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ADVANTAGES AND LIMITATIONS OF DUCKWEED-BASED WASTEWATER TREATMENT SYSTEMS

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ABSTRACT

In order to find a reliable, simple and cost-effective small wastewater treatment system, an experimental research programme on duckweed-based treatment systems was carried out. In spite of the profitable characteristics of duckweed (high productivity, high protein content, wide geographic distribution, control of negative impacts from conventional wastewater treatment ponds), the results obtained confirm that their extensive use in Italy seems difficult because of the high requirement of land area and the ceasing of growth in winter months (at least in Northern Italy). In temperate climates, a reasonable use of duckweed looks to be the production of good quality secondary effluents (BOD and SS removal) from small communities, especially in seasonal (summer) wastewater treatment plants. Another use is algae removal from facultative lagoon effluents. Nitrogen removal can only be reasonably obtained in duckweed-covered ponds with supplemental aeration. Because of several constraints due to the markets and to environmental regulations, harvested duckweed has to be disposed of as sewage sludge (e.g. compost or biogas production). © 1997 IAWQ. Published by Elsevier Science Ltd

KEYWORDS

Algae removal; aquatic plants; denitrification; duckweeds; harvesting; nitrification; Northern Italy; seasonal wastewater treatment plants; small wastewater treatment systems; temperate climate

INTRODUCTION

The great interest in the use of aquatic macrophytes, in particular duckweed, for wastewater treatment is due to the demand for adequate treatments of small community wastewater which cannot be sewered to a centralized wastewater treatment system in a cost-effective way. These treatments must be reliable and easy to operate and must have low capital and operating costs. Sometimes, the use of macrophytes in water pollution control seems to be able to meet those requirements (Brix, 1991, 1993; O'Brien, 1981; Reddy and DeBusk, 1987; Stowell *et al.*, 1981).

Duckweed is a small floating aquatic plant, well known for its high productivity and high protein content, that in temperate climates, and particularly in Italy (Corradi *et al.*, 1981), can offer good possibility of use, unlike water hyacinth (*Eichhornia crassipes*, used especially in tropical and sub-tropical climate), since it is more resistant to low temperature (Brix, 1991; Buddhavarapu and Hancock, 1991; O'Brien, 1981; Oron *et al.*, 1985; Radoux and Kemp, 1992; Zirschky and Reed, 1988).

DUCKWEEDS

Characteristics

Morphology. Duckweed (*Lemnaceae*) is a family of floating monocotyledons consisting of 4 genera (*Lemna*, *Spirodela*, *Wolffia* and *Wolffiella*) and 28 species (Sculthorpe, 1967). Their structure is very simple and distinct leaves and stems, distinguishable in other vascular plants, are replaced by a fusion of both, called fronds. They are green and have a small size (1-3 mm). They also have short but dense roots (1-3 cm).

Growth conditions. Duckweed grows on a wide range of quiescent or slow-current waters, and also relatively polluted waters, saline waters and eutrophic water bodies (Oron *et al.*, 1986). Typical pH range is 4.5-7.5, though duckweed growth is completely inhibited only at pH greater than 10 (Zirschky and Reed, 1988).

Duckweed are able to grow at water temperatures as low as 5-7°C (Buddhavarapu and Hancock, 1991; Oron *et al.*, 1986) and at atmospheric temperatures as low as 1-3°C (Brix, 1993; Harvey and Fox, 1973; O'Brien, 1981). Below these temperatures, the plants survive by lying dormant on the pond bottom until warmer temperatures return (Buddhavarapu and Hancock, 1991; Zirschky and Reed, 1988). Copelli *et al.* (1982) report that, in Northern Italy, duckweed can vegetate from April until November (water temperatures above 5°C and solar radiation above 150 cal m^{-2} d^{-1}).

Duckweed fronds grow in colonies that, in particular growing conditions, form a dense and uniform surface mat, even 2-cm thick (Zirschky and Reed, 1988). Maximum surface density is 130 gDW m^{-2} (Reddy and DeBusk, 1987).

