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Duckweed culture for wastewater renovation and biomass production

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Abstract

Outdoor experiments were conducted in shallow mini-ponds (20 and 30 cm deep) for evaluating the performance of the duckweed species *Lemna gibba* as a purifier of domestic wastewater. It was found that under adequate operational conditions, the quality of secondary effluents meets irrigation reuse criteria. The annual yield (dry matter) of duckweed, harvested two to three times a week, is about 55 ton/ha, with a protein content of 30%. Hence, by cultivating duckweeds the ammonia in ponds for domestic wastewater treatment is converted into valuable protein rich biomass which subsequently can be used for animal feed or agricultural fertilization. The economic benefit of the additional by-product of the biomass reduces wastewater expenditures in the range of 0.020 to US$0.050 per each treated m^3 of wastewater.

Keywords: Duckweed; Wastewater; Economic renovation

1. Introduction

Rapid water use from conventional sources and natural scarcity in arid zones have lead to a spiraling increase in the demand for water. This growing demand can be satisfied primarily when marginal sources such as saline and run-off water, and treated wastewater will be developed and utilized. However, use of non-conventional waters must be subjected to considerations of environmental pollution and economic feasibility.

In arid regions such as California, the African and Middle Eastern deserts, the conservation and reuse of non-conventional waters has become essential. The search for alternative water sources is vital for maintenance of regular agricultural activity. In these regions, total consumption by the agriculture sectors can reach up to 80% of potential conventional water

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sources. Alternative water sources have to be developed in order to meet the growing demand for water.

Reuse of domestic-treated wastewater for agricultural irrigation is a feasible and multi-purpose activity. Reuse of treated wastewater solves ecological and water shortage problems simultaneously. The application of effluent for irrigation also has the advantage of diminishing the need for artificial fertilization. Treated wastewater can be reused for a broad pattern of purposes, such as agriculture and golf courses irrigation, aquifer recharge and industrial cooling (Asano, 1988; Bouwer, 1991; Asano et al., 1992). In the past mainly sprinkle irrigation of industrial crops was implemented. The transfer to drip irrigation and primarily to subsurface systems extended the possibilities of wastewater reuse for irrigation of processing and edible vegetables (Rose et al., 1982; Burau et al., 1987; Oron et al., 1991). However, the problems akin with wastewater reuse are still reuse criteria and the required control phases (WHO, 1989; US EPA, 1992).

Treatment of wastewater is compulsory in most countries, primarily to prevent health risks. It was realized however, that treatment is advantageous also for environmental pollution control. Domestic wastewater has traditionally been treated by conventional methods, such as stabilization ponds, aerated lagoons, trickling filters, activated sludge with one or more phases, and currently by implementing sequential batch reactors (SBR) methods. One of the main drawbacks of wastewater treatment is the associated high expenses. A possible direction to reduce the expenses can be obtained by enhancing the use of the by-products of the treatment process. The by-products, which include among the rest effluent, methane gas for energy generation and dry sludge for fertilization, have an economical value and can turn the whole procedure into an economic enterprise (Wolverton and McDonald, 1980).

Aquatic plants can also be used for wastewater treatment and recycling. The aquatic plants are generally classified into emergent plants, plants in suspension, and floating plants (Reddy and DeBusk, 1985; Edwards et al., 1987). The difference between groups arise mainly from the location of foliage, namely the bulk of leaves, relative to the surface of the water body. The list of potential plants includes water lettuce (*Pistia stratiotes* L.), pennywort (*Hydrocotyle umbellata* L.), cattail (*Typha latifolia* L.), hidrilla (*Hydrilla verticillata*), azolla (*Azolla caroliniana* Willd.), salvinia (*Salvinia rotundifolia* Willd.), Thai Pak Bung plants (*Ipomoea aquatica*), and waterweed (*Elodea nuttallii*) (Reddy and DeBusk, 1985; Hashimoto et al., 1987; Bishop and Eighmy, 1989). Three of the major groups of plants are the various algae species, water hyacinth [*Eichhornia crassipes* (Mart) Solms] and duckweed plants (O'Brien, 1981; Wolverton and McDonald, 1981; Tchobanoglous et al., 1989; Kumar and Garde, 1989; Edwards et al., 1992).

