Duckweed based wastewater treatment (DWWT): design guidelines for hot climates

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Abstract Conventional wastewater treatment systems are expensive in either investment or running costs. On the other hand, waste stabilisation ponds may be unable to meet effluent standards for nutrients. Wastewater treatment using duckweed therefore becomes more significant as an option capable of achieving effluent standards and generating revenue from selling the duckweed. However existing duckweed based wastewater treatment (DWWT) systems have high land requirements despite being able to reduce concentrations of organic compounds and pathogens to acceptable levels. Improved guidelines for the design of DWWT are necessary to obtain a reliable and cost-effective wastewater treatment plant using duckweed. This guideline provides a DWWT design program using spreadsheets for different configurations of wastewater treatment units using duckweed. The design program developed suggests that a combination of anaerobic ponds, DWWT systems and maturation ponds can minimise land requirements and capital costs while achieving specified effluent standards. In order to achieve effluent standards, the land required is typically from 1.5 to 1.8 m^2/capita (excluding associated facilities), capital costs are in the range from 7.9 to 9.7 USD/capita, with a retention time from 15 to 18 days. Income generation is dependent mainly on the social and cultural acceptability of duckweed use within the community.

Keywords Duckweed; wastewater treatment; design; guidelines; reuse; operation and maintenance

Introduction

Conventional wastewater treatment systems are unlikely to be suitable for developing countries due to the lack of finance for construction and running costs and lack of skilled staff. Waste stabilisation ponds (WSP) are likely to be appropriate in hot climates, as they are low in cost and easy to operate and maintain. However they may not achieve secondary effluent standards in terms of reduction of TSS and nutrients because of algal growth in the ponds. Therefore duckweed based wastewater treatment (DWWT) becomes more promising to achieve effluent standards including those for nutrients. In addition to reducing organics and pathogens, DWWT can also reduce concentrations of nutrients (ammonium and phosphates) and heavy metals, although removal efficiencies for these parameters are slightly lower than for WSP systems (Iqbal, 1999).

This study investigates the optimum design of wastewater treatment using duckweed and produces design guidelines for DWWT particularly in hot climates. The equations are derived from previous experimental data collected by different researchers in different conditions. The guidelines are accompanied by a simple program in spreadsheet form to estimate the area requirements, the removal efficiencies, and the costs including investment, operation and maintenance (O&M) costs and present value (PV) of different options for wastewater treatment using duckweed.

Principle of DWWT

Duckweed has the capability to purify wastewater in collaboration with both aerobic and anaerobic bacteria. The duckweed mat, which fully covers the water surface, results in three zones in DWWT ponds. These are the aerobic zone (10 cm below the duckweed mat) (Skillicorn *et al.*, 1992), the anoxic zone and the anaerobic zone, as shown in Figure 1. In

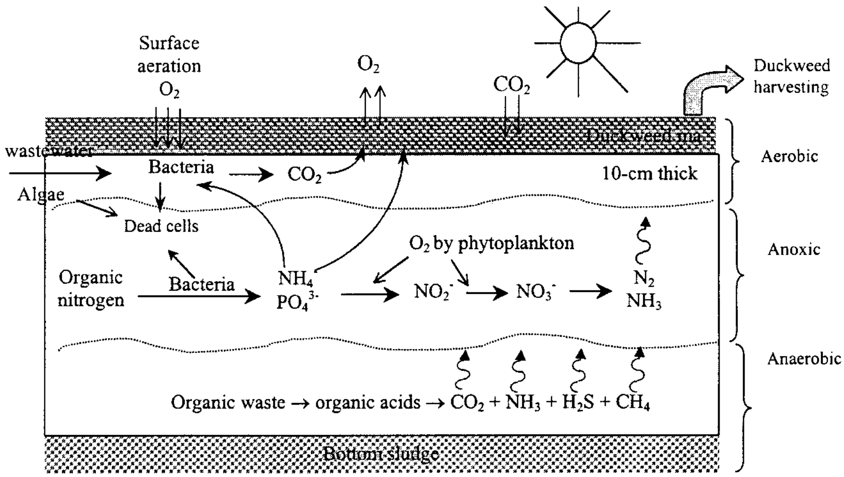

Figure 1 Schematic of biological process in DWWT

the aerobic zone, organic materials are oxidised by aerobic bacteria using atmospheric oxygen transferred by duckweed roots. Nitrification and denitrification take place in anoxic zones, where organic nitrogen is decomposed by anoxic bacteria into ammonium and ortho-phosphate, which are the intermediate products used as nutrients by the duckweed (Metcalf and Eddy, 1991). Organic matter in the bottom of the ponds is decomposed by anaerobic bacteria and this produces gases such as carbon dioxide (CO_2), hydrogen sulphide (H_2S) and methane (CH_4) (Metcalf and Eddy, 1991).

