and pH of wastewater were measured at each of the sites using a WTW Multi 3430 SET G probe. Suspended solids (SS), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), ammonia nitrogen ($N\text{-}NH_4^+$), total phosphorus (TP) and orthophosphate phosphorus ($P\text{-}PO_4^{-3}$) were analyzed in the laboratory according to Standard Methods (2005).

The arithmetic mean, standard deviation (SD) and the percentage reduction of every chemical parameter were calculated for each site. To determine whether any changes in the parameters within the Lemna Systems were significant, and if the presence of duckweed had a significant influence on wastewater treatment, the data were compared by one-way analysis of variance without repetition. Statistical analyses were performed using SAS Institute Inc. version 9.2 software.

Results

Plant growth on the water surface occurred only in the Falęcin Stary. In both Raków and Bąkowiec, duckweed was absent despite the introduction of plants several times from natural stands. In Falęcin *Lemna minor* created the monospecific community. The area covered by plants and their biomass changed during the growing season. The distribution of plant biomass was not uniform across the whole pond area, and varied in different squares of the grid. The SD was high in consecutive months. The comparison of two investigated biomass showed that the biomass of *Lemna minor* differed significantly only at the beginning of vegetation season (Table 2). At the beginning of June 2010 the biomass of plants was harvested, and the mean biomass per m^2 of the overgrown area was decreased two-fold. The biomass was rapidly replenished and by August, the maximum biomass of duckweed was recorded. The second harvest of duckweed took place in August.

The mean temperature and pH values recorded in wastewater were very similar during the investigated period in the three Lemna Systems. At the three consecutive sampling stations, the mean temperature of the wastewater decreased and the pH and dissolved oxygen increased. The pH remained quite stable at each site, whereas the temperature and dissolved oxygen varied considerably. The mean concentration of dissolved oxygen was lower in AP than in LP (Table 3).

The reduction of SS, COD and BOD_5 in the samples collected from consecutive sites was similar in each wastewater treatment plant. The removal efficiency was high in the aerated pond (62–77% for SS, 75–84% for BOD5 and 54–68% for COD) and very low in the Lemna pond in the systems with and without duckweed. When the SS, COD and BOD_5 were compared within the system, significant differences ($P = 0.05$) were noted only between samples collected at the first site and the other sites in all three wastewater treatment plants (Fig. 1). About 50% of measurements of SS and BOD_5, the basic parameters used to establish water quality according to the Water Law Act (2001) in Poland, exceeded the required standards.

The quantification of different nitrogen forms indicated that the sequence of main N-removal processes, ammonification-nitrification-denitrification, did not proceed efficiently in the treatment systems. In the best case, the total Kjeldahl nitrogen and ammonia nitrogen concentration was depleted by only 20%. The presence of duckweed had

Table 1. Characteristics of the three Lemna Systems wastewater treatment plants in Central Poland (AP – aerated pond, LP – Lemna pond)

Location	Year of construction	Flow m^3/day	Area (ha)		Depth (m)		Retention (day)	
			AP	LP	AP	LP	AP	LP
Falęcin	1993	300	0.25	0.4	2.5	4.0	25	30
Rakow	1993	300	0.28	0.32	4.0	3.8	20	40
Bąkowiec	1993	300	0.51	0.52	3.0	3.0	20	21

Table 2. Seasonal changes in area overgrown by duckweed and its dry mass per m^2 (mean + SD, n = 10) in the Lemna System at Falęcin Stary

Month	% of pond area covered by duckweed		Dry mass of duckweed (g/m^2)	
	2010	2011	2010	2011
Mar	0.5 ± 0.4	0	1 ± 0	0
Apr	12 ± 3	2 ± 1	70 ± 54.	1 ± 1*
May	37 ± 7	10 ± 5	132 ± 131	10 ± 9*
Jun	94 ± 9	75 ± 10	333 ± 112	279 ± 170
Jul	96 ± 37	80 ± 16	195 ± 70	280 ± 176
Aug	95 ± 10	75 ± 30	377 ± 230	289 ± 188
Sep	95 ± 13		268 ± 223	
Oct	85 ± 16		153 ± 112	
Nov	63 ± 22		99 ± 79	
Dec	15 ± 12		14 ± 6	