Microscopic algae and other unicellular organisms grow in high-rate oxidation ponds that yield relatively good quality effluent for reuse, and algal biomass which can be utilized as a substitute for animal feed (Shelef et al., 1978). Potentially, the treatment cost for wastewater recycling in high-rate algae ponds can be reduced when the algal biomass is considered as an extra valuable food substitute. However, the implementation of high-rate algae ponds on a commercial scale is still restricted due to relatively high harvesting and drying expenses.

Water hyacinth plants are capable of removing high levels of BOD_5, suspended matter, nitrogen, and a significant level of refractory organic trace matter (Orth and Sapkota, 1988).

Phosphorus removal, however, is limited to the plants' needs and usually does not exceed 65% of the content of the wastewater (Hausser, 1984). Nutrient removal decreases under cold climatic conditions. The advantage of obtaining a relatively high hyacinth yield (around 30 g/m^2 dry matter per day) is off set by a low nutrient value, low digestability, expensive harvesting, and high evaporation losses (Benton et al., 1978).

Duckweed plants comprise a pattern of properties which indicate the attractiveness of their culture even if grown on domestic (organic) wastewater (Culley et al., 1981; Zirschky and Reed, 1988; Edwards et al., 1992). The plants grow successfully on wastewater and efficiently remove phosphorus stored in large stagnant water bodies. The growth rate is diminished slightly during the cold winter months (December to February) and the hot summer period (June to August). However, these fluctuations are not significant and can be considered while utilizing the universal chart (Fig. 4). The plants have the advantage of converting degradeable pollutants directly into protein-rich fodder. Duckweed can also be used for agricultural fertilization, while the effluent is suitable for irrigation (Oron et al., 1987; So, 1987).

Paddy rice areas in Thailand are converted into shallow fertilized water ponds (around 40 cm deep) for cultivating floating Water Mimosa (WM) plants (*Neptunia Oleracea Lour*) in combination with duckweed plants. The WM plants are sold for culinary human consumption in bundles of 15 to 20 kg a unit for about US$7.0 each. Local farmers in Thailand claim that the integrated growth of WM with duckweed improves the quality of the WM. The duckweed plants are subsequently harvested and utilized in these integrated farm systems for feeding of silver barb (*Puntius gonionotus*) and Tilapia species fishes. In Vietnam, the plants are sold wet for ducks feeding at a cost of US$0.02/kg.

The purpose of this work was therefore to verify that domestic wastewater treatment and renovation with duckweed plants has environmental and economical advantages.

1.1. Duckweed growth characteristics

The relative growth rates of duckweed plants are comparatively high: 0.10 to 0.35 g per g per day (day^{-1}). Nutrients are directly absorbed from the wastewater by each frond and not via a central system as in other higher plants. The plants are capable of direct assimilation of organic molecules such as carbohydrates and various amino-acids (Porath and Pollock, 1982). Duckweed have an extreme uptake preference for ammonia over nitrate, which is important for the build-up of amino-acids and proteins associated with reduced energy requirements for the assimilation process (Fig. 1).

1.2. Duckweed for environmental control

The use of aquatic plants for wastewater treatment and renovation, and biomass production provide a favorable alternative for ammonia removal from polluted water bodies. Instead of releasing the nitrogen to the atmosphere (generally by sophisticated mechanical methods), it is trapped by the aquatic plants and subsequently converted into protein-rich biomass. The direct conversion of ammonia into natural protein by duckweed plants is of high efficiency in regards to energy conversion as compared with other green plants (Fig. 1).

