SANDEC Report No. 6/99

Duckweed Aquaculture

Potentials, Possibilities and Limitations for Combined Wastewater Treatment and Animal Feed Production in Developing Countries

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March 1999

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Acknowledgements

This review would not have been possible without the genuine interest and financial support by the Department of Water & Sanitation in Developing Countries (SANDEC) at EAWAG. I wish to express my sincere gratitude to SANDEC and its staff for the agreeable working atmosphere and for having offered me the opportunity of gaining deep insight into an interesting subject.

In particular, I am much obliged to Sylvie Peter for her professional and thorough linguistic revision of the text and to Swen Vermeul for his valuable support regarding its layout and logical structure.

Moreover, I would like to thank Prof. Huub Gijzen and Prof. Peter Edwards for providing relevant literature and information.

Duebendorf, March 1999

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Acronyms

AIT	Asian Institute of Technology, Bangkok, Thailand
FAO	UN Food and Agriculture Organisation
EAWAG	Swiss Federal Institute for Environmental Science & Technology, Duebendorf, Switzerland
DWRP	Duckweed Research Project (discontinued), Dhaka, Bangladesh
ODA	Overseas Development Administration
PRISM	Projects in Agriculture, Rural Industry, Science and Medicine, an NGO in Bangladesh
U. S. EPA	U. S. Environmental Protection Agency
SANDEC	Dept. of Water & Sanitation in Developing Countries at EAWAG

Currency Conversions

Bangladeshi Taka: 1 BdT = 0.026 ... 0.021 US$ (1993...1999)
Taiwan Dollar: 1 TwD = 0.025 US$ (1985)

Glossary

Aquaculture	Artificial and commercial cultivation of aquatic products.
Batch	Pond or stagnant water body loaded with excreta or wastewater at regular or irregular intervals for biological treatment. The treated water may be discharged from the pond and replaced by a next load of wastewater.
Frond	Name of the flat oval-shaped body of duckweed plants.
Lemnaceae	Botanical family of duckweeds.
Nutrients	Chemical elements necessary for biological growth, notably N and P, found in agriculture as fertilisers, but causing pollution when discharged arbitrarily into water bodies.
Pathogens	Organisms causing disease in man.
Plug-flow	Channel-like, often serpentine shaped pond system where wastewater flows slowly but continuously from its inlet to its outlet, while being biologically treated.

Abbreviations

Al	Aluminium
BOD	Biochemical oxygen demand
Ca	Calcium
CaO	Lime
CH_4	Methane gas
Cl	Chloride
CO_2	Carbon dioxide gas
COD	Chemical oxygen demand
dry wt	Dry weight
FCR	Feed conversion ratio
Fe	Iron
HCO_3^-	Bicarbonate
HRT	Hydraulic retention time
K	Potassium
K_2O	Potassium oxide
M.Sc.	Master of Science
Mg	Magnesium
N	Nitrogen
N_2	Nitrogen gas
Na	Sodium
NGO	Non-governmental organisation
NH_3 (-N)	Ammonia (-nitrogen)
NH_4^+ (-N)	Ammonium (-nitrogen)
NO_3^-	Nitrate
Ntot	Total nitrogen
o-PO_4^{3-}	*Ortho*-phosphate
P	Phosphorous
P_2O_5	Phosphorous pentoxide (Phosphoric anhydride)
S	Sulphur
t/ha·y	Annual production in tons per hectare
TKN	Total Kjeldahl nitrogen
TP, Ptot	Total phosphorous
TSS	Total suspended solids
UASB	Up-flow anaerobic sludge blanket
wet wt	Wet weight

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Foreword

What is this literature review about and what is its background?

This literature review provides a first overview of the possibilities, potentials and limits of duckweed aquaculture and its combined use in wastewater treatment and animal feed production in low and middle-income countries. It is somewhat limited as critical literature on duckweed field use is scarce and difficult to obtain (e.g. unpublished internal documents). According to NGOs and commercial suppliers, the duckweed projects seem very positive and promising, and the practical problems encountered with their application rarely mentioned.

Which were the major information sources for this review?

Nevertheless, extensive scientific literature is available on the taxonomy, physiology and ecology of duckweed. The comprehensive monographic study by Landolt (1986) and Landolt and Kandeler (1987) lists over 3400 references. This can be attributed to the fact that duckweed is regarded by botanists and plant physiologists the same way as *E. coli* is viewed by microbiologists and biochemists, namely a model organism for physiological, biochemical and metabolic studies, easy to handle and cultivate under laboratory conditions. This monographic study is of key importance for further research on the use of duckweed. Other references of major importance are the literature review by Gijzen and Khondker (1997) and the DWRP reports (DWRP 1996, 1997a and 1997b) which give a comprehensive overview of the “state of the art” of duckweed-based treatment/production systems and duckweed related research. These references were a major source of information for the present document.

The current review focuses on the *combined* use of duckweed in wastewater treatment and animal feed production in economically less developed countries. Despite the fact that most of the available literature originates from industrialised countries and often describes either the wastewater treatment or the feed production aspect of duckweed, but its dual use is rarely discussed.

Summary

Why have duckweed treatment/ farming systems, so far, not achieved a major breakthrough?

For more than twenty five years, duckweed aquaculture has been regarded as a potential technology to combine both wastewater treatment and feed production in developing and industrialised countries. However, real-scale application of the technology dates back to about ten years. So far, it has not achieved a major breakthrough. System management never appeared sophisticated enough to reveal decisive advantages of duckweed aquaculture over existing technologies. Nevertheless, the experience gained so far reveals interesting data with regard to BOD and nutrient removal, including nutritional value for raising animals.

What are the potentials of duckweed-based wastewater treatment?

The rapidly growing and small floating aquatic plants of the botanical family of *Lemnaceae* are capable of accumulating nutrients and minerals from wastewater. The latter are finally removed from the system as the plants are harvested from the pond surface. Because of their comparatively high productivity and nutritional value, particularly their high content of valuable protein, they provide an excellent feed supplement for animals such as fish or poultry. Duckweed holds the potential to create a financial incentive for controlled faeces and wastewater collection in both rural and urban areas and, therefore, improve sanitary conditions. When duckweed biomass is used for animal production, the generation of income and nutritional improvement appear as possible side-benefits from the wastewater treatment process. Thus, the full potential of duckweed aquaculture lies in its combined use in the fields of sanitation, food production and income generation.

Yet, this combined potential is far from being fully realised in economically less developed countries, and only partially exploited in industrialised nations.

What is the current use of duckweed in the USA?

In the USA, use of duckweed-covered lagoons for tertiary treatment is classified by the U.S. EPA as an innovative/alternative technology. Duckweed is used as a wastewater purifier mainly for treatment of secondary effluents from aerated and non-aerated lagoons. The systems are operated at minimal duckweed production and the biomass is generally composted or landfilled. The harvested duckweed has so far rather been regarded as an undesirable by-product of the treatment process and rarely used as a feed supplement, however, feeding applications are currently being developed.

What is the aim of duckweed application in developing countries?

In economically less developed countries, duckweed systems aim at combined secondary and tertiary wastewater treatment with valorisation of the biomass. Full-scale applications are, for example, known from Taiwan, Bangladesh and India, where duckweed, grown on urban and rural wastewater, is used as a feed supplement for raising fish, chickens and ducks.

What kind of waste can be treated by duckweed?

Duckweed has been used for treatment of raw and diluted sewage, septage, animal manure from cattle and pigs, and stabilisation pond effluents. Potentially, the plants can be used to treat various liquid waste streams, including industrial wastewaters from food processing or fertiliser industries, provided their nutrient content is high enough to sustain duckweed production. Since *Lemnaceae* show a very high capacity of accumulating heavy metals and organic xenobiotics in their tissues, it makes them potentially suitable for removal of these compounds from industrial wastewaters.

How do industrial wastewaters limit duckweed cultivation?

Industrial wastewaters containing high concentrations of BOD, oil and grease seem to limit duckweed growth. Use of biomass as feedstuff is restricted to duckweed grown on wastewaters containing extremely low levels of heavy metals and organic toxins. Due to the high bioaccumulation of such compounds in duckweed potential health hazards may not be excluded.

Besides public health risks resulting from a possible accumulation of toxins in the food chain, the technology faces several other limitations:

Which external climatic and environmental factors limit duckweed application?

The biological characteristics of the plants limit their efficient application to subtropical and tropical zones. Moreover, duckweed cultivation is not feasible in very windy regions and in rapidly flowing water streams. As an aquaculture farming method, the technology requires a year-round supply of (waste)water containing a high load of nutrients. Therefore, the technology is less suited for arid regions with scarce water resources.

What are the land and soil quality requirements of duckweed-based wastewater treatment and piscicultural systems?