BOD/COD removal. Due to a full coverage of the duckweed mat, aerobic BOD removal is likely to be less important than anaerobic BOD removal in DWWT ponds. Therefore the principle of BOD removal in DWWT is probably similar to that described for the anaerobic and facultative ponds (Zirschky and Reed, 1988).

TSS removal. Total suspended solids (TSS) are mainly reduced by: (1) the process of sedimentation; (2) biodegradation of organic matters; (3) absorption of a minor fraction by duckweed roots and (4) inhibition of algal growth (Iqbal, 1999). TSS removal in DWWT ponds should be more effective than in uncovered ponds as algae will not grow in DWWT ponds with lack of light penetration.

Nutrient removal. Duckweed growth is considerably dependent on the availability of nutrients in the form of ammonium and phosphate. Nitrogen compounds as well as ammonium are reduced from DWWT by: (1) uptake of ammonium by the duckweed; (2) sedimentation of SS with organic nitrogen; (3) volatilisation of ammonia; and (4) nitrification and denitrification (Iqbal, 1999). Phosphorus is normally reduced in DWWT ponds by: (1) plant uptake; (2) adsorption onto clay particles and organic matter; (3) chemical precipitation; and (4) sludge removal (Iqbal, 1999).

Pathogen removal. Pathogen removal is likely to be less effective in DWWT ponds than in WSP. This is caused by: (1) less light radiation; (2) absence of antibacterial substances produced by algae; (3) less oxygen concentration; and (4) absence of very alkaline conditions. However DWWT ponds with long retention time can be competitive in reducing pathogens (Iqbal, 1999).

Heavy metal removal. Heavy metals can be reduced from DWWT ponds by: (1) sedimentation as sludge; (2) plant uptake (copper and arsenic) and (3) absorption during polishing processes. However heavy metals can influence the performance of the treatment if concentrations of iron, zinc, aluminium, chromium and copper in the wastewater are higher than 20 mg/l, 20 mg/l, 30 mg/l, 0.l mg/l and 1 mg/l respectively (Boniardi and Rota, 1998).

Advantages and disadvantages

Compared to other wastewater treatments, DWWT systems have several advantages such as high nutrient removal, inhibition of algal growth, prevention of odour and insect breeding, reduction of the effect of chlorine by-products, relatively low cost and high possibility for income generation. However the duckweed mat results in low pathogen removal, and an inability to receive shock loading if DWWT is used without other treatment methods. The mat also makes DWWT unsuitable for use in certain conditions such as windy areas. Cultivation of duckweed in the wastewater ponds has a negative effect on duckweed use for animal feed where the duckweed might contain toxic organic compounds and heavy metals.

Experience from DWWT Bangladesh shows that the cost of a DWWT system is about one-tenth of that for a conventional system for design and construction, but DWWT occupies approximately three times as much land as is required for equivalent conventional systems (Aquasan, 1995). Although DWWT systems require less land than WSPs, a DWWT system is 25% more expensive for investment and O&M costs due to the requirements of seepage prevention and skilled labour (Aquasan, 1995).

Methods

This study is purely dependent on the publications of previous experiments and experiences of DWWT. The data from the previous experiments were obtained from publications such as books, journals, the internet, and correspondence. The experiments executed by several researchers vary from laboratory-scale to full-scale DWWT systems, therefore the data gathered are various and sometimes contradictory. The data needed for design are the effects of temperature, depth, retention time, pH and alkalinity on BOD/COD, total suspended solid (TSS), nutrients (ammonium and phosphate) and faecal coliform removal.

After collection, the data were examined and sorted with some assumptions to obtain the approximate equations. The equations for volumetric loading of DWWT ponds and first order rate constants for BOD/COD, TSS, nutrient (ammonium and phosphate) and faecal coliform removal were derived from regression analysis using Excel. Due to the similarity of biological processes to waste stabilisation ponds (WSP), those basic equations were based on equations applied to WSP and were analysed to obtain the best values of correlation coefficient (R2) which were closest to 1.