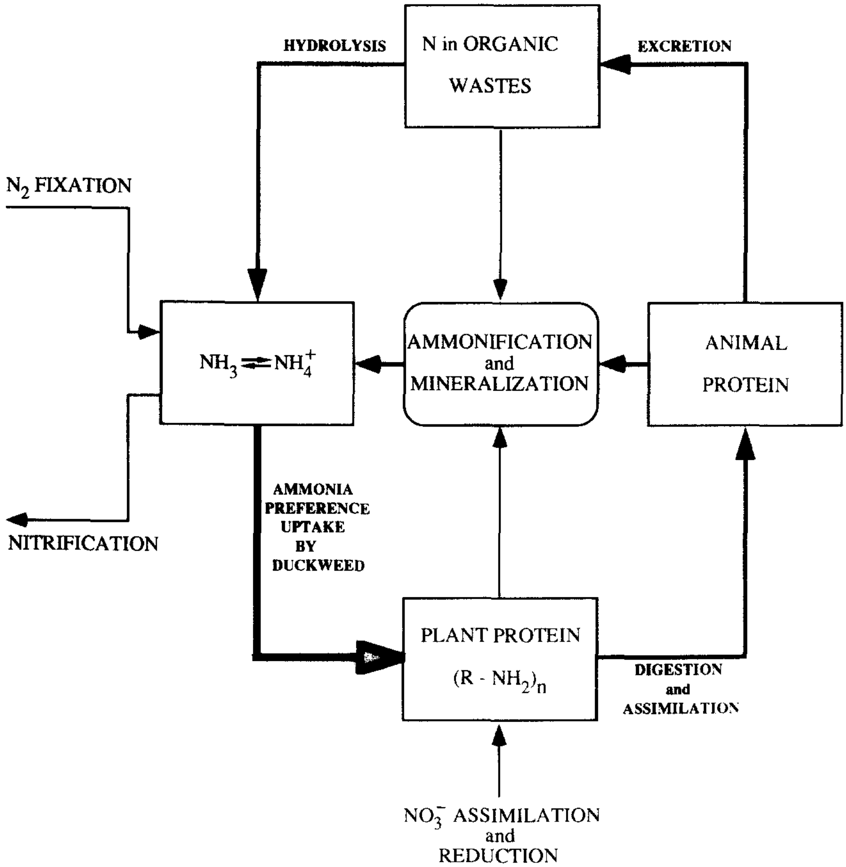

Fig. 1. The role of duckweed plants in the nitrogen cycle.

1.3. Nutritional value of duckweed plants

Duckweed plants have a relatively high nutritional value because the entire plant body consists of metabolically active non-structural tissue (Wolverton and McDonald, 1981). Lignin and cellulose content is around 2.7% and 10% (percent of dry weight) compared with 6.0% and 21.5%, respectively for water hyacinth. The low fiber content has a beneficial impact on digestability when used for animal feed.

1.4. Plants handling in ponds

Duckweed plants form a floating mat which can be easily handled and harvested. Chopping or separation prior to consumption by animals is not required as for water hyacinth. Simple skimming of the fronds is sufficient, although drying will sometimes be required for easier handling and consumption.

2. Materials and methods

2.1. Experimental layout

Outdoor experiments have been ongoing for several years at the Blaustein Institute for Desert Research of the Ben-Gurion University of the Negev, Kiryat Sde-Boker, Israel. The institute is located in a dry region: mean annual precipitation is around 80 mm, mean maximal and minimal day temperatures are around 31.7°C (July) and approximately 14.1°C during winter (January), respectively. The series of experiments began during May of each year (the experiments started during the summer of 1983) and lasted for about four months. The plants were cultivated in 24 mini-ponds (50×40 cm) with a depth of 20 cm, each containing 40 l of wastewater. Additional experiments have been conducted in larger ponds with a depth of 30 cm, containing around 200 l of wastewater. The ponds were operated as semi-continuous reactors after reaching steady state conditions. The retention time varied between 3 and 10 days, although preliminary experiments were also extended to 20 days. Withdrawal of effluent from the ponds and addition of the supernatent were proportional to designated retention times.