Duckweed treatment and farming systems have relatively high land requirements. 2 to 3 m^2 per inhabitant are necessary for duckweed-based wastewater treatment systems. Duckweed-based pisciculture requires a duckweed/fish pond area ratio of at least 1:1 to provide enough duckweed to sustain fish production. A flat to slightly sloped topography is preferable. Soils with a poor water retention capacity or extreme pH values are less suitable for duckweed and fish production.

What technical aspects have to be taken into consideration when designing a duckweed-based wastewater treatment lagoon?

Adequate primary treatment of raw wastewater is indispensable prior to duckweed treatment. Anaerobic pretreatment in earthen sedimentation ponds with a clay lining or closed settlement tanks are a good option for primary treatment. Duckweed treatment systems can either be designed and operated as plug-flow or batch systems. Continuous flow through lagoons are suggested for medium-scale applications at community or (peri-) urban level. Ponds operated as batch reactors are commonly encountered at village-level. Optimum water depths are reported between 0.4 and 1 m. Plug-flow design should allow a HRT of at least 20 days with a length to width ratio of 1:10 or more. In general, a narrow pond design is more suitable as it allows operational work to be carried out from the pond perimeter and avoids direct contact of workers with the wastewater. A floating bamboo or plastic containment grid system is required to prevent the plants from drifting to the shore by the action of wind and water current. Vegetables and fruit planted on the pond embankments can serve as a protection for duckweed from wind and direct sunlight. Besides, the co-crops may generate additional net income.

What are the labour requirements for operation and maintenance of a duckweed treatment system?

Operation and maintenance of a duckweed treatment farm require a high input of skilled labour. Almost daily attention is necessary to maintain optimum growth conditions and treatment efficiencies. Duckweed biomass has to be harvested at regular intervals to remove nutrients or toxins from the system. The harvested amount should ensure a more or less dense duckweed cover on the water surface to prevent algae growth and development of odours and mosquito breeding.

How significant is the removal of BOD, TSS, nutrients, mosquitoes, odours, heavy metals, and organic toxins in duckweed-covered lagoons?

The removal of organic matter, nutrients, mosquitoes, and odours in duckweed-covered lagoons, and the relative contribution of a duckweed mat to it, are far from being well understood, especially with regard to BOD removal. However, a positive effect of duckweed on the efficient removal of TSS, heavy metals and organic compounds has been clearly demonstrated. Since nutrient removal by duckweed is reported to vary around 50±20 %, the total nitrogen and phosphorous input recovered in the harvested biomass amounts to 50±20 %.

Removal efficiencies of over 90 % for BOD, over 74 % for nutrients and 99.78 % for faecal coliforms were reported from a duckweed-covered sewage lagoon in Bangladesh. The studied system, however, treated sewage of relatively low strength as regards BOD and experienced substantial nutrient losses due to seepage.

What are the main advantages and disadvantages of duckweed treatment systems in comparison with waste stabilisation ponds and water hyacinth systems?

Duckweed treatment systems have a competitive economic advantage over waste stabilisation ponds and water hyacinth systems due to the generation of a valuable, protein rich biomass. The latter two systems, however, seem to be more robust with regard to high BOD loads.

How important are the public health risks related to the transfer of pathogens in excreta/ wastewater-duckweed-fish systems?

The risk of pathogen transfer in duckweed systems has hardly been assessed. The few studies conducted so far have not revealed serious public health risks. Though duckweed shows a tendency to accumulate bacteria from wastewater on its surface, fish fed on excreta-grown duckweed was judged safe for human consumption following gutting, washing with safe water and thorough cooking. Moreover, duckweed-fish cultivation in two-pond systems separates fish production from direct contact with the wastewater.

Why is duckweed a valuable feed supplement for fish and poultry?

Average annual duckweed productivity in tropical and subtropical regions is estimated at 10 to 30 t (dry wt)/ha with an annual per ha protein production of about ten times that of soybean. Due to its contents of high quality protein, minerals, vitamins and pigments, duckweed proved to be a valuable fresh and dried feed supplement for raising fish and poultry. Whether duckweed feed has a positive effect on the growth of pigs and ruminants is currently uncertain.

What factors are likely to influence the sociocultural acceptance of duckweed treatment and farming systems?

Indirect reuse of excreta via duckweed has a potentially greater chance to meet with social acceptance, especially in countries where direct excreta reuse is put under a cultural or religious taboo. In regions where duckweed is introduced as a novel crop, the technology is likely to meet with initial rejection due to its intensive and aquacultural nature. The possible benefits of a duckweed treatment system, such as income generation, reduced odours and mosquito breeding, as well as clean water, may favour its social acceptance.

Under what conditions is wastewater-based duckweed-fish production economically profitable?

Experiences at a demo farm and to some extend also at village level in Bangladesh proved that, on the basis of operating costs and positive gross margins, integrated sewage/excreta-duckweed-fish farming is economically feasible. The operating profit at demo farm level was achieved by relatively high financial and skilled labour inputs, by a sufficient and year-round supply of nutrients and water, and by sophisticated management. Nevertheless, the positive operating profits achieved during four consecutive years (1994-1997) are remarkable, especially since wastewater treatment plants worldwide are generally never operated at a profit. However, high interest and repayment charges due to large capital investments, and high expenses for supplementary feed other than duckweed, were the reported factors responsible for net financial loss of farming groups practising excreta-based duckweed-fish production at village level.

Which research fields related to duckweed treatment/farming systems should receive further attention?

As regards duckweed-based treatment and farming systems in developing countries, the following major research fields were identified:

- Public health and environmental effects of duckweed treatment/farming systems
- Design and operation of duckweed-based pond systems for combined wastewater treatment and biomass production
- Economic assessment of wastewater-based duckweed farming models
- Sociocultural and institutional aspects of wastewater-based duckweed farming
- Duckweed production and feeding applications

Chapter One

Climate and Site Selection

Lemnaceae show a worldwide geographic and climatic distribution ranging from cold temperate to tropical regions with the exception of waterless deserts and permanently frozen polar regions. In arid and extremely wet areas (Malaysia, Iceland and others), natural occurrence of duckweed is also rare (Landolt 1986). Most species, however, are found in moderate climates of subtropical and tropical zones. The small floating vascular plants grow on still, nutrient-rich fresh and brackish waters. The family of *Lemnaceae* consists of the 4 genera: *Spirodela, Lemna, Wolffia,* and *Wolffiella*, with a total of about 37 species worldwide.

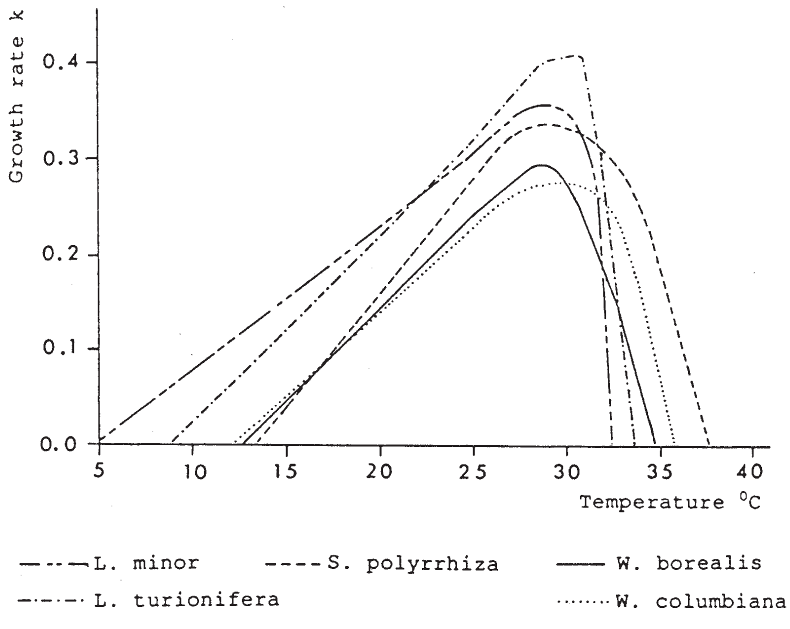
Efficient use of duckweed is restricted to semitropical and tropical zones.

Temperature Requirements

The minimum water temperature allowing their use in wastewater treatment is reported to be 7 °C (Reed et al. 1988, USEPA 1988, WPCF 1990). Depending on the species, optimum growth rates between 25 °C and 31 °C (Fig. 1), however, limit an efficient application for wastewater treatment in warmer climates. Experience in Bangladesh revealed a significant decrease in productivity, and, therefore, treatment efficiency of *Spirodela* and *Lemna* below 17 °C, and severe heat stress at temperatures above 35 °C (PRISM 1990).

Minimum water temperature for duckweed growth lies at 7 °C, optimum temperatures range between 25 °C and 31 °C. The plants experience severe heat stress at temperatures above 31 °C to 35 °C.

Figure 1. *Growth rate of different Lemnaceae species in relation to temperature (after Docauer 1983, in Landolt 1986).*



In regions where temperatures drop below 0 °C during part of the year, the plants sink to the bottom of the water body and remain inactive in a form called turion until warmer conditions

Duckweed survives periods of frost in an inactive form called turion at the pond bottom.

return. In such climates, only seasonal use of duckweed for nutrient removal is possible.