The simple program was developed using spreadsheet and some options of wastewater treatment using duckweed were determined to obtain the optimum treatment efficiencies and duckweed production to generate revenue. Options of the treatment were investigated in combination with primary and post treatments. The options of the treatments are focused on domestic wastewater for hot climates in developing countries.

The guidelines for operation and maintenance were also included in this study, which consist of technical, institutional, economic, financial and socio-cultural aspects. A comparison between the duckweed system in Bangladesh and the DWWT program is carried out to assess the efficiency of the latter in producing optimum and effective wastewater treatment and duckweed production. The flow diagram for the methodology is shown in Figure 2.

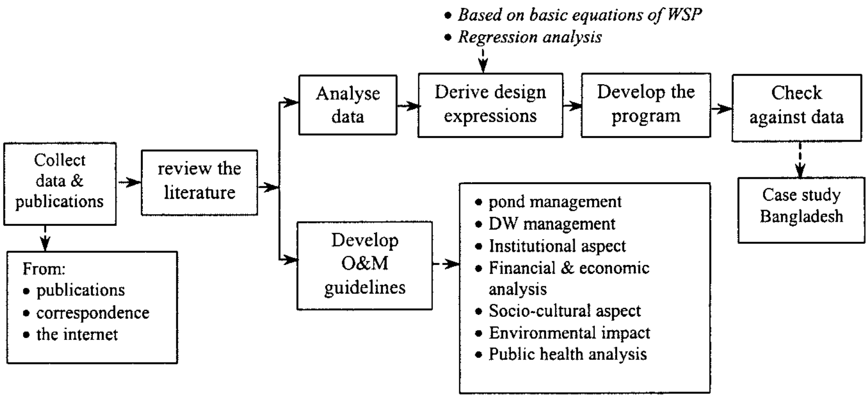

Figure 2 Methodology of the research project

Results and discussion

Standard design criteria of DWWT

Hydraulic retention time (HRT). Hydraulic retention time (HRT) for reducing organic materials depends on the influent BOD, but 10 to 20 days is acceptable to reduce BOD to 30 or 20 mg/l. HRT influences the performance of treatment, the yield and the protein content of duckweed produced. The longer the retention time, the higher the efficiencies of treatment in reducing pathogens, but this causes more anaerobic conditions and lower protein content of duckweed produced.

Water depths and flow velocity. There are no exact values for water depths to produce high treatment performance but shallow ponds are likely to be better than deep ponds, but increase the land area required. Water depths between 0.6 and 1.5 m are likely to be most suitable to minimise temperature gradients over the depth of the pond. As DWWT is a plug flow system, a horizontal velocity 0.1 m/sec is appropriate to prevent disturbance of the duckweed mat (Edward, 1992).

BOD/COD loading. DWWT is designed on the basis of volumetric BOD or COD loading due to the possible anaerobic process underneath the duckweed mat. Mandy's experiment proved that DWWT ponds tolerate maximum influent COD concentrations from 300 to 500 mg/l (Mandi, 1994). The formulae for organic loading are mostly dependent on temperature as written below.

BOD loading rate (λ_v, g/m^3/d) are as follows: (where T is temperature, ºC)

90% of BOD removal $\lambda = 0.2995\,T + 3.3308$ $R^2 = 0.8465$

95% of BOD removal $\lambda = 0.2302\,T + 2.5601$ $R^2 = 0.8465$

Temperature. Although there are still different ideas about the temperature requirements for duckweed growth, the production of duckweed will decrease when the temperature is below 17ºC or above 35ºC (PRISM, 1990 as quoted by Iqbal, 1999).

Duckweed production. The factors to optimise duckweed production are nutrient concentrations, dissolved oxygen (DO), salinity, pH, plant density, wind effects and water management. Duckweed grows optimally at nitrogen concentrations of from 15 to 60 mg/l and can be harvested 2 or 3 times a week. Alaerts *et al.* (1996) reported that production rates of DWWT Bangladesh are from 4.5 to 5 gr/m^2/d. According to Oron (1994), yield of dry duckweed can be estimated with the equation of $Yield\ (gr/m^2.d) = 73.33\ t^{-0.576}\ d^{\ 0.615}$,