2.2. Wastewater characteristics

Raw domestic sewage was taken prior to disposal into the facultative treatment pond, located nearby at Kibbutz Sde-Boker, Israel. The samples were pre-treated in special cones for settling for 4 to 8 h. The supernatent was utilized as the raw wastewater media, and the settled sludge was discarded. It is assumed that in conventional sewage treatment plants (consisting of a settling phase) a large portion of the sludge is further biodegraded under anaerobic conditions.

2.3. Water analysis

Standard methods are used for the analyses of the raw sewage and effluent (Standard Methods, 1980). The analyses included electrical conductivity (EC) of the water, reaction (pH), oxygen concentration, ammonia, nitrate, COD, BOD_5 and suspended matter measurements.

2.4. Duckweed plant analyses

The preliminary experiments included three duckweed species, *Wolffia arrhiza*, *Spirodela polyrrhiza* and *Lemna gibba*. It was determined in preliminary experiments that under local environmental conditions, *Lemna gibba* was the preferable species for continuing the outside tests. The analyses included growth rate, the yield (dry matter), nitrogen removal, related protein content and temperature stratification in the effluent. General observations included color of plants, size of leaves and length of roots.

3. Results

3.1. General observations

The effluent in the ponds, after reaching steady-state conditions, was relatively clear. Algal growth was depressed, subject to harvesting rate of the duckweed (three times a week). The EC of the effluent was in the range of 1.2 to 1.6 dS/m. Total suspended solids (TSS) in the raw sewage was between 172 and 348 mg/l and in the supernatent in the range of 91 to 237 mg/l for the five monitored samples.

When the effluent surface was not fully covered with duckweed plants, light penetrates into the wastewater, providing adequate conditions for algal growth. Generally, a retention time of less than 5 days was associated with a healthier appearance of the plants. When the retention time exceeded 5 days, the plants became pale-green in color and the roots grew longer, expressing a temporary shortage in nutrients.

In order to maintain a reasonable duckweed yield, the plants should be harvested two to three times per week. Harvesting is based on simple collection (or skimming) of the plants from the pond surface. The plants can be used in dry or wet mode. A full-scale practical harvesting method is under development.

3.2. Effluent quality

Settling significantly improved the quality of the supernatent used as the raw matter, probably due to a decline in carbon content. By settling, a large portion of the carbon could be removed, however, the ammonia remained almost without change. Generally, under a retention time of about 5 days, the effluent quality is suitable for agricultural reuse according to Israeli standards (ISQW, 1981). The concentration of filtered BOD_5 (BOD_5f), which is one of the major parameters defining the secondary effluent quality in Israel, was around 40 mg/l, subject to the retention time employed. Generally, there is a relatively high correlation between BOD_5f and other derived parameters, such as suspended matter. Nitrate content in most experiments was negligible (Table 1).

3.3. Duckweed performance

The relative growth rate (RGR) (day^{-1}) of the plants is given by:

$$RGR = \ln(W_t / W_o) / t \quad (1)$$

where W_t, W_o are the duckweed plants weight at time t and zero reference time respectively, and t is the time interval in days. In most experiments, RGR varied between 0.31 day^{-1} for a retention time of 3 days, to around 0.24 day^{-1} for the extended time of 10 days. The RGR and the related duckweed yields are only slightly subject to environmental variations. The function describing the variations in RGR is given by:

$$RGR = 0.536\ \theta^{-0.214} d^{0.205} \approx 0.5[d/\theta]^{0.2} \quad (2)$$

where θ is the retention time (days) and d is the effluent depth in the pond (m). It was found that the relative growth rate is slightly higher in deeper ponds.

Table 1
Concentration ranges of major constituents in treated wastewater (mg/l)

Effluent depth (m)	Retention time (days)	COD	Ammonia	BOD_5
Raw	Sewage	308–825 (43)	23–91 (30)	324–360 (4)
Supernatant		117–598 (43)	15–106 (30)	149–188 (4)
0.2	3	169–335 (9)	25–37 (7)	75 (1)
0.2	5	134–234 (9)	24–34 (7)	65 (1)
0.2	10	105–229 (9)	11–21 (7)	73 (1)
0.3	5	134–269 (9)	26–33 (7)	60 (1)
0.3	10	115–243 (9)	20–30 (7)	nm*

* Not monitored.
Number of samples in parentheses.