Surprisingly, a company called Lemna Corporation is using duckweed for tertiary post-treatment of wastewater in desert climates and regions with very cold winters (-20 °C to -30 °C). The high temperatures are buffered by increasing pond depths of up to 5 m. Under freezing conditions, their treatment relies on the addition of aeration to keep the ponds partially free from ice. The microbial degradation process slows down but is not completely stopped in contrast to the nutrient uptake by duckweed which is inactivated and, hence, does not contribute to the treatment efficiency in winter (Lemna Corp. 1994).

Influence of Wind

Duckweed cultivation is unsuitable in very windy regions.

Duckweed is very sensitive to wind and, therefore, not suitable for wastewater treatment in very windy regions. Duckweed is blown in drifts to the shore of the ponds, where it piles up and subsequently dies. If plants are not redistributed, which requires manual labour, it will lead to decreased treatment efficiency due to incomplete coverage of the pond surface. A complete duckweed cover has to be maintained to suppress algal growth, nutrient competition and development of odour and mosquito breeding.

Influence of Water Current

Fast water currents limit duckweed cultivation.

Lemnaceae are very sensitive to water current. The natural habitat of the free floating plants are stagnant or almost quiescent water bodies. *Lemnaceae* can withstand higher water currents when the plants are protected by larger ones like *Eichhornia* or *Phragmites*. In water bodies without rooted plants, *Lemnaceae* can withstand a water movement of 0.1 m/s velocity (Duffield and Edwards 1981). A sufficiently low flow velocity has, therefore, to be considered in duckweed treatment systems designed as plug-flow.

Effects of Dryness and Rain

Duckweed cultivation requires a year-round and high supply of water.

Climates with pronounced rainy and dry seasons limit an application of duckweed. A major constraint of duckweed use in some economically less developed countries is the drying up of ponds during dry seasons, especially if wastewater flows are too low to compensate for losses through evapotranspiration and pond leakage. If additional water supply is not available or too costly, duckweed productivity and treatment efficiency can drop drastically during dry seasons. Although community facilities may succeed in maintaining duckweed production through higher wastewater flows and the supply of additional water, the treatment systems may lack effluents during dry seasons, thus preventing reuse of the treated water for irrigation, pisciculture or other purposes.

Duckweed cultivation is intensive in terms of water. Ideally, water resources like wastewater, surface and groundwater should be available throughout the year to maintain a minimum water level of 20 cm during dry periods, and also to buffer heat, nutrient and pH extremes by dilution (Skillicorn *et al.* 1993). Nevertheless, duckweed wastewater treatment may be potentially suitable for dry areas with limited water resources, as a complete cover of duckweed was reported to reduce evapotranspiration by about one-third compared to open water (Oron *et al.* 1984).

Floods can simply wash duckweed and pond infrastructure away or can dilute the wastewater to be treated to such an extent that nutrient concentrations become too low for duckweed growth. Flood protected land should, if possible, be selected in flood prone areas, as constructive flood protection measures are often too expensive for low-income countries.

The effect of rainfall on duckweed growth is unclear. Various positive effects have been reported and include improved nutrient uptake by cleansing absorption surfaces, exertion of physical force for quick separation of daughter from mother fronds, and addition of sulphur, phosphate, nitrate, and bicarbonate. Possible negative effects include prolonged rainfall which drastically cuts off light, dilution of nutrients and partial submerging of the photosynthetic parts of the plants (Gijzen and Khondker 1997).

Rainfall has both positive and negative effects on duckweed growth.

The main constraints in coupled duckweed-fish production reported by rural farming groups in Bangladesh include a lack of duckweed and water during dry seasons, as well as floods (DWRP 1996).

Land Requirement

Land requirement for duckweed wastewater treatment is estimated at 2 to 3 m^2 per inhabitant, not including the possibly required area for primary wastewater treatment. The availability of suitable land for duckweed application becomes a key element, especially in areas where land is scarce due to population pressure and urban development. Nevertheless, urban and peri-urban duckweed systems are known or planned.

Duckweed wastewater treatment systems require relatively large areas of land for pond construction.

Unproductive marginal land along roads and paths or derelict ponds may be a suitable choice to cultivate duckweed, as rental or purchase prices for such land are usually lower than for arable soil.

Additional land for fish ponds is necessary in the case of integrated duckweed-fish production in two-pond systems. The required duckweed/fish pond area ratios of 1:1 to 2:1 are reported to provide enough duckweed for fish production. The optimal duckweed/fish pond area ratio will probably vary according to the site, duckweed productivity, available space, and other low-cost fish feeds (DWRP 1997a).

Land requirement for combined duckweed and fish production in separate ponds is at least twice as high as for duckweed production alone.

Cultivation of duckweed and fish in the same pond could decrease land demand, however, experience with one-pond duckweed/fish systems has not been reported so far.
According to Edwards *et al.* (1990), the area required for indirect duckweed/tilapia production in separate ponds, using septage as a fertiliser for duckweed production, was about three times greater than that required for cultivation of tilapia in ponds directly fertilised with septage. However, the yield of tilapia fed on septage-grown duckweed (6.7 t/ha·y) was almost double than that of tilapia grown in ponds directly fertilised with septage.

Ideal Site Topography

A flat to slightly sloping and even topography is necessary for construction of duckweed treatment lagoons, channels and ponds. Steeper or uneven sites require higher amounts of earthwork, thereby significantly increasing the costs of the system (Metcalf and Eddy 1991).

Soil Characteristics

Soils with a good water retention capacity are most suitable for duckweed aquacultural systems.

Sites with slowly permeable (hydraulic conductivity <5 mm/h) surface soils or subsurface layers are most suitable for duckweed systems, as percolation loss through the soil profile is minimised. The pond bottom is expected to seal with time due to deposition of colloidal and suspended solids and growth of bacterial slimes. Sites with rapidly permeable soils may be used after sealing with clay or artificial materials (Metcalf and Eddy 1991).

Depth to the groundwater table and distance to surfacewater streams may be other limiting factors. Nearby groundwater tables and surfacewater streams lying at a lower level than the pond system may enhance percolation, especially during dry seasons. Dense bottom and side sealings are essential to prevent loss of nutrients and deterioration of groundwater and surrounding surfacewater quality.

Duckweed treatment systems built on sandy soils may suffer from significant nutrient loss due to percolation. This in turn leads to a deterioration of the surrounding ground and surfacewater quality and to lower duckweed yields.

In practice, complete sealing is often difficult to achieve. Nutrient mass balance of a full-scale duckweed treatment system in Bangladesh revealed that about 30 % of the nutrients were lost during the dry season through the side embankment. The sandy characteristics of the soil (hydraulic conductivity was found to be over 50 mm/h) and a nearby flowing river lying lower than the system were responsible for the leakage, even though the bottom was sealed with a 30 cm clay layer (Rahman 1994, Alaerts *et al.* 1996).

If affordable, concrete pond lining is recommended for systems treating industrial wastewater.

Concrete lining can be used to completely exclude seepage. The costs of this lining are dependent on the size of the system. For large-scale systems, concrete lining will significantly increase fixed costs. Concrete lining is recommended where wastewater contains toxic compounds which could potentially deteriorate the quality of surrounding water.

A clay lining of 30 cm is a feasible option. Although the costs for this lining are low and the material quite reliable, total seepage prevention cannot be ensured (PRISM unpublished).

Clay lining is a feasible low-cost option to significantly reduce seepage.

A second critical soil parameter is pH. The optimum pH for duckweed growth ranges between 4.5 and 7.5 (Landolt 1986). Other authors report a more narrow pH optimum ranging from 6.5 to 7.5 (Skillicorn *et al.* 1993). Therefore, highly acid and alkaline soils are unsuitable for duckweed cultivation. Alkaline conditions favour, in particular, the transformation of ammonium to ammonia which is harmful to duckweed.
A study conducted in the Pathumthani Province in Thailand using family pour-flush latrine effluent for duckweed cultivation revealed that acid sulphate soils with pH values around 4 could be raised to values around 7 by adding quicklime (CaO) to the pond's bottom and slopes.

Alkaline soils are unsuitable for duckweed aquaculture. Acid soils can be somewhat buffered by the use of lime.

Chapter Two

Duckweed for Domestic, Agricultural and Industrial Wastewater Treatment

Duckweed wastewater treatment is potentially suitable for small-scale application at rural level and for medium-sized facilities at community, (peri-)urban and industrial level.