Table 1 The equations for calculation of effluent quality from DWWT systems

Parameters	Effluent quality	Rate constants (for depth ≥ 0.6 m)
BOD	$L_e = L_i\, e^{-k1.t}$	$K_1 = 0.158\ (1.052)^{T-20}$
COD	$L_e = L_i\, e^{-k1.t}$	$K_1 = 0.131\ (1.065)^{T-20}$
TSS	$S_e = S_i\, ((-1.18/T)\ \text{Ln}\ (t) + (6.5/T)$	–
NH_4^+	$C_e = C_i\, 0.640\, e^{-kn.t}$	$K_n = 0.137\ (1.009)^{T-20}$
PO_4^{3+}	$P_e = P_i\, 0.8485\, e^{-kp.t}$	$K_p = 0.012\ (1.491)^{T-20}$
Faecal coliform	$N_e = N_i\, e^{(-kd.t)}$	K_d =0.7–1.4 (Steen *et al.*, 1998)

where *t* is a retention time (days) and d is the pond depth (m). That equation is used in the design program because no comparable equations for full-scale ponds are available. The relative growth rates (RGR) and yields of duckweed are estimated to range from 0.12 to 0.3 day^{-1}, and from 5 to 10 gr/m^2.d.

Removal efficiencies

The efficiencies of BOD, COD, TSS, ammonium, phosphate and pathogen removal can be estimated from the basic data such as retention time, depth and wastewater composition. The formulas to estimate effluent quality are presented in Table 1.

In these formulas, t is retention time (days), T is a water temperature (ºC).

Physical design of DWWT ponds

The plug flow system seems to be appropriate for DWWT, due to continuous and even distribution of the nutrients, ensuring contact between the wastewater and duckweed and minimising the possibility of short-circuiting. The length/width ratio should be designed as more than 38:1 to encourage excellent plug flow conditions (Alaerts *et al.*, 1996). It is possible to design DWWT as a batch system, designed to minimise short-circuiting and to distribute the nutrients. Aeration may increase the treatment performance, but unless it is managed carefully it will disturb the duckweed mat and generate open areas, which will reduce the removal efficiencies. DWWT ponds can be protected from wind by providing floating booms made from bamboo, PVC pipes or plastic grid systems to avoid incomplete duckweed mat coverage. An incomplete duckweed mat will stimulate algal growth and encourage odours and mosquito breeding.

Primary and post treatment stages may be necessary to accompany DWWT systems in order to achieve effluent standards. Provision of anaerobic treatment prior to DWWT ponds has been suggested because the simple organic molecules produced by anaerobic bacteria can be used directly in the metabolism of duckweed (Steen *et al.*, 1999). Examples of primary treatment stages are anaerobic ponds, sedimentation ponds and settling tanks. Post treatment stages may be used for pathogen removal and aeration of anaerobic effluents. Examples of post treatments are maturation ponds, chlorination, step cascades, weirs, etc.

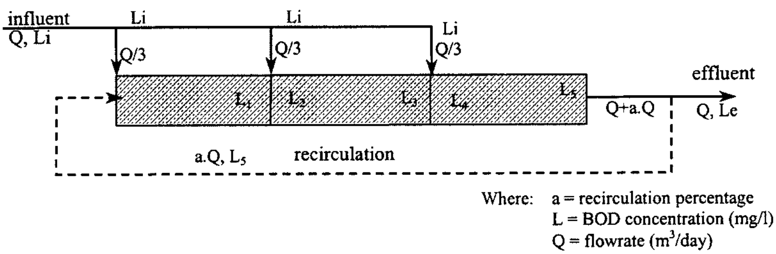

Figure 3 DWWT plug flow – step feed with recycle

Multiple inlets are designed to distribute nutrients along the length of ponds (see Figure 3), which can increase the protein content and yield of the duckweed. However multiple inlets will decrease the removal efficiencies of some pollutants, unless effluents are recirculated. The BOD effluent for three inlets for instance, can be estimated from the following formulae.

30% BOD Removal $L_e = L_i\,(0.927–0.014T)\,e^{-(0.006T+0.122).t}$

50% BOD Removal $L_e = L_i\,(0.896–0.014T)\,e^{-(0.006T+0.132).t}$

Where L_e is effluent BOD, L_i is influent BOD, T is temperature (ºC) and t is retention time (days).

Development of a DWWT design program

A design program has been developed to obtain the optimum design of DWWT in removing pollutants and producing duckweed as a by-product. The program consists of five options of wastewater treatments using duckweed, which are:

Option 1 Anaerobic ponds and DWWT 2 (90%) and/or maturation ponds
Option 2 Anaerobic ponds, DWWT 1 and/or maturation ponds
Option 3 Primary settlement, DWWT 2 (90%) and/or maturation ponds
Option 4 DWWT 2 (90%) and/or maturation ponds
Option 5 Anaerobic ponds, DWWT 2 (95%) and/or maturation pond.