Growth rates. Duckweed are counted among the most vigorously growing plants on earth. Each frond absorbs its nutrients from water directly through the whole plant and not only through a central root system as in other, higher plants (Oron *et al.*, 1985). Harvey and Fox (1973) obtained a doubling of frond number of *Lemna minor* every 4 days, under laboratory conditions (constant temperature of 24°C and 12-hour dark and light photoperiod). Oron *et al.* (1986) report specific growth rates (i.e. growth rates related to original mass) of 0.10-0.35 gDW $(gDW)^{-1}$ d^{-1}, equivalent to doubling times of 2,3-7,3 d. Reddy and DeBusk (1987) report annual productivity (or growth rates) of 6-26 tDW ha^{-1} yr^{-1} (16-71 gDW m^{-2} d^{-1}). Specific growth rates increase if atmospheric and water temperatures, nutrient content in wastewater and harvesting frequency increase (Radoux and Kemp, 1992) and surface density decreases (Ward, 1987). As productivity is the product of specific growth rate and surface density, there is an intermediate duckweed density corresponding to the maximum productivity (Ward, 1987).

Chemical composition. Apart from having high productivity, duckweed have high protein content and low fiber content. As a matter of fact, unlike the other, higher plants, the entire plant body consists of metabolically active, nonstructural tissue (Oron *et al.*, 1985; Zirschky and Reed, 1988). Culley and Epps (1973) have found protein content of 140-260 g $(kgDW)^{-1}$ in duckweed harvested from natural water bodies and 290-410 g $(kgDW)^{-1}$ in duckweed harvested from wastewater ponds, nitrogen content of 20-40 gN $(kgDW)^{-1}$ and 40-60 gN $(kgDW)^{-1}$ respectively, phosphorus content of 2-10 gP $(kgDW)^{-1}$ and 13-29 gP $(kgDW)^{-1}$ respectively, and fiber content of 90-120 g $(kgDW)^{-1}$ and 60-90 g $(kgDW)^{-1}$ respectively. This is due to the higher nutrient content in wastewater than in natural waters and to the vigorous growth of duckweed kept young through a frequent harvesting. Reddy and DeBusk (1987) report nitrogen and phosphorus contents of 25-50 gN $(kgDW)^{-1}$ and 4-15 gP $(kgDW)^{-1}$ respectively. Typical water content of duckweed is 94-95% (Corradi *et al.*, 1981; Oron *et al.*, 1987; Oron and Willers, 1989; WPCF, 1990).

Main affects of duckweed on wastewater treatment ponds

Duckweed play, compared to water hyacinths, a less direct role in the treatment process as they lack an extensive root system and therefore provide a smaller surface area for attached microbial growth (Brix, 1991; Stowell *et al.*, 1981, Zirschky and Reed, 1988). Therefore, most of the biological activity in a duckweed-covered pond is due to bacteria and other microorganisms suspended in the water column, as with any other conventional lagoon system (Zirschky and Reed, 1988). However, duckweed form a dense surface mat that covers the entire water surface, restricting light penetration and water aeration by direct diffusion from the atmosphere, minimizing wind effects on water and reducing evaporation from water surface.

Restriction of light penetration and algae and mosquito control. Zirschky and Reed (1988) report that a 25-gDW m^{-2} surface mat reduces light penetration by 35%, while a 195-gDW m^{-2} surface mat reduces light penetration by 94%. This can be used to prevent the undesirable growth of photosynthetic microorganisms, as microalgae (Hancock and Buddhavarapu, 1993; Stowell *et al.*, 1981; Zirschky and Reed, 1988). Moreover, the dense surface mat of duckweed prevents mosquito larvae from reaching the water surface (Culley and Epps, 1973), otherwise from water hyacinth ponds (Oron *et al.*, 1986).

Restriction of gas-liquid oxygen transfer and odour control. The dense cover of duckweed prevents oxygen from entering the water by diffusion. This fact, together with the lack of photosynthetic oxygen production by phytoplankton, makes the water largely anaerobic (Brix, 1991; Culley and Epps, 1973). However, some oxygen produced during photosynthesis is conveyed through the duckweed roots into the water (Stowell *et al.*, 1981; Zirschky and Reed, 1988) and supports the formation of a 10-cm thick aerobic layer in the root zone (Hancock and Buddhavarapu, 1993). This layer favours the oxidation of the rising gases (reduced products of anaerobic fermentation of organic matter), preventing odour diffusion.