Duckweed wastewater treatment systems have been studied for dairy waste lagoons (Culley *et al.* 1981, Whitehead *et al.* 1987), raw and diluted domestic sewage (Skillicorn *et al.* 1993, Oron 1994, Mandi 1994, Hammouda *et al.* 1995, Alaerts *et al.* 1996), secondary effluents (Harvey and Fox 1973, Sutton and Ornes 1975), waste stabilisation ponds (Wolverton 1979), septage-loaded ponds (Edwards *et al.* 1992), and fish culture systems (Porath and Pollock 1982, Rakocy and Allison 1984). Several full-scale systems are in operation in Taiwan, China, India, Bangladesh, Belgium, and the USA (Edwards 1987, Zirschky and Reed 1988, Alaerts *et al.* 1996, Koerner *et al.* 1998).

Duckweed systems have been applied for treatment of various domestic and agricultural wastewaters.

The duckweed treatment plants installed so far almost exclusively treat domestic or agricultural wastewaters. Hardly any literature is available on the treatment of specific industrial wastewaters (Gijzen and Khondker 1997). Potentially, duckweed may also be applied for the treatment of industrial wastewaters, provided their nutrient content is high enough (see also Chapter Four, pp. 45). Effluents with both a high BOD and nutrient load may require adequate primary treatment to reduce the organic load. The upper BOD limit of tolerance for duckweed growth is unknown. In Niklas (1995), *Lemna gibba* was reported to grow on waters with a COD of over 500 mg/l. However, Skillicorn *et al.* (1993) reported that a simple rule of thumb for dilution of primary effluent is to ensure that BOD_5 at the head of a duckweed

With a sufficiently high level of nutrients, duckweed systems are potentially suitable for treatment of industrial wastewaters.

plug-flow treatment system is maintained below 80 mg/l. Industrial wastewaters with a high BOD load and low nutrient content are less suitable to favour duckweed growth.
Mdamo (1995) reported that duckweed growth on paper mill effluents was only observed when BOD was relatively low (150 mg/l) and nutrients were added externally. High BOD removal of over 98 % was observed when 2 mg per m^2 of both N and P were added daily. Without the addition of nutrients, almost no duckweed growth was observed on the paper mill wastewater. Neither did wastewater with a very high BOD level (2900 mg/l) promote duckweed growth.

High concentrations of BOD, oil, grease, and detergents may hamper duckweed growth.

Apart from high BOD concentrations, fatty acids, oil and grease were reported to have a negative effect on duckweed growth. This is probably due to adsorption to the plants' submerged surfaces and subsequent inhibition of nutrient uptake. Duckweed is reported to tolerate rather high concentrations of detergents (Gijzen and Khondker 1997). Skillicorn *et al.* (1993), however, suggest that high concentrations of detergents may destroy the duckweed's protective waxy coating, thereby rendering the plant more vulnerable to diseases.

Duckweed may be used for extraction of heavy metals and organic compounds from industrial wastewaters. However, the harvested biomass should definitely not be introduced into the food chain, but rather burnt and/or disposed of in sealed landfills.

The efficient absorption of heavy metals and other (organic) toxic compounds could be used for extraction of such toxins from industrial wastewaters. It is, however, important that the biomass is harvested at regular intervals, otherwise, the toxins will settle on the sediments with the decaying plants. The harvested plants should be burnt and/or disposed of in sealed landfills.

Duckweed for food production should only be grown on wastewaters with extremely low toxin concentrations. Even low concentrations in the raw wastewater may become hazardous due to the manifold bioaccumulation in duckweed and, possibly, in the food chain.

Separate collection of toxin containing domestic and industrial wastewaters is recommended. In practice, separation of critical industrial wastewaters is very difficult as the countries concerned dispose of only elementary or no wastewater collection systems. A few point sources of industrial wastewater pollution, such as for example from leather tanneries, may render, due to mixing, most of the domestic wastewater unsuitable for food production not only in cities but also in villages.

Design Considerations

Type and quantity of wastewater to be treated are decisive factors in the design of duckweed treatment systems and for infrastructural requirements necessary to ensure daily nutrient inputs and use of biomass (Tab. 1).

Table 1. *Different duckweed treatment systems depending on type and amount of wastewater.*

Type of wastewater		*Domestic*	*Non-domestic*
Origin of wastewater	*Village*	*Community/(peri-)urban*	*Industries*
Hydraulic load (m^3/d) Population	<5 50-150	>100-1500 1000-15,000	<1500
Infrastructure required to ensure daily flow of nutrients	Pour-flush-type latrines	• Sewage system (separation of waste-water containing toxins) • Access for septage trucks	• Sewage system
Primary treatment	• Water-sealed pits • Submerged bamboo baskets	• Open or closed settling tanks • Sedimentation ponds • Waste stabilisation ponds	• Open or closed settling tanks • Sedimentation ponds • Waste stabilisation ponds • Biogas digesters (high BOD waste)
Secondary and tertiary treatment	Duckweed ponds (batch)	Duckweed ponds (plug-flow)	Duckweed ponds (plug-flow)
Use of biomass	Desired	Possible	Restricted

Metcalf and Eddy (1991) suggest that duckweed systems, exploiting mainly the wastewater treatment aspect of duckweed, can be designed as conventional stabilisation ponds with the addition of a floating grid system to control the effects of wind. However, reliable design and operation guidelines aiming at the dual use of duckweed in wastewater treatment and optimum biomass production are lacking. They can be operated as batch or plug-flow (continuous flow) systems. Easy access to the pond surface for operation and maintenance should be ensured in site selection and design of a duckweed treatment pond system. Therefore, a narrow, channel-like pond design is more convenient than wider ponds.

Duckweed treatment systems can be designed and operated as batch or plug-flow systems. A narrow pond design should allow operation and maintenance work from the pond embankment in order to avoid direct contact of workers with wastewater.

Primary Treatment of Raw Wastewater

Primary treatment of raw wastewater is essential for initial separation of some of the settleable fraction of pathogens, settleable solids and floating material. In the case of plug-flow systems, efficient sedimentation is important to prevent degradation of initial treatment runways. Adequate pretreatment is also important to release organically bound nitrogen and phosphorous through microbial hydrolysis, as the availability of NH_4^+ and *o*-PO_4^{3-} was suggested to be the limiting step for fast duckweed growth (Alaerts *et al.* 1996). Anaerobic pretreatment promotes the release of organically bound NH_4^+ and *o*-PO_4^{3-}, the favoured forms of nutrients for duckweed growth.

Primary treatment of raw wastewater is essential for overall treatment performance and supply of nutrients for duckweed growth.

Compared to open systems, closed primary treatment systems enhance TSS removal due to the absence of light and subsequent inhibition of algal growth. Another advantage of a closed system is the possibility to collect and use the biogas generated. However, pretreatment using closed settling tanks, biogas digesters or anaerobic up-flow sludge blankets (UASB) are techni-

Closed primary treatment systems are technically more difficult and costly to install and operate than open systems. However, they are more efficient and allow the use of biogas.

cally more difficult and costly to install and operate. Despite their high efficiency, they are more suitable for treatment of highly concentrated industrial and municipal wastewaters.

Biogas digesters followed by duckweed treatment systems are a potential method for substantial carbon, nitrogen and phosphorous recovery and reuse from wastewaters containing high BOD and nutrient loads.

The use of biogas digester effluents for duckweed cultivation seems promising. In a duckweed wastewater treatment system, the organic carbon fraction is not assimilated and converted into valuable biomass by the plants themselves, but degraded by aerobic, anoxic and anaerobic microbial processes on the plants' surfaces, in the water column and sediment. The carbon is finally released from the system as CO_2 and CH_4 green house gases and microbial sludge.

Anaerobic pretreatment in a biogas digester (partially) allows recovery of the carbon fraction via the biogas, whereas nutrients like nitrogen and phosphorous in the remaining effluent can be (partially) recovered by duckweed. In this way, optimal reuse of energy and nutrients can be obtained. Moreover, anaerobic pretreatment seems to favour nutrient availability of nitrogen and phosphorous due to hydrolysis of complex organic N and P compounds.

Biogas digesters followed by duckweed effluent treatment may be a suitable system combination for treatment of waste(water) with a high BOD load, such as from sugar, rubber and food processing industries or from rice mills.

Earthen anaerobic sedimentation ponds are a simple and low-cost option for primary treatment in low-income countries.

Use of conventional earthen anaerobic sedimentation ponds is an efficient, low-cost and easy manageable alternative for primary treatment, especially in low-income countries. The most widespread design criteria include a depth of 2-3 m, a HRT of 1-6 days, construction of berms or baffles to prevent short-circuiting and clay lining. However, compared with closed set-

Photograph 1: *Duckweed cultivation pond at village level in Bangladesh during the dry season. Nutrients are supplied by low-cost pour-flush latrines masked by vegetation on the right pond embankment. Excreta of latrine users is collected via a pipe and digested in the shown bamboo baskets from where the nutrients are released by diffusion.*

tling tanks, biogas digesters and UASBs, conventional ponds offer the following disadvantages: higher land requirements, unused biogas, bad smells and unpleasant physical aspect, higher TSS load in the effluent due to algal growth, and a potential danger of percolation if a concrete lining is missing. The formation of a crust on the water surface after a few months may reduce odours, algal growth and favour anaerobic conditions. In venting the effluent 0.5 m below the surface, the floating material is hindered from moving to subsequent treatment processes.