Similarly, the protein content decreased from approximately 32% for a short retention time of 3 days to around 20% for an extended retention of 10 days. The function derived from the field data for the protein content is given by:

$$PRT = 124.87\ \theta^{-0.423} d^{0.571} \quad (3)$$

where PRT is the protein content in percent. The protein content is also slightly higher for ponds operated at a depth of 30 cm (Fig. 2).

According to the results, the dry yield of duckweed decreases with the extension of the retention time, probably due to nutrients shortage. This result is in contradiction to ammonia removal, which increases with a longer retention time. The ammonia removal increases from about 40% at a retention time of 3 days to approximately 90% when the ponds are operated under a retention time of 10 days. Ammonia removal in the shallow ponds (20 cm) is greater than in the deeper ones (30 cm) (Fig. 3). According to the results, optimal retention time for duckweed ponds is in the range of 4 to 8 days, subject to operational conditions.

3.4. Evapotranspiration losses in duckweed ponds

The floating duckweed mat suppresses temperature and inhibits evaporation. Due to the plant direct full contact with the surface of the effluent, a larger fraction of radiation is probably returned to space (a higher albedo), as compared to open-surface water bodies. This is akin with a reduced evaporation rate and keeps the bulk water temperature relatively low. The lower evaporation rate from the duckweed ponds also depends on plant density namely, the harvesting program (Oron et al., 1987).

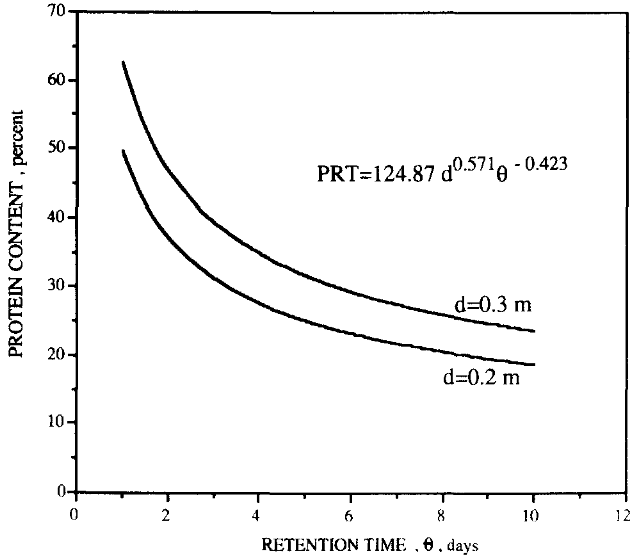

Fig. 2. Effect of retention time and effluent depth on protein content in duckweed plants used for wastewater treatment.

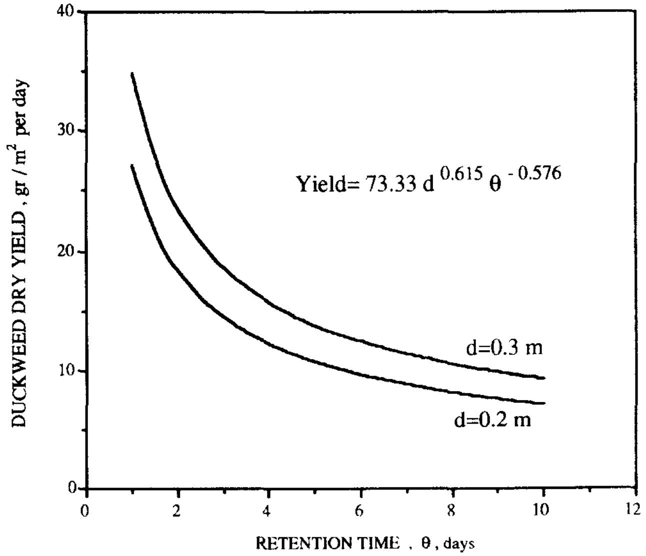

Fig. 3. Effect of retention time and effluent depth on duckweed biomass yield.