* significant differences between years, P<0,05

Table 3. Variations in temperature, pH and dissolved oxygen (mean ± SD, n = 18) in wastewater samples collected at the three consecutive sampling stations in 2010–2011. 1 – inlet to AP, 2 – inlet to LP, 3 – outlet from LP

Parameter	Location of Lemna System	Sites		
		1 AP	2 LP	3 LP
Temperature (°C)	Falęcin	11.4 ± 6.7	10.8 ± 6.4	11.0 ± 7.2
	Raków	13.7 ± 7.7	12.7 ± 7.4	11.9 ± 6.3
	Bąkowiec	13.9 ± 7.9	13.4 ± 9.0	12.8 ± 8.4
pH	Falęcin	7.6 ± 0.4	8.1 ± 0.4	8.1 ± 0.3
	Raków	7.5 ± 0.3	8.4 ± 0.6	8.3 ± 0.6
	Bąkowiec	7.9 ± 0.1	8.9 ± .4.0	8 .8 ± 0.4
Dissolved oxygen (mg/L)	Falęcin	0.3 ± 0.2	4.0 ± 2.5	5.0 ± 2.1
	Raków	0.4 ± 0.4	5.4 ± 2.3	7.5 ± 1.8
	Bąkowiec	1.3 ± 1.7	9.5 ± 5.6	6.9 ± 2.2

no effect on the reduction of TKN, $N\text{-}NH_4^+$. Average TKN concentrations were almost equal in samples collected at the inlet and outlet of the Lemna ponds in all three wastewater treatment plants (Fig. 2).

The removal efficiency of total phosphorus and phosphate phosphorus was very low in all investigated Lemna Systems. Aeration ponds played the main role in the removal of phosphorus (Fig. 3).

In 2010, a dry mass of 240 kg of duckweed was harvested in LS in Falęcin Stary, which was equivalent to the removal of 2.6 kg of phosphorus and 10.3 kg of nitrogen within the plant biomass. This represented only 0.3% of the nitrogen and 0.2% of the phosphorus in the wastewater flowing annually through the Lemna System in Falęcin Stary (Table 4).

Discussion

Since Lemna System wetlands are still highly controversial, it is important to determine whether the design of such wastewater treatment plants is optimal and if they operate effectively. This study examined the functioning of three full-scale surface flowing wastewater Lemna Systems built according to the Lemna Corporation design and operated for the past two decades. The three plants differed in the occurrence of duckweed. Over the last decade, the plant in Falęcin has operated with *Lemna*, while the other two, in Raków and Bąkowiec, have operated without. This allowed us to compare the functioning of full-scale operating systems with and without *Lemna* and to determine how the presence of duckweed influences the efficiency of wastewater treatment. The overall efficiency of wastewater treatment in full-scale Lemna System plants is usually evaluated by comparing parameters of the inlet and outlet water (Barbusiński et al. 2006, Miernik and Wałęga 2006).Very little is known about the role of duckweed (Ozimek 1996) although the designers of this system stressed that both direct and indirect functions of duckweed are very important. The direct role of plants in nutrient cycling is proportional to their biomass. The maximal biomass of *Lemna minor* in the Falęcin LSt was ten times higher than that in natural eutrophic waters in a cold climate, but similar to the value found in the LS at Mniów (Ozimek and Czupryński 2003) and lower than that reported for natural