Sludge from primary treatment should, if possible, be analysed for heavy metals and organic toxins. If found to meet established standards, it can be used, after stabilisation, as a fertiliser in agriculture.

Latrines of the pour-flush type (Phot.1, Figs. 2 and 3) were used for nutrient supply to duckweed ponds in villages. In the examples shown, the water-sealed pit and the submerged bamboo case serve as some kind of pretreatment stage for anaerobic digestion. Moreover, they prevent faeces and ablution material for anal cleaning from freely floating around in and on the pond.

At village level, some kind of pretreatment can be achieved by anaerobic decomposition of excreta in the containment structures of pour-flush-type latrines.

Figure 2. *Low-cost pour-flush latrine. Excreta is collected and digested in the submerged bamboo case placed directly in the duckweed pond releasing nutrients through diffusion (PRISM).*

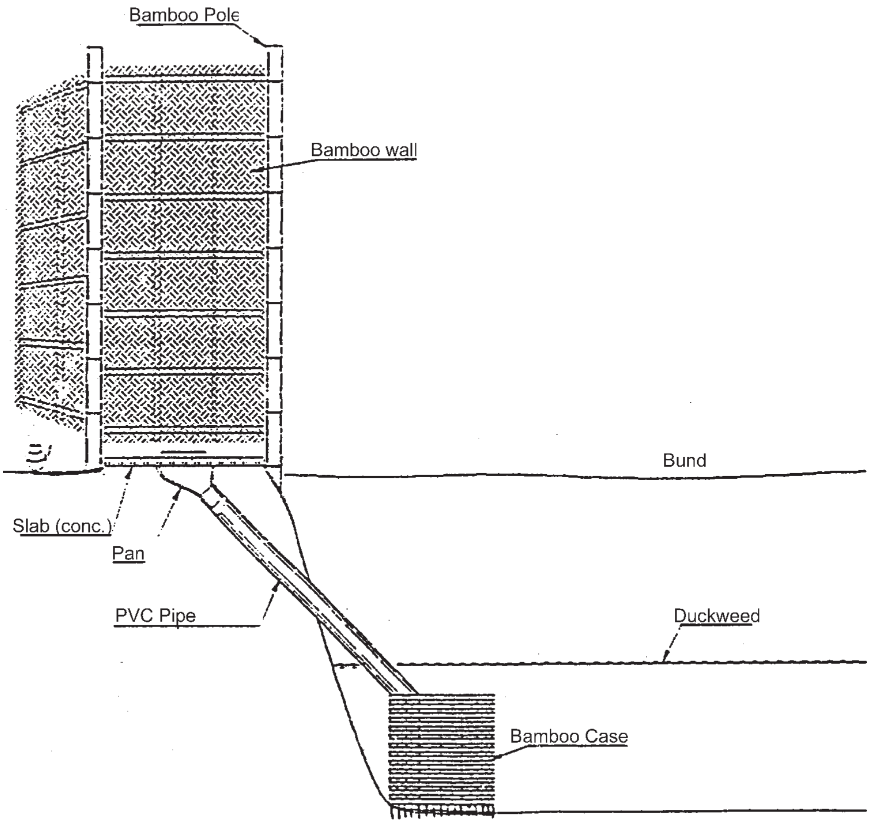
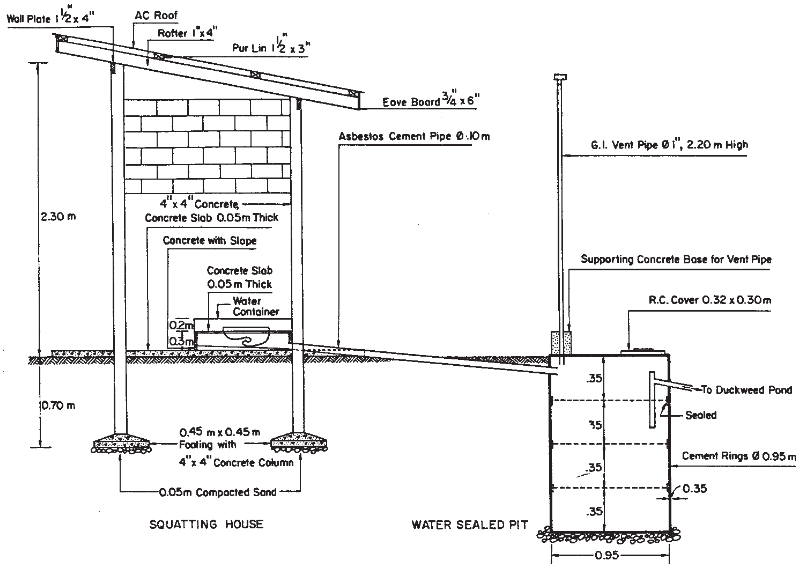


Figure 3. *Family/village level pour-flush pit latrine. Settleable solids sink to the bottom of the water-sealed pit where they undergo anaerobic decomposition. The liquid effluent overflows from the pit into the adjacent duckweed pond, while sludge remains at the bottom of the pit from where it has to be removed periodically (Edwards et al. 1987).*



Pond Design

As aforementioned, two basic principles for pond design and operation are used for duckweed treatment, namely plug-flow and batch systems.

Plug-flow design is suitable for treatment of large and regular wastewater flows originating from communities and peri-urban areas.

A plug-flow (continuous flow through) design (Phot. 2) seems to be the more suitable treatment option for larger wastewater flows originating from communities and (peri-)urban areas, as it ensures an improved and more continuous distribution of the nutrients. A plug-flow design also enhances the contact surface be-

Photograph 2: *Duckweed-covered serpentine plug-flow lagoon in the USA for tertiary treatment of effluent from three facultative lagoons followed by a wetland buffer. Design flow is reported at 19,000 m^3/d, with peak flows reaching 38,000 m^3/d. (Photograph: Lemna Corp. 1994).*

tween wastewater and floating plants, thereby, minimising short-circuiting. To ensure plug-flow conditions, a high plug-flow length to width ratio of 10:1 or more is necessary (Hammer 1990). Alaerts *et al.* (1996) reported excellent treatment results with a length to width ratio of 38:1. Moreover, a narrow, channel-like design allows easier access to the water surface for operation and maintenance work.

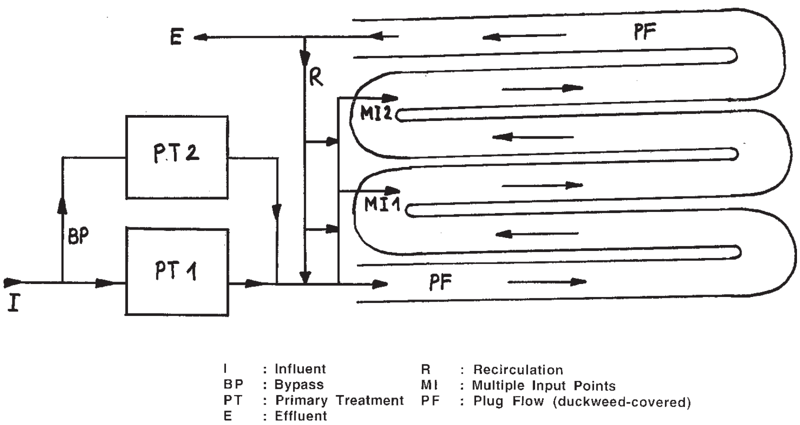
In a plug-flow system, duckweed productivity, nutritional value and nutrient removal efficiency decline gradually with increasing retention time. Depletion of nutrients causes plants to visually become brownish at some stage in the plug-flow runway, to grow slower and take up less nutrients per time than plants in the initial stages of the plug-flow. Furthermore, their protein content drops and their fibre content increases. At this point, the two so far parallel running processes of efficient wastewater treatment and high duckweed production begin to diverge. Yet, if this occurs at the very end of a duckweed plug-flow system and if the required effluent standards are met, the objective of combined wastewater treatment and production of high quality feed is attained.

Duckweed can be used for combined wastewater treatment and production of high protein biomass up to the point where nutrient limitation diverges the two so far parallel running processes.

However, reliable design guidelines are missing to dimension a duckweed plug-flow lagoon in such a way that nutrient starvation occurs at the very end of the system. The system could, therefore, either be oversized if effluent standards are already met at early fractions of total retention time, leaving most of the system's surface underused with regard to protein production, or undersized where effluent standards are not met at the end of the plug-flow. Thus, an ideal duckweed plug-flow system should include both multiple wastewater input points and a recirculation system (Fig. 4).

To achieve optimum treatment efficiency and protein production, an ideal plug-flow design should include multiple wastewater inlet points and allow recirculation of the final effluent.