Minimization of wind effects on water. The dense cover of duckweed minimizes the wind effects on water and sedimentation processes, inhibiting roiling of settled matter (Stowell *et al.*, 1981; Zirschky and Reed, 1988).

Reduction of evaporation from water surface. Evapotranspiration from a duckweed-covered pond is lower than evaporation from an open water surface, at the same environmental conditions (solar radiation, air temperature and humidity, windspeed), though it is higher than grass evapotranspiration (FAO, 1977; Oron *et al.*, 1985; Oron, 1990).

Contaminant removal mechanisms

SS, BOD and pathogens removal. SS, BOD and pathogens removal mechanisms are the same as encountered in conventional wastewater treatment ponds.

N removal. Nitrogen can be removed by direct uptake by and subsequent harvesting of duckweed, volatilization of ammonia and bacterial nitrification/denitrification. Volatilization plays a negligible role because of pH lower than 8-9. Harvesting plants to remove nitrogen is generally inefficient (Stowell *et al.*, 1981) and shows a slight increase of removal efficiency in shallow ponds (30-50 cm depth). As a matter of fact, mean annual N uptake by duckweed is 350-1200 kgN ha^{-1} yr^{-1} (Reddy and DeBusk, 1987). In order to achieve a 75%-N removal, 23-78 m^2 PE^{-1} (1 PE=10 gN d^{-1}; Andreottola *et al.*, 1994) and a significant solid waste handling capacity are needed. Nitrification of ammonia-nitrogen can occur in the oxidized root zone of duckweed, denitrification occurs into reduced environments in the water column or in the sediments. Because of low depth of the aerobic layer, the nitrification step of the nitrification/denitrification process is the rate-limiting one. In order to obtain nitrogen removal by nitrification/denitrification, either the use of supplemental aeration or the treatment of nitrified wastewater is needed.

P removal. Phosphorus can be removed by direct uptake by duckweed or chemical storage in the sediments. Ultimate disposal will be harvesting duckweed and dredging the sediments. Mean annual P uptake by duckweed is 116-400 kgP ha^{-1} yr^{-1} (Reddy and DeBusk, 1987) and, in order to achieve a 75%-P removal, 12-41 m^2 PE^{-1} (1 PE=1.7 gP d^{-1}; Andreottola *et. al.*, 1994) are needed. Anyway, the phosphorus removal potential of aquatic systems is variable and transitory (Stowell *et al.*, 1981).

Potential use of the harvested duckweed biomass

Harvested duckweed, if grown on domstic wastewater lacking in heavy metals and other hazardous compounds, can be used as agricultural fertilizer and in the production of high-quality ("green") compost. An alternative use is the generation of biogas from anaerobic digestion. One of the major problems is the high water content that can be reduced by natural drying.

In spite of the very high nutritional value of duckweeds, their actual use as animal feed does not seem a reasonable proposal, because of several constraints due to the markets and to environmental regulations. It follows that harvested duckweed would have to be disposed of as sewage sludge.

Practical information on the use of duckweed

Physical features of duckweed-covered ponds. Duckweed basins should be constructed with a large length/width ratio (higher than 10) to encourage plug-flow conditions in order to prevent short-circuiting (Zirschky and Reed, 1988) and to simplify harvesting operations. Although dense, the surface mat of duckweed is susceptible to movement by the wind. Therefore, artificial wind breaks (O'Brien, 1981), emergent aquatic macrophytes (Zirschky and Reed, 1988), trees (Culley and Epps, 1973) or, more simply, floating barriers are used to minimize disturbance. As a matter of fact, high winds may pile duckweed into thick mats and, beside the incomplete coverage of the pond surface, plant decomposition can be increased with the consequent odour production (Brix, 1991, 1993; Buddhavarapu and Hancock, 1991). Because of the anaerobic environment inside the pond, post-aeration of the effluent is needed before the discharge (Zirschky and Reed, 1988).