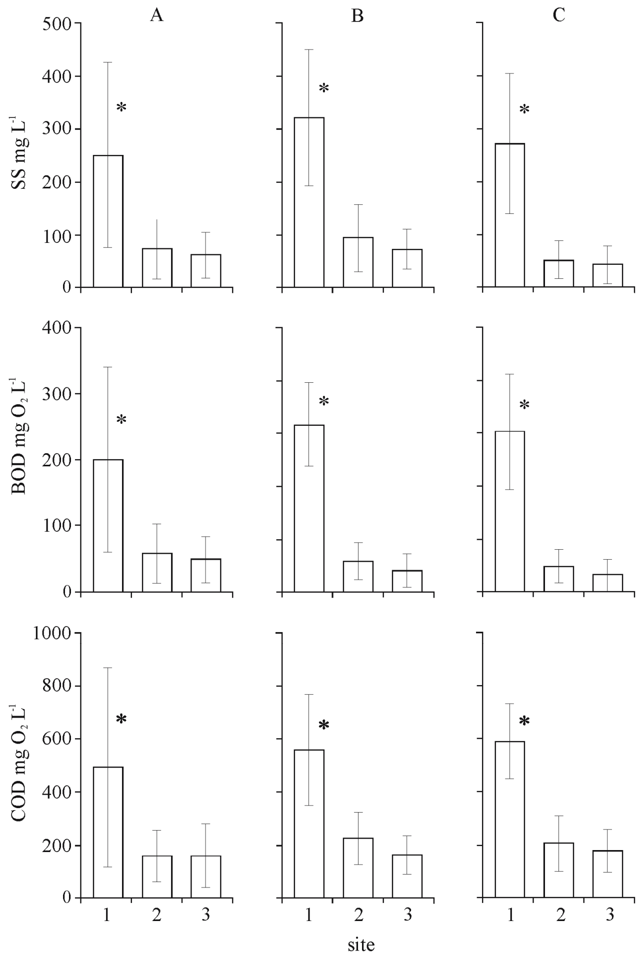

Fig. 1. Changes in concentration of SS, BOD_5 and COD (mean ± 1SD, n= 18) on consecutive sites (1 – inlet to AP, 2 –inlet to LP, 3 – outlet from LP, * indicated significant difference within system, P = 0,05) in three Lemna Systems (A – Falęcin Stary, B – Raków, C – Bąkowiec)

waters in a warm climate (Culley and Epps 1973). Despite this high biomass of *Lemna minor*, its effect on the treatment of wastewater at this plant was apparently insignificant. The aerated pond played the main role in the reduction of SS, BOD and COD in the investigated Lemna Systems. Their fractions removed in the Lemna pond were very small and there were no differences in this activity recorded in the ponds with and without *L. minor*. The presence of *L. minor* had a negligible effect on TSS, BOD and COD of the wastewater. Classical stabilization ponds, which have been in use in many countries since the 19th century, produce similar results. According to Körner et al. (1998) the role of duckweed in the degradation of organic material is to supply additional oxygen and to provide a surface for bacterial growth. Previously, these authors failed to confirm the suggestion that duckweed acts to decrease the BOD_5 by heterotrophic uptake of organic compounds (Korner et al. 2003).

The removal of nutrients was generally poor in both the aerated and Lemna ponds and was very similar in the systems with and without duckweed. Quantification of different nitrogen forms indicated that the sequence of the main N-removal processes (i.e. ammonification – nitrification – denitrification) did not proceed efficiently in this treatment system. The removal of TN and ammonium nitrogen was low and occurred mainly in the aerated pond. Similar results have been reported for the Lemna System with *Lemna* in Mniów (Ozimek and Czupryński 2003b) and a system without *Lemna sp.* in Swierklaniec (Barbusiński et al. 2006). Therefore, the direct role of duckweed in the removal of nitrogen and phosphorus from wastewater is not important. Through plant biomass it was only possible to remove 0.3% of nitrogen and 0.2% of phosphorus flowing annually into this Lemna System. Similar values were reported for the Lemna System at Mniów (Ozimek and Czupryński 2003b). The management of duckweed biomass is expensive and time consuming, and the planning of the annual harvest is

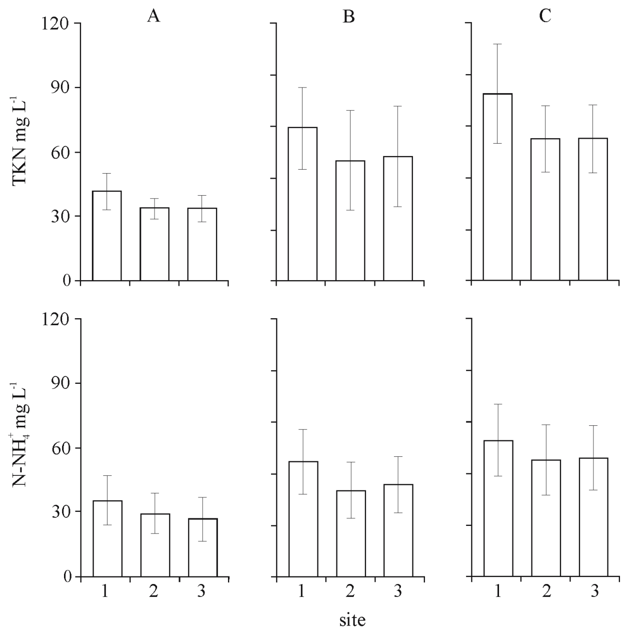

Fig. 2. Changes in concentration of TKN and $N\text{-}NH_4^+$ (mean ± 1SD, n= 18) on consecutive sites (1 – inlet to AP, 2 – inlet to LP, 3 – outlet from LP) in three Lemna Systems. (A – Falęcin Stary, B – Raków, C – Bąkowiec)