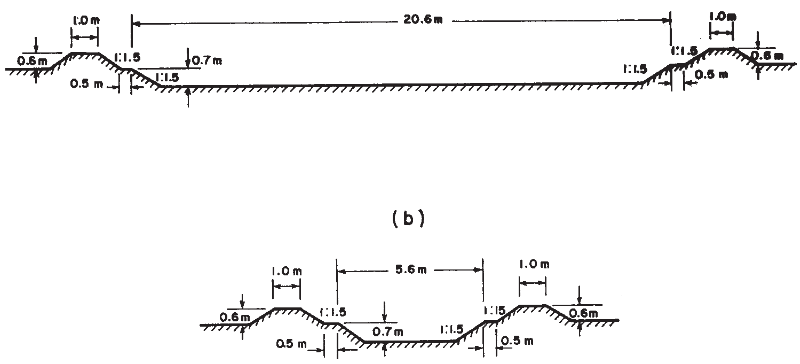
Figure 4. *Ideal plug-flow system for combined duckweed-based wastewater treatment and protein production.*



Batch-operated ponds (Phot. 3, Fig. 5) are a feasible option for introduction of duckweed aquaculture in villages where already existing ponds can often be used and, thus, save capital costs for extra earth work. In comparison with a continuous flow through system, duckweed growth may be enhanced near the nutrient inlet points as a result of reduced nutrient mixing and distribution. A narrow pond design allowing duckweed harvesting from the embankment is also favoured here.

Photograph 3: *Batch-operated pond for duckweed cultivation at village level showing dense duckweed cover and pour-flush latrine influent for nutrient supply in the background (Bangladesh).*

Figure 5. *Example of batch-operated pond for duckweed cultivation at village level. (100 m² at 0.5 m depth). (a) length and, (b) width section of duckweed pond (Edwards et al. 1987).*



Hydraulic Retention Time (HRT)

Hydraulic retention time in duckweed treatment systems should amount to at least 20 days to ensure acceptable pathogen removal.

The HRT is dependent on the organic, nutrient and hydraulic loading rate, depth of the system and harvesting rate (Metcalf and Eddy 1991). To ensure acceptable pathogen removal and treatment efficiency, comparatively long retention times in the range of 20 to 25 days are postulated for duckweed (plug-flow) systems (Metcalf and Eddy 1991).

Water Depth

The critical factor with respect to water depth is to ensure vertical mixing in the pond to allow the wastewater to be treated to come into contact with the duckweed fronds for nutrient uptake and BOD degradation through attached microbial populations. An outlet structure is recommended in order to vary the operating depth (Metcalf and Eddy 1991).

Reported pond depths range from 0.3 to 2.7 m up to even 5 m (Lemna Corp. 1994). The majority of authors report an optimal depth ranging from 0.4 to 0.9 m, implying that a maximum depth of one meter is sufficient for acceptable temperature buffering. Higher depths are also a feasible option for systems with relatively low BOD loads, a low recirculation rate and high land costs. Shallow system depths are, however, better suited for high organic loads, a high recirculation rate and for regions with inexpensive land prices.

Both shallow and deeper pond depths are currently being applied, depending on organic load and land availability.

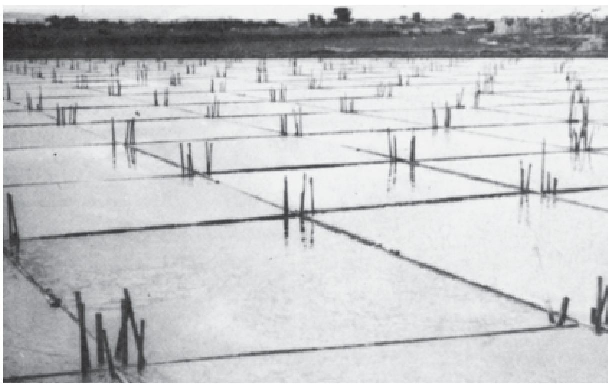
Organic Loading Rate

Average organic loading rates expressed in terms of BOD_5 for plant systems without artificial aeration should not exceed 100 to 160 kg/ha·d in order to obtain an effluent quality of 30 mg BOD/l or less (Metcalf and Eddy 1991, Gijzen and Khondker 1997). Odours can develop at lower loading rates, especially where the sulphate concentration in the wastewater is greater than 50 mg/l. It seems that duckweed is less suitable for the treatment of wastewaters containing high BOD loads.

Duckweed systems alone appear to be less suitable for treating wastewaters containing high BOD loads.

Wind Protection

Since duckweed is very susceptible to wind drifts and water currents, stabilisation of the plants on the water surface is of prime importance. In regions with moderate winds, drifts are prevented through floating grids dividing the pond surface into cells or compartments. Floating bamboo poles divided into small square or rectangular areas of 2 to 5 by 4 to 8 meters are most commonly



Photograph 4: *Large-scale commercial duckweed cultivation on organically polluted surfacewater in the city of Chiai, Taiwan (1985), showing floating bamboo square grids on the water surface to prevent duckweed from drifting. (Photograph: Edwards et al. 1987).*

Photograph 5: *A high density polyethylene grid system is used for duckweed stabilisation on the water surface in the shown duckweed-based polishing lagoon in the USA. It receives 500 m^3/d of combined municipal, septic and industrial wastes after pretreatment in an aerated lagoon. (Photograph: Lemna Corp. 1994).*

used (Phot. 4). The size of the grid is determined by mean wind conditions and, in the case of flow through systems, by maximum projected flow velocity in the system. The higher the wind and flow velocities, the smaller the cells and the higher the system's costs. With a design life of around two years and an average per hectare cost of about US$ 500, a bamboo grid systems offers a feasible solution to the problem of wind drifts (PRISM 1990). Furthermore, vegetation on the pond embankment contributes to dispersing and protecting against wind.

Lemna Corporation has developed a patented UV-stable high density polyethylene grid system (Phot. 5). The square shaped grids have a surface area of 25 to 50 m^2 and a reported design life of several years. This robust grid system is resistant to environmental extremes, however, the per hectare costs of such a system appear to be too high for low-income countries (PRISM 1990). For middle-income countries, a more durable and expensive grid system may be an economically more feasible option on a long term than a less expensive bamboo grid system which has to be replaced frequently.

Operating Considerations

Labour Requirement for Duckweed Farming

Duckweed aquaculture is a highly labour-intensive farming method requiring skilled labour and sophisticated management.

Duckweed survives a wide range of environmental extremes, but grows best in a narrow band of optimum growth conditions. Maintenance of these optimum conditions requires regular, skilled and experienced labour, as well as sophisticated management. Therefore, duckweed(-fish) farming is highly labour-intensive and needs almost daily attention throughout the year. This may be a

Photograph 6 (top) : *Transport of fresh duckweed in a wickerwork basket to the weighing station and adjacent fish pond, using a wooden board, a bamboo pole and strings for suspension of the basket (Bangladesh).*

Photograph 7 (left): *Freshly harvested duckweed grown on diluted sewage is filled into a wickerwork basket, where it remains for some time to allow some water drainage and pathogen removal by sunlight irradiation (Bangladesh).*

***Photograph 8:** Determination of duckweed wet weight using a spring scale and record keeping (Bangladesh).*

***Photograph 9:** Distribution of fresh sewage-grown duckweed into floating bamboo feeding zone of fish pond. The feeding zone prevents the floating duckweed from being undiscovered by fish through dispersal in the fish pond (Bangladesh).*

reason why duckweed aquaculture has, so far, not become a major waste reuse option in developing countries.
The availability of labour resources is generally not the limiting factor. Especially in areas where agricultural labour is seasonally underemployed, duckweed cultivation can create an alternative employment opportunity. However, recruiting of people for wastewater-based duckweed farming may become difficult in regions where the tasks related to excreta reuse have a very low employment status (WHO 1989).

Initial work may include earth work for pond excavation, sealing of ponds, planting of vegetation on the embankment as protective measure against heat and wind, duckweed seed stock collection from locally adapted wild colonies, seeding of duckweed, construction of wastewater and freshwater supply installations like open or closed channels, pumps, access ramps for septage trucks, or installation of latrines.

Operational and maintenance work includes harvesting (Phot. 6), weighing (Phot. 8), and transport of plants (Phot. 7), feeding of duckweed and supplementary feed to animals like fish (Phot. 9), heat and wind stress management, pest control, nutrient supply, water level maintenance, floating grid maintenance, pump operation and repair, maintenance of the duckweed cover, pond repair, periodic desludging, bookkeeping, to name but only the most important tasks. Standard monitoring of chemical wastewater parameters and pathogens is recommended whenever feasible.

Work related to animal cultivation, as in the case of integrated duckweed/animal farming, may account for a large part of total labour input, especially for pisciculture. Fish stocking, harvesting, transport and marketing, pond excavation, sealing and repair, water supply, feeding, fertilising ponds, continuous fish growth and health monitoring, aeration measures when concentrations of dissolved oxygen become critical, night-time guarding against theft, and bookkeeping are the most important tasks in pisciculture.