Harvesting. Duckweed are easy to harvest because they form no structural unity which would make cutting or chopping necessary (Culley and Epps, 1973; Oron *et al.*, 1985). Harvesting must balance duckweed production (Corradi *et al.*, 1981) and can be necessary in order to reduce the BOD and solids load to a duckweed pond (Stowell *et al.*, 1981). The harvesting operation can be carried out by means of specially designed aquatic harvesters (Buddhavarapu and Hancock, 1991) or mechanical skimming devices (Culley and Epps, 1973; O'Brien, 1981; Oron, 1990). Manual harvesting is labour intensive and can be used only in smaller systems.

EXPERIMENTAL PROGRAMME

A 5-month (August-December 1993) experimental research was been carried out on a demonstrative pilot-plant with the aim to evaluate the behaviour of a duckweed-covered pond in Northern Italy at low temperature conditions.

MATERIALS AND METHODS

Experimental layout

The experimental research was carried out on a demonstration pilot-plant located in Gorgonzola, near Milan (Italy). The pilot-plant (volume 435 m^3, surface area 350 m^2, length 70 m, width 5 m, and depth 2.3 m) was fed with a primary settled urban wastewater (flow rate of 1.15 $m^3\ h^{-1}$ and mean influent BOD concentration of 142 mgBOD l^{-1}, corresponding to hydraulic retention time of 16 d, volumetric organic loading rate of 9 gBOD $m^{-3}\ d^{-1}$, and per capita surface area of 5.4 $m^2\ PE^{-1}$).

The pilot-plant used a square grid (3.05 x 3.05 m^2) of floating barriers to contain the growing plants and to prevent their movement by the wind. The surface was then divided in 17 different sectors.

The pilot-plant was designed to obtain nitrification, by means of air supply in three sectors. During the experimental period the blower has been switched off, in order to study the behaviour of a completely natural duckweed-covered pond.

Sampling and analyses

Wastewater sampling was carried out on the influent and the effluent stream and in three different points of the basin (corresponding to hydraulic retention time of 4, 8 and 12 d respectively). Total suspended solids (TSS), COD, BOD_5, ammonia-nitrogen (NH_4^+-N), nitrate-nitrogen (NO_3^--N), TKN and total phosphorus (TP) were measured according to Italian Standard Methods (IRSA-CNR, 1979). Total nitrogen (TN) was calculated as the sum of TKN and NO_3^--N.

Temperature and dissolved oxygen were measured every work day in several points of the pilot-plant. Duckweed productivity (on a dry weight basis) was measured monthly in the entire basin.

Wastewater characteristics

The mean characteristics of the primary settled wastewater fed to the pilot-plant were: 125 mg l^{-1} total suspended solids, 316 mg l^{-1} total COD, 142 mg l^{-1} total BOD, 42 mg l^{-1} total nitrogen, 24 mg l^{-1} ammonia-nitrogen and 2.6 mg l^{-1} total phosphorus.

Operating conditions

The pilot-plant was managed with the aim of maintaining a constant 90-gDW m^{-2} surface density of duckweed that, in November and December, was reduced to 75 gDW m^{-2} because of the ceasing of the duckweed growth. Duckweed harvesting and density correction have been carried out manually every month, in all the 17 sectors. In order to favour data elaboration, the pond surface was ideally divided in 3 different zones: "influent end", "central zone" and "effluent end".

In Figure 1, minimum and maximum air temperature at Monza meteo-station and wastewater temperature at the effluent end of the pilot-plant are shown. At the end of November and in December, wastewater temperature decreased from 10 to 5°C along the basin, in spite of the thermal insulation due to duckweed.

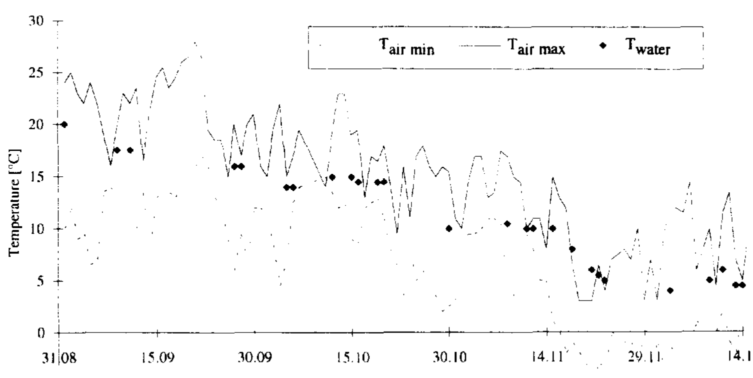

Figure 1. Minimum and maximum air temperatures at Monza meteo-station and wastewater temperature at the effluent end of the pilot-plant.