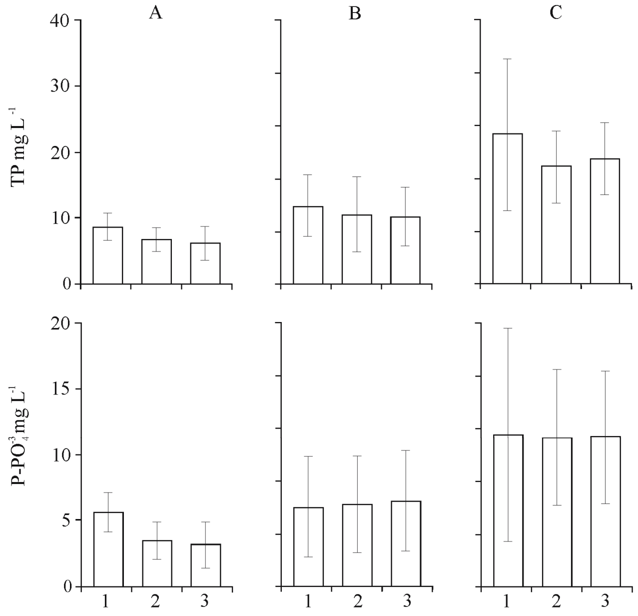

Fig. 3. Changes in concentration of TP and $P\text{-}PO_4^{-3}$ (mean ± 1SD, n= 18) on consecutive sites (1 – inlet to AP, 2 – inlet to LP, 3 – outlet from LP) in three Lemna Systems (A – Falęcin Stary, B – Raków, C – Bąkowiec)

Table 4. The role of duckweed in the removal of nitrogen and phosphorus from the Lemna System. in Falęcin Stary

Annual loading with wastewater (kg)		Mass removed from system with duckweed (kg)			% removal of loading from system with duckweed biomass	
Nitrogen	Phosphorus	Dry mass	Nitrogen	Phosphorus	Nitrogen	Phosphorus
3300	1100	240	10.3	2.6	0.3	0.2

problematic because it is difficult to predict the likely biomass of duckweed from year to year.

Therefore, the efficiency of wastewater treatment in LS is similar to that found in classical stabilization ponds, which are cheaper in both construction and operation. The results of the present study demonstrate that the role of duckweed is of little importance in the Lemna System.

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Rzęsa nie poprawia efektywności oczyszczania ścieków komunalnych w oczyszczalniach typu Lemna System

Streszczenie: Badania prowadzono w trzech czyszczalniach hydrofitowych z powierzchniowym przepływem ścieków typu Lemna System, zbudowanych według projektu Lemna Corporation. Składają się one ze stawu napowietrzanego i stawu rzęsowego wyposażonego w system barier mających na celu równomierne rozmieszczenie roślin. Stawy poprzedzone są osadnikiem wstępnym. Według projektantów odpowiednia praca tych oczyszczalni związana jest z występowaniem rzęsy na powierzchni stawu rzęsowego. Badano efektywność oczyszczania ścieków komunalnych w trzech oczyszczalniach Lemna System usytuowanych w centralnej Polsce ze szczególnym uwzględnieniem roli stawu rzęsowego i samej rzęsy. Oczyszczalnie różniły się między sobą występowaniem rzęsy. W dwóch z nich (w Rakowie i Bąkowcu) w trakcie całego okresu badań rzęsa nie występowała, natomiast w trzeciej (w Falęcinie Starym) w okresie wegetacyjnym pokrywała do 90%.powierzchni stawu. Efektywność oczyszczanie ścieków nie różniła się w oczyszczalni z rzęsą i bez rzęsy. Rzęsa nie wpływała istotnie na efektywność oczyszczania ścieków. We wszystkich oczyszczalniach główną rolę w redukcji zanieczyszczeń odgrywał staw napowietrzany.