The vegetation grown on the pond embankments requires irrigation, fertilisation, weed removal, pest management, harvesting, transport, and marketing.

Four to five workers were employed for daily operation and maintenance of a sewage-duckweed-fish system (0.6 ha of duckweed-covered lagoon, 0.6 ha of fish ponds) in Bangladesh.

Harvesting of Duckweed

Regular harvesting of duckweed is essential to continuously remove nutrients or toxins from the system and to maintain a productive and nutritive crop.

The quantity and frequency of duckweed harvesting plays a major role in the treatment efficiency and nutritional value of the plants. Regular harvesting ensures that the accumulated nutrients or toxins are permanently removed from the system. Because younger plants show a better nutrient profile and higher growth rate than older plants, regular harvesting is important to maintain a healthy and productive crop. Laboratory results from Whitehead and Bulley (in Reddy and Smith 1987) revealed that under conditions of high nutrient loading, an increase in the cropping rate resulted in improved nutrient removal. At lower nutrient loading rates, the cropping rate should be reduced. An almost complete cover should remain on the pond surface after plant harvesting.

Optimum standing crop density to achieve highest productivity is site specific.

The standing crop density, which realises the highest duckweed productivity, will determine the harvesting frequencies and amounts. The correlation between standing crop density and absolute biomass productivity peaks at some optimal density and gradually declines as increasing density inhibits growth through crowding. Optimal standing crop densities are site-specific and have to be determined through practical experience (Skillicorn *et al.* 1993).

Alaerts *et al.* (1996) reported a standing crop density of 1600 g(wet wt)/m^2 for a duckweed-covered sewage lagoon in Bangladesh. Koles *et al.* (1987) reported an optimum standing crop density for treatment of nutrient-rich algae culture (fertilised with pig excreta) effluent in Florida of 1250 g(wet wt)/m^2. Lower standing crop densities of 400 to 800 g(wet wt)/ m^2 were reported by PRISM (unpublished), DWRP (1996), and Skillicorn *et al.* (1993). Each cell should be harvested back to optimal standing crop density at rates dependent on the plants' productivity. Reported harvesting frequencies and amounts vary widely (Tab. 2).

Table 2. *Harvesting frequencies and amounts as reported by different authors.*

Application level	*Species*	*Harvesting frequency (days)*	*Amount harvested (in % of standing crop)*	*Reference*
Community level Bangladesh	*S. polyrrhiza*	1	10-25%	Skillicorn*et al.* (1993), PRISM
Laboratory-scale	*S. polyrrhiza, L. minor*	1	10%	Whitehead and Bully in Reddy and Smith (1987)
Community level Bangladesh	*S. polyrrhiza*	2 (wet season) 3 (dry season)	____	Alaerts *et al.* (1996)
Large-scale Commercial level Taiwan cities	*Lemna, Wolffia*	7	80%	Edwards *et al.* (1987)
Village/family level Thailand	*S. polyrrhiza*	11.3 (mean)	____	Edwards *et al.* (1987)
Pilot-scale	*Spirodela, Lemna*	1-3	25%	Edwards *et al.* (1992)
Large-scale	*Lemnaceae*	weekly (nutrient removal) monthly (secondary treatment)	____	Metcalf and Eddy (1993)
Pilot-scale	*L. gibba, S. punctata*	biweekly	____	Koles *et al.* in Reddy and Smith (1987)

The choice of harvesting technique is dictated by system design and by labour and equipment costs. For shallow ponds, the most simple harvesting techniques include manual skimming of the plants from the pond surface with a net (Phots. 10 and 11), or moving the floating plants to one corner of the pond with a bamboo pole and removing them with baskets (Phot. 12). Two people were reported to require 3.5 hours for manual harvesting of duckweed from a 0.3 ha pond in Taiwan. Large-scale harvesting in industrialised countries is carried out with mechanical harvesting machines requiring, however, deep ponds (Phot. 13).

Relief of Heat Stress

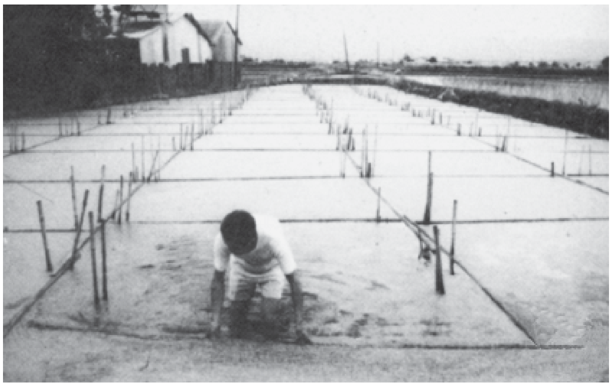
As aforementioned, duckweed growth rapidly declines at temperatures above 31 °C to 35 °C, as the plants experience severe heat stress. Relief of heat stress during extremely hot days can be achieved by manual dunking of the plants and by splashing or spraying them with a fine mist of water. This is an efficient and immediate way of lowering temperatures by 5 °C to 10 °C, though quite intensive in terms of work.

Duckweed experiences severe heat stress at temperatures above 31 °C to 35 °C. Manual dunking of plants, planting of shading vegetation on the pond embankment and an increase in the water volume of ponds can relieve from heat stress.

Cultivation of plants on the embankments of the ponds will shade the duckweed cover and protect it from direct sunlight. In addition, the sale of the co-produced plants, such as papaya, ba-

***Photograph 10:** Manually harvested sewage-grown duckweed using a net (Bangladesh).*

***Photograph 11:** Manually harvested duckweed using a net. The pond is fertilised with human excreta, supplied by the pit's overflow of the pour-flush pit latrine shown in the background (Thailand). (Photograph: Edwards et al. 1987).*



***Photograph 12:** Manually harvested duckweed grown on organically polluted surfacewater using a bamboo pole to move the floating duckweed to the pond's corner for removal (City of Chiai, Taiwan). (Photograph: Edwards et al. 1987).*

***Photograph 13:** Diesel-powered mechanical harvester for biomass removal in larger duckweed-based wastewater treatment lagoons in the USA. (Photograph: Lemna Corp. 1994).*

nana, sugar cane, bamboo, etc., can generate additional net income.

Another alternative to buffer high temperatures is to increase water depth up to 150 cm. Increased water volume and the inflow of cool groundwater have a buffering effect and significantly lower peak temperatures. The availability of sufficient and suitable water resources can be problematic and result in a cost increase. Since ponds must be designed to hold a meter or more of water, the pumping costs will increase significantly. The increased water pressure of raised water levels may accelerate water loss through percolation (PRISM 1990).

Removal Mechanisms

Duckweed wastewater treatment systems are, at their core, conventional facultative pond systems. They differ from the latter, however, in that they a) achieve a higher nutrient removal from the wastewater by harvesting the biomass, b) work to inhibit rather than to encourage algal growth, c) may have an aerobic zone of only a few centimetres in comparison to facultative ponds with aerobic zones of up to one meter in depth, and d) undergo only slight variations in temperature, dissolved oxygen concentrations and pH which show wide diurnal fluctuations in facultative ponds. These more consistent conditions are believed to favour the continuous growth of degrading microbial populations (Lemna Corp. 1994, PRISM unpublished).

Environmental conditions and treatment processes prevalent in duckweed-covered lagoons differ significantly from those encountered in facultative ponds.

The following paragraphs contain a brief description and discussion of the removal mechanisms for TSS, BOD, nitrogen, phosphorous, heavy metals, and organic toxins, as assumed by various authors. Removal of pathogens is discussed separately under Chapter Three, pp. 45.

TSS Removal

TSS are removed mainly by sedimentation and biodegradation of organic particles in the pretreatment and duckweed pond system. A minor fraction is absorbed by the roots of the duckweed fronds, where organic particles undergo aerobic biodegradation by microorganisms, and part of the degraded products is assimilated by the plants.

Two characteristics of duckweed treatment systems are believed to play an important role in TSS removal. A complete mat of duckweed inhibits penetration of sunlight and subsequent growth of algae. Large amounts of algae contribute significantly to TSS concentrations. Though algae take up considerable amounts of N, P and other nutrients and may, therefore, contribute to their removal, the nutrients are released again by biodegradation when algae settle, die off and become available again for algal growth. A dense mat of duckweed can, therefore, reduce algal contribution to TSS. This is one of the reasons why a complete duckweed cover is essential for treatment efficiency of duckweed systems. Compared to facultative ponds, a second, more uncertain factor favouring sedimentation of TSS in duckweed systems is attributed to the quiescent conditions prevalent in the water column under the duckweed cover, as a consequence of the more consistent vertical temperature profile.

Algal contribution to TSS is low in duckweed systems since penetration of sunlight is greatly reduced by a dense duckweed cover inhibiting subsequent algal growth.

BOD Removal

The mechanisms of BOD removal in duckweed ponds and the relative contribution of the plants towards BOD removal are far from being fully understood. Generally, it can be said that BOD is substantially removed by both aerobic and anaerobic microorganisms associated with the plants' surfaces, suspended in the water column and present in the sediment. Landolt and Kandeler

BOD is aerobically digested by microorganisms attached to the duckweed fronds. Anaerobic processes are responsible for BOD removal in the sediment.

(1987) reported the direct uptake of small hydrocarbons by duckweed, however, heterotrophic growth probably plays a minor role in total BOD removal.

Aerobic degradation of BOD may be less important in duckweed systems than in water hyacinth systems due to lower oxygen supply and smaller plant surface area for attached bacterial growth.

Aerobic BOD removal is assumed to be less important in a duckweed treatment system than for example in a water hyacinth system. Aerobic BOD removal depends on oxygen supply and surface area available for attached bacterial growth. *Lemnaceae,* however, possess a relatively small surface area for attached growth of mineralising bacteria compared to other aquatic macrophytes with larger submerged root and leaf surfaces (Zirschky and Reed 1988). The dense cover of duckweed on the water surface would also inhibit both oxygen from entering the water by diffusion from the air and photosynthetic production of oxygen by phytoplankton as a result of the poor light penetration (Culley and Epps 1973, Brix and Schierup 1989). According to Zirschky and Reed (1988), BOD removal could even decrease in ponds covered with duckweed because of the limited oxygen transfer into the water.

Alaerts *et al*. (1996), however, found that with a BOD loading rate of 48-60 kg/ha·d, a water depth of 0.4-0.9 m and a HRT of about 20 days, the water column in a duckweed-covered sewage lagoon system always remained aerobic. Surprisingly, the authors calculated an aeration rate through the duckweed-covered surface of 3-4 gO_2/m^2, which is slightly higher than oxygen transfer through an uncovered surface (Srinanthakumar *et al.* 1983). This leads to the conclusion that aerobic conditions occur at least in the top layer of a duckweed pond within and under the plant cover due to photosynthetic production of oxygen and surface aeration. Interesting results were also observed by Koerner *et al.* (1998) who reported that COD removal was significantly faster in the presence of duckweed than in its absence. They believe that the structure of duckweed surface and the way oxygen is supplied are important elements, since the positive influence of a living duckweed population on COD removal could not be simulated by artificial plastic duckweed surfaces and oxygen pumps.

Depending on the organic loading rate, water depth and HRT, the prevalent redox conditions in a duckweed-covered pond system can become anoxic to anaerobic. In this case, the main factors responsible for BOD removal in duckweed treatment systems are probably similar to those described for the anaerobic zone of facultative ponds (Reed *et al.* 1988). Step cascade aeration prior to discharge is a low-energy possibility for reaeration of an effluent containing low levels of dissolved oxygen.

Nitrogen Removal

The nitrogen balance in a duckweed treatment system is determined by plant uptake, denitrification, volatilisation of ammonia, microbial uptake, and sedimentation. Regarding the relative importance and kinetics of the different removal processes, overall conclusions are either unknown or difficult to draw, as determining factors like nitrogen availability, redox and pH conditions are largely dependent on N and BOD loading rates, including specific design and operation of a duckweed treatment system.

Besides plant uptake, denitrification and volatilisation of ammonia are quantitatively relevant processes for nitrogen removal in duckweed systems.

Existing results suggest that approx. 50 % (± 20 %) of the total nitrogen load is assimilated by duckweed, while the remaining nitrogen is removed by indirect processes other than plant uptake of which nitrogen loss to the atmosphere by denitrification and volatilisation of ammonia are suggested to play a major role (Alaerts *et al.* 1996, Gijzen and Khondker 1997, Koerner and Vermaat 1997).

Particularly in ponds with aerobic and anaerobic environments favouring microbial nitrification and denitrification, ammonium (NH_4^+) is first oxidised to nitrate (NO_3^-) and subsequently reduced to atmospheric nitrogen (N_2) which is released from the system.

At alkaline pHs above 8, the ammonium-ammonia (NH_3) balance shifts towards the unionised form which results in a loss of nitrogen through volatilisation of ammonia. Besides, ammonia is toxic to duckweed.

It is unknown how far nitrogen fixation by cyanobacteria, which can form a symbiontic relationship with *Lemnaceae* (Duong and Tiedje 1985), contributes to the overall nitrogen balance in a duckweed treatment system.

Phosphorous Removal

Plant uptake and sedimentation are quantitatively relevant for phosphorous removal in duckweed systems.

In a duckweed treatment system, phosphorous is normally removed by the following mechanisms: plant uptake, adsorption to clay particles and organic matter, chemical precipitation with Ca^{2+}, Fe^{3+}, Al^{3+}, and microbial uptake. Except for plant uptake, the latter three mechanisms cause a storage of phosphorous in the system. As no volatile intermediates such as N_2 or NH_3 as in the case of nitrogen are formed, ultimate phosphorous removal is only possible by plant harvesting and dredging of the sediment.

The plants' uptake capacity depends largely on the growth rate, harvesting frequency and available *ortho*-PO_4^{3-}, the favoured form of phosphorous for duckweed growth. In the warmer season when the growth rate is highest, phosphorous removal rate is also highest. The uptake of phosphorous by duckweed is enhanced by frequent harvesting and adequate pretreatment of raw wastewater to release organically bound *ortho*-PO_4^{3-}.

Besides plant uptake, adsorption and precipitation are probably the other dominant mechanisms for phosphorous removal in a duckweed treatment system. These particle/sediment-water phase interactions are very complex and depend on the redox potential, pH and concentrations of reactants. Aerobic conditions contribute to the precipitation of phosphorous through oxidised forms of Fe and Al. However, phosphorous is again released under anaerobic conditions prevailing in the sediments.

Removal of Heavy Metals and Organic Compounds

Since duckweed are capable of accumulating high amounts of heavy metals and organic compounds, its use is to be limited to only wastewater treatment.

As aforementioned, *Lemnaceae* can tolerate and accumulate high concentrations of heavy metals and organic compounds with accumulation factors ranging between multiples of 10^2 and 10^5. As regards this particular duckweed characteristic, Landolt and Kandeler (1987) cite over 60 references. It seems that the concentration factor for heavy metals is much higher at low metal concentrations.

This fact suggests a possible use of duckweed for efficient removal of metals from wastewaters. It is, therefore, important that the plants are harvested at regular intervals to prevent the metals from settling on the sediments with the decaying duckweed. The duckweed thus produced should under no circumstances be used in food production (Gijzen and Khondker 1997). As reported, heavy metals can be regained from the plant tissues through low temperature caronization (Niklas 1995). Potential applications for removal of chromium from wastewaters of leather processing industries or removal of arsenic for drinking water purification are worth investigating.

Toxins may enter a duckweed aquaculture systems not only through (industrial) wastewaters, but also through additional water resources such as surface or groundwater.

Compared to Swiss sewage sludge and compost standards, heavy metal analysis of a duckweed plug-flow lagoon using an anaerobic sedimentation pond for pretreatment in Bangladesh revealed acceptable concentrations of lead, cadmium, chromium, copper, nickel, mercury, and zinc in duckweed and in the sludge of the sedimentation pond (Iqbal 1995). The wastewater was of domestic origin. The sediment of the plug-flow was not analysed. The major sink for the aforementioned metals was the sludge of the sedimentation pond and not the duckweed, except for copper and arsenic which showed higher concentrations in duckweed than in sludge. High concentrations of arsenic in duckweed used as fish feed, are of serious concern as it is highly toxic for humans. Arsenic was introduced into the system through the additional supply of groundwater during the dry season. The duckweed produced during the dry season, when sewage is diluted with groundwater, should no longer be fed to fish until the risk of arsenic accumulation in the food chain is assessed. Geogenic arsenic contamination of groundwater is a severe calamity in Bangladesh.

In case of nutrient depletion, the “polishing theory” sustains that starved plants begin to process great amounts of water in search of growth nutrients. In this process, they absorb virtually all chemical substances present in the wastewater. During this polishing process, organic toxins and heavy metals are most likely to be absorbed. It is interesting to note that this theory can only be partially supported by the study: concentrations of lead, chromium and nickel were about twice as high in duckweed harvested from the polishing zone (last section downstream of the plug-flow where nutrient depletion occurs) than in duckweed harvested at the inlet of the plug-flow (wastewater inlet). The cobalt and cadmium concentrations were about the same. For copper and arsenic, however, concentrations in duckweed were about five to six times higher at the plug-flow's inlet than at its outlet.

Organic toxins enter a duckweed treatment system mainly via the (industrial) wastewater, but also through external sources such as pesticides sprayed against duckweed pests (see Chapter Four, pp. 51), contaminated additional water resources, and to an unknown fraction also via rain and air deposits.