The meaning of DWWT 2 (90%) is DWWT method 2 with BOD loading equation for 95% of BOD removal. DWWT 1 is DWWT method 1, which is using BOD removal for design of DWWT system, while DWWT method 2 uses BOD loading for design of DWWT. The results of the program are presented in the Table 2.

Calculation suggests that DWWT ponds combined with anaerobic ponds and maturation ponds require the least retention time and constitute the optimum treatment option using duckweed because they require the least area and have the lowest costs. For a flow rate of 10,000 m^3/day, these combinations of treatment units including DWWT show investment

Table 2 The result of sample calculation using the DWWT design program

Description	Unit	Option 1 AP, DWWT 2 (90%), &/ MP	Option 2 AP, DWWT 1 (90%), &/ MP	Option 3 PS, DWWT 2 (90%), &/ MP	Option 4 DWWT 2 (90%), &/ MP	Option 5 AP, DWWT 2 (95%), &/ MP
Population	Capita	100,000	100,000	100,000	100,000	100,000
Flow rate	M^3/day	10,000	10,000	10,000	10,000	10,000
Total Areas	Ha	15.48	13.47	23.86	31.77	17.88
Retention time	Days	15.19	13.52	22.88	30.50	17.57
Removal efficiencies:						
• BOD		98.59	96.16	99.29	99.80	99.11
• COD		97.82	94.06	98.90	99.69	98.62
• TSS		95.74	95.01	96.63	90.13	96.11
• NH_4^+		88.86	77.44	97.59	99.19	93.42
• PO_4^{3-}		71.15	55.42	88.78	94.28	79.15
• Faecal coliform		99.99977	99.99966	99.99999	100.00000	99.99982
Economic analysis						
• Investment cost	USD	966,312	737,615	1,590,660	2,117,644	1,169,741
• Revenue	USD/yr	27,025	21,707	35,279	39,855	30,215
Present values	USD	(813,986)	(638,091)	(1,336,628)	(1,793,967)	(980,882)
Percentage		45%	36%	75%	100%	55%

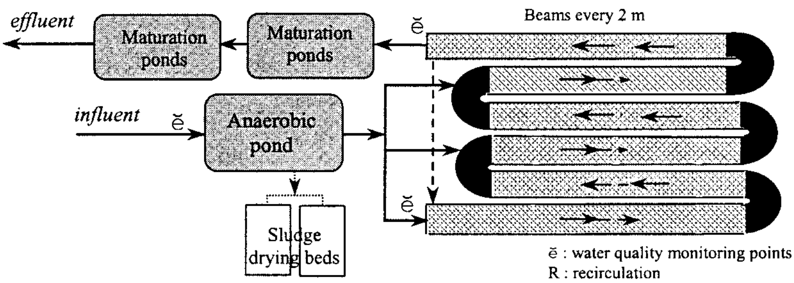

Figure 4 Recommended wastewater treatment using DWWT systems

costs ranging from 7.9 to 9.7 USD/capita and areas of from 1.5 to 1.8 m^2/capita, with retention time from 15 to 18 days. DWWT units for 95% BOD removal are designed to produce high duckweed yield and might be applied in particular areas where duckweed use as animal feed is socially and culturally acceptable.

The land requirements and the capital costs for wastewater treatment using duckweed with multiple inlets and recirculation are approximately 30% and 20% respectively higher than those with a single inlet. The requirements for areas and present values (PV) for DWWT units with multiple inlets are estimated to be from 1.2 to 1.5 times greater than those for DWWT with a single inlet. The recommended wastewater treatment system using duckweed is presented in Figure 4.

Operation and maintenance

The operation and maintenance of wastewater treatment using duckweed includes pond management, duckweed management and institutional management.

The general operation and maintenance requirements for DWWT ponds are as follows:
- DWWT ponds should be commissioned before the anaerobic ponds;
- provision of sludge treatment such as sludge drying beds;
- removing scum, grit, solids and any weeds growing in the embankments of the ponds;
- examining the effluent to ensure that it contains no duckweed;
- monitoring and evaluating the water quality and duckweed production.