4. Economic considerations

4.1. A sewage treatment plant with duckweed

The above observations can be utilized for assessing the economic benefits of constructing a treatment plant based on duckweed culture. The detailed economic assessment is for a residential area of 150 000 inhabitants. The daily sewage flow for this municipal area is around 30 000 m^3/day. The required volume for the duckweed ponds, ignoring evaporation and seepage losses, will be 150 000 m^3, at retention time of 5 days and a depth of 0.3 m. The proposed plant consists of modular settling and duckweed ponds.

(a) Settling ponds for pre-treatment of the raw sewage.
(b) Duckweed ponds and adjacent facilities for drying.
(c) A large reservoir for long-term storage of the effluent which is mainly required in arid regions.

The conditions in the treatment plant resemble a plug flow reactor. Continuous flow in the ponds system is maintained by gravity. Only withdrawal of the effluent from the storage reservoir requires pumps, adjusted to operational reuse settings for irrigation. The suggested treatment and renovation facility is similar to the pond layout comprising the facultative facilities for the city of Beer-Sheva, Israel (Oron and DeMalach, 1987). Such a layout is typical for arid zones with scarce water sources.

4.2. Economic assumptions

The following assumptions were made for the economic analysis:

(a) The expenses and cash flow return are for a new plant. Raw sewage is transported to the plant by the municipal authorities. Expenses for the construction of the reservoir are not included in this analysis since storage is not an essential component of the treatment process.
(b) The treatment facilities include service roads between the ponds, with a peripheral strips (4 m wide at the top of each modular pond) for local traffic maintenance.
(c) Land value is based on an annual net return from an agricultural field (cotton) assessed at US$1000/ha per year. In certain cases, the land used may be a governmental property, and hence may be allocated for the treatment facilities with a minimal, perfunctory, or very low cost.
(d) The expenses for ponds construction include soil compacting without lining. Excavation expenses are estimated at US$1.30/$m^3$ up to a maximum depth of 4 m.
(e) The life span of a combined sewage treatment and biomass production plant is assessed at 25 years at an interest rate of 8%. The associated capital recovery factor (CRF) is 0.0936.
(g) The protein content of duckweed plants for shallow ponds at a depth of 30 cm and a retention time of 5 days is around 30%. The gross return for duckweed plants with this content of protein can be assessed at US$0.20/kg, similar to soybean or fish meal.
(h) The life span for harvesting equipment is based on life span of 8 years at an interest rate of 8%, namely a capital recovery factor of 0.174.

Table 2
Design criteria for a duckweed treatment and renovation plant for wastewater flow of 30 000 m^3/day

Item	Value/description
Settling ponds (modular)	
Length	250.0 m
Base width	10.0 m
Banks slope	1:1.5
Maximal depth (including freeboard)	3.0 m
Maximal wastewater depth	2.5 m
Top width at 3.0 m depth	19.0 m
Top length at 3.0 m depth	259.0 m
Top width including service roads	27.0 m
Top length including service roads	267.0 m
Surface area including service roads	0.721 ha
Maximal effluent surface at 2.5 m	0.451 ha
Maximal pond volume at 3.0 m depth	11 132 m^3
Maximal effluent volume at 2.5 m depth	8758 m^3
Process design	
Retention time	7 h
Flow per pond	1250 m^3/h
Hydraulic loading	66 574 m^3/(ha/day)
BOD_5/COD	0.564
Number of required ponds	1
Duckweed ponds (modular)	
Length	250.0 m
Base width	10.0 m
Banks slope	1:1.5
Maximal wastewater depth	0.3 m
Maximal depth including 0.5 m freeboard	0.8 m
Top pond width at 0.8 m depth	12.4 m
Top width including service roads	20.4 m
Top pond length at 0.8 m depth	252.4 m
Top length including service roads	260.4 m
Wastewater pond width at 0.3 m depth	10.9 m
Wastewater pond length at 0.3 m depth	250.9 m
Effluent surface at 0.3 m depth	0.273 ha
Pond surface at 0.8 m depth	0.313 ha
Surface area including service roads	0.531 ha
Pond volume at 0.8 m depth (excavation)	2252 m^3
Wastewater volume at 0.3 m depth	785.2 m^3
Process design and operation	
Retention time	5 days
Inflow rate per pond	157.0 m^3/day
Hydraulic loading	574.2 m^3/(ha/day)
BOD_5 loading rate	97.3 kg (ha/day)
BOD_5/COD	0.504
BOD_5f in effluent	<40.0 mg/l
Mean dry duckweed yield	12 g/(m^2/day)
Duckweed harvesting rate	Twice a week
Number of required ponds	191
Drying beds	
Approximate total required area (at 10 cm raw matter depth and 8 drying days)	10 ha