RESULTS AND DISCUSSION

Duckweed growth rate

In Figure 2a, duckweed productivity in October and November in the three different zones of the pilot-plant is shown. Duckweed productivity not only decreased dramatically from October to November, due to the decrease of air and wastewater temperature, but also, in the same month, from the influent end to the effluent end. This can be explained assuming that duckweed are able to assimilate only superficial nutrients that, without vertical mixing in the water column, decrease along the basin. Moreover, especially in November, the temperature of the effluent wastewater was lower than that of the influent wastewater.

Duckweed productivities were lower than those measured in October and November in another pilot-plant located in Northern Italy (3.91 gDW m^{-2} d^{-1}; Copelli *et al.*, 1982), where duckweed was harvested weekly (and not monthly) and basin depth was lower (0.6 m versus 2.3 m).

<u>TSS and COD removal</u>

TSS removal efficiency (Figure 2b) was good in the whole experimental period (55-80%). TSS effluent concentration ranged between 26 to 54 mgTSS l^{-1}. TSS removal was lower at the end of autumn, probably because of the partial degradation of dead and settled duckweed.

COD removal efficiency (Figure 2c) was higher than 75%, in the first half of the basin, until October (effluent wastewater temperature higher than 15°C), whereas it decreased to 60%, in the whole basin, in December (wastewater temperature in the range 5-10°C along the basin). COD effluent concentration ranged between 62 and 129 mgCOD l^{-1}. COD removal was lower at the end of autumn, probably because of the decrease of wastewater temperature and the partial degradation of dead and settled duckweed.

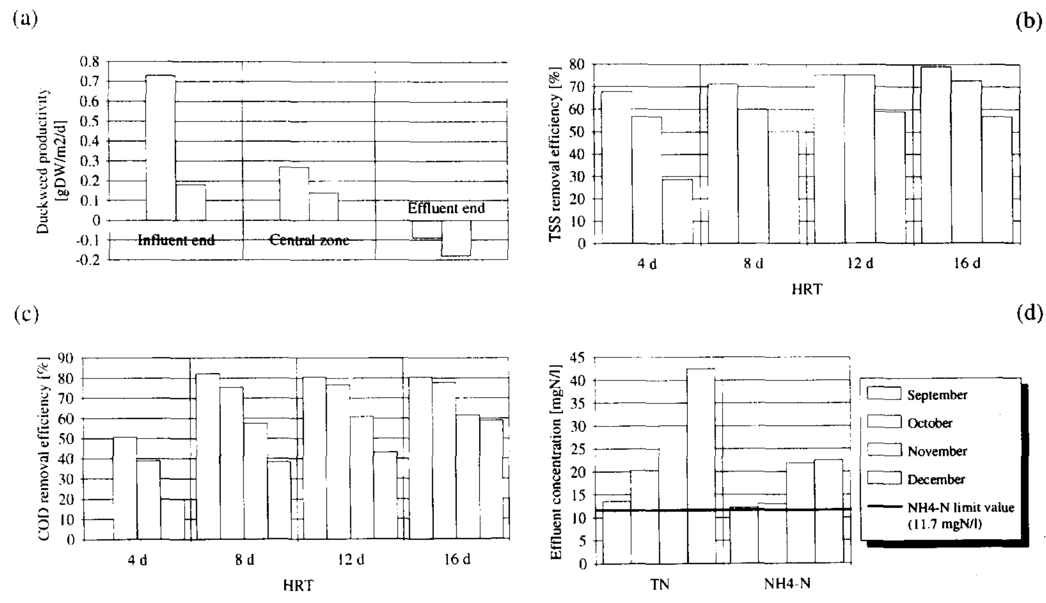

Figure 2. Experimental results of the pilot-plant: (a) duckweed productivity, (b) TSS removal efficiency, (c) COD removal efficiency and (d) total nitrogen and ammoniacal-nitrogen effluent concentrations.