Duckweed should be conveyed fresh and planted within 4 to 5 hours of harvesting (Skillicorn *et al.*, 1993). The ponds should be free from algae and any macrophytes before duckweed is planted into the ponds. Using local and native species of duckweed is suggested due to easy adaptation to the local climate and water conditions. 1 to 4 days after seeding, the duckweed can be harvested by manual or mechanical equipment. The method of harvesting is dependent on the availability of funding and labour. Duckweed can be reused as fish feed, poultry feed and agricultural fertiliser.

For any DWWT system a sound institutional structure is needed to reduce environmental pollution, to control public health, and to generate income from selling dry duckweed or other duckweed by-products. According to Skillicorn *et al.* (1993) the formation of an institutional centre is essential to maintain the sustainability of a DWWT system. A suggested institutional structure is shown in Figure 5. The tasks of the centre are (1) dissemination of the technology including introduction and adaptation of the technology to the specific local conditions; (2) developing guidelines for design, farming systems and reuse; (3) providing training for individual farmers, farming co-operatives, government and local NGO staff. Support from the government to the centre is important particularly for regulating the quality of effluent and duckweed, economic incentives and tax arrangement for local farmers. Finally the centre should provide continuous supervision in technical assistance and financial reinforcement until the institution becomes independent.

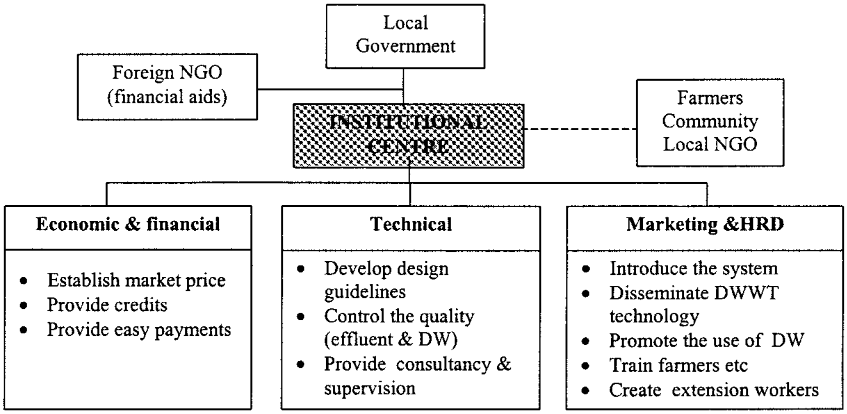

Figure 5 Recommended institutional structure for wastewater treatment plant using DWWT systems

The acceptability of duckweed by-products should be analysed from economic, financial, and socio-cultural aspects. The issues to be considered in economic and financial analysis are the determination of affordable pricing of duckweed by-products and the credit requirements for low-income farmers to farm using duckweed by-products. The following ideas are intended to develop public acceptability:

- dissemination of the financial benefits of duckweed;
- creating public confidence in the safety and quality of the final product;
- developing a pilot project to examine the feasibility of DWWT and its benefits;
- providing credit for duckweed farmers at low interest rates;
- involving the user in all stages of project planning and implementation;
- developing self-help schemes based on the willingness of the community to participate.

Case study

A comparison between the land areas and operating efficiencies for the duckweed system in Bangladesh and those predicted from the DWWT program has been carried out. DWWT design program suggests that the land area for DWWT Bangladesh could be reduced slightly to achieve the effluent standards. There is a significant difference in the total income generation because DWWT Bangladesh generates revenue from selling fish as a by-product, whereas the total revenue predicted from the DWWT design is obtained from selling dry-duckweed, which is likely to be cheaper than fish. Experience from DWWT in Bangladesh shows that DWWT reuse is acceptable in rural areas among low-income communities.

Conclusion

DWWT systems are feasible for developing countries in hot climates to provide low-cost treatment of domestic wastewater particularly in rural areas. Use of harvested duckweed is likely to be acceptable to some communities since it has minimal effect on public health. The design program developed is appropriate as a guideline for designing wastewater treatment using duckweed. A combination of DWWT systems with anaerobic ponds and maturation ponds is likely to be most efficient in terms of minimising land requirements and costs. This program should be reviewed and refined to assess the practicality and feasibility of wastewater treatment using duckweed. Further research on pathogen removal to obtain decay rates in DWWT ponds, and to determine optimal water depths for DWWT ponds is necessary. Further research on pathogen removal to obtain decay rates in DWWT ponds, the effect of pH and alkalinity and determination of effective water depths for DWWT ponds are necessary.

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