Table 3
Input and output assessed costs for a duckweek renovation facility based on a daily flow of 30 000 m^3/day

Item	Total size	Total cost (US$)	Cost per (US$ year)	Cents per year per/m^3
(a) Input costs				
Land				
Settling ponds	0.721 ha	721 (at US$1000/ha)	721	0.007
Duckweed	101.4 ha	101 462 (at US$1000/ha)	101/462	0.927
ponds	10 ha	10 000 (at US$1000/ha)	10 000	0.091
Drying beds				
Construction costs				
Settling ponds	11 132 m^3	14 471 (US$1.3/$m^3$)	1354 (CRF=0.0936)	0.012
Duckweed	430 037 m^3	559 047 (US$1.3/$m^3$)	52 327 (CRF=0.0936)	0.478
ponds	10 ha	10 000 (US$0.1/$m^2$)	937 (CRF=0.0936)	0.009
Drying beds	382 units	191 000 (US$500/unit)	17 878 (CRF=0.0936)	0.204
Manholes	3820 m	76 400 (US$20/m)	7151 (CRF=0.0936)	0.065
Piping				
Contingency	(15% of constuction)	850 918	79 646 (CRF=0.0936)	0.727
Operation expenses				
Labour (five employees)		150 000	150 000	1.370
Three harvesting trucks		99 000 (US$33 000/unit)	17 226 (CRF=0.174)	0.157
Maintenance (50% of trucks)			8613	0.079
Sub total (expenses)			447 315	4.126
(b) Return				
Duckweed	(12 g/m^2/day) 52.2 ha	457 577 (at US$0.2 kg)	457 577	4.179
(c) Grand net benefit (cost)				0.053

The settling ponds: The wastewater depth in the settling ponds is 2.5 m, the bottom width 10 m and the length 250 m (Table 2). At a banks slope of 1:1.5 the wastewater surface area will be 0.451 ha and the volume 8758 m^3. The gross surface area of each settling pond including extra excavation for the ponds' shoulders and service roads is 0.721 ha (Table 2).

The duckweed ponds: The effluent depth in the duckweed ponds is 0.3 m, the bottom width 10 m and the length 250 m (Table 2). At a banks slope of 1:1.5 the wastewater surface area will be 0.273 ha and the volume 785.2 m^3 (Table 2). The gross surface area of each duckweed pond including extra excavation for the ponds shoulders and service roads is 0.531 ha.

Assuming a daily flow of about 157.0 m^3/day per pond, the above layout necessitates the construction of about 191 modular ponds (30 000/157.0 $\simeq$ 191). The retention time of the effluent in the duckweed pond will therefore be 5 days (785.2/157.0 $\simeq$ 5). The required gross duckweed treatment layout will be 101.4 ha. An adjacent drying bed area would