<u>N and P removal</u>

TN and NH_4^+-N effluent concentrations (Figure 2d) ranged between 14 and 43 mgN l^{-1} and between 12 and 23 mgN l^{-1} respectively. No samples complied with Italian limit value for ammonia (15 mgNH_4^+ l^{-1}, that is 11.7 mgNH_4^+-N l^{-1}). Since duckweed productivity was low, the dominant N removal mechanism was nitrification/denitrification. NO_3^--N was not detected in any sample. The result is that nitrification without supplemental aeration is very poor and between nitrification and denitrification the rate-limiting one is nitrification.

TP removal decreased from September (40%) to December (8%). Effluent concentration was always lower than 2 mgP l^{-1}, with an average influent concentration of 2.6 mgP l^{-1}.

Duckweed-based wastewater treatment systems

On the basis of experimental results and the information deduced from a literature review, it can be assumed that duckweed can be used for secondary treatment (SS and BOD removal) and for tertiary treatment (algae control and N removal). However, duckweed-based systems must be preceded by adequate pre- and primary treatments (also in Imhoff tank) in order to avoid accumulation of sludge and floating matter in the pond.

Secondary treatment (BOD and SS removal). Secondary treatment can be achieved in deep, duckweed-covered lagoons (2-5 m), fed with primary effluents, where anaerobic and facultative bacteria carry out organic matter degradation. As in anaerobic or facultative lagoons the duckweed play a negligible role in wastewater treatment but are used for odour, mosquitos and algae control. Typical BOD removal is 60-80% (depending on loading rates and temperature) and typical volumetric organic loading rates are 15-30 gBOD m^{-3} d^{-1}. In order to achieve an 80%-BOD removal, 1.6-3.2 m^3 PE^{-1} (1 PE=60 gBOD d^{-1}; Andreottola *et al.*, 1994) are needed.

Tertiary treatment (algae control). Algae control can be achieved in deep, duckweed-covered lagoons (1.5-3.0 m deep), fed with facultative lagoon effluents, where algae die and settle. Since most algae will not settle until the cells are dead and the precise time required for algae death is not well defined; Design criteria are not very accurate. Zirschky and Reed (1988) report hydraulic retention times of 20-25 d.

Tertiary treatment (N removal). N removal can only be reasonably obtained in duckweed-covered ponds with supplemental aeration, in order to enhance nitrification, or in ponds fed with nitrified wastewater. It can be achieved in deep, duckweed-covered lagoons (up to 2 m), fed with secondary effluents, where nitrification occurs in artificially aerated zones of the lagoon and denitrification in the anoxic water column. In order to obtain additional N removal by plant uptake and, mainly, prevent plant death and release of accumulated nutrients into the water, it is considered to be necessary to harvest the duckweed frequently (weekly basis).

CONCLUSIONS

Results obtained from a literature review and experimental tests on the use of duckweed-based treatment systems in Northern Italy confirm that, in spite of the profitable characteristics of duckweed (high productivity, high protein content, wide geographic distribution, control of negative impacts from conventional wastewater treatment ponds), their extensive use seems difficult because of the high requirement of land area and the ceasing of growth in winter months.

In a temperate climate, a reasonable use of duckweed looks to be the production of good quality secondary effluents (BOD and SS removal) from small communities, especially in seasonal (summer) wastewater treatment plants, since in winter the duckweed ponds work simply as anaerobic or facultative lagoons. Another use is algae removal from facultative lagoon effluents. Nitrogen removal can only be reasonably obtained in duckweed-covered ponds with supplemental aeration, in order to enhance nitrification, or in combination with other oxidative biotreatments, since nitrogen removal by duckweed uptake needs large areas and is not to be proposed.

In spite of the very high nutritional value of duckweeds, their actual use as animal feed does not seem a reasonable proposal, because of several constraints due to the markets and to environmental regulations. It follows that harvested duckweed has to be disposed of as sewage sludge (e.g. compost or biogas production).

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