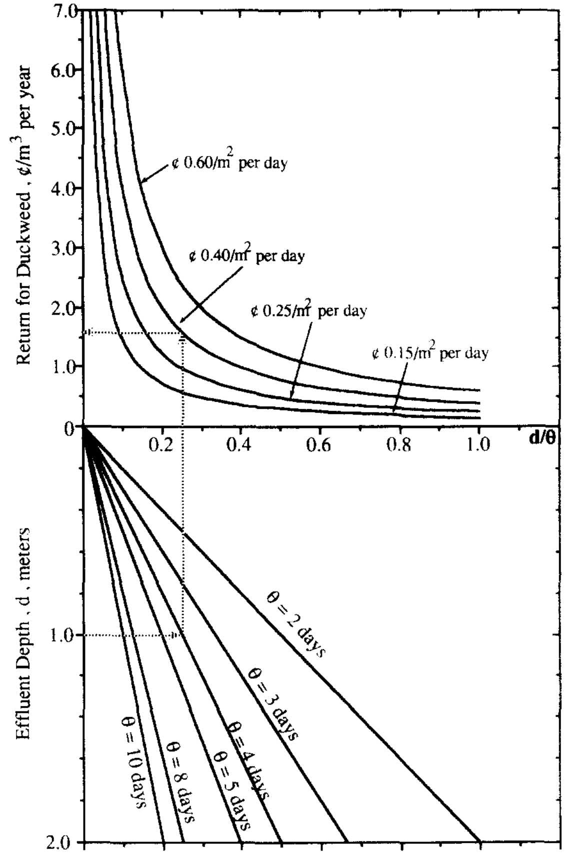

Fig. 4. The effect of retention time and effluent depth on return for duckweed biomass in sewage treatment facilities.

require another 10 ha, at an estimated ratio of duckweed ponds to drying beds of 1:10. Considering all the above fixed and variable expenses yields a total cost of about US\$0.0413/m^3 (Table 3). The return for the above data for each m^3 is around US\$0.0418/m^3 (at a yield of 12 g/m^2 per day and a return of US\$0.2/kg), resulting in a net treatment benefit of about US\$0.0005/m^3 (Table 3).

The annual return for the duckweed biomass can be approximated by Re (\$/m^3 per year):

$$\mathrm{Re} = y\, c\, \theta 10^{-3}/\mathrm{d} \tag{4}$$

where y is the duckweed dry yield (g/m^2 per day) and c is the price for the duckweed (cents per kg). The yield function y is:

$$y = 73.33\, d^{0.615} \theta^{-0.576}. \tag{5}$$

The term $y\, c\, 10^{-3}$ expresses cash flow return (cents/m^2 per day, depending on the yield and product value). Taking different combinations for the term ($y\, c\, 10^{-3}$) which expresses growth conditions and the product value and the term (θ/d) for the engineering and operational settings enables to estimate the return for a broad pattern of situations (Fig. 4).

In this preliminary economic assessment, the expenses for wastewater treatment are approximately US\$0.050 per m^3 which in the range of conventional treatment in oxidation ponds. Water savings due to reduced evaporation from the duckweed ponds were not taken into account although they might improve the overall economy of the project.

5. Summary and conclusions

Duckweed can be used to treat and renovate organic wastewater to a secondary level suitable for irrigation. The duckweed biomass can be used for animal feed or for agricultural fertilization (So, 1987).

It is always imperative to assess the economic value of harvested duckweed plants and the water value saved due to reduced evaporation. According to protein composition and content, the duckweed plant value can be assessed at US\$0.20/kg, similar to soybeans. The equivalent value of the plants, when used for agricultural fertilization, is estimated at 100 kg/ha, similar to commercial fertilizers. Experiments have verified that the yield of Chinese flowering cabbage doubled when fertilized with duckweed (So, 1987). The annual requirement for ammonium sulfate fertilization for an agricultural field is around 100 kg/ha. The expenses for this type of fertilizer is around US\$180/ha. The duckweed plants provide the field with phosphate and potassium which raise the value of the fertilizer to approximately US\$250/ha, therefore, a return of around US\$0.20/kg is reasonable.

One may argue that some of the values considered in the analyses are perhaps over-or under-estimated. An extra detailed study and related analysis will provide supplementary information regarding the potential of duckweed use and the akin components of the system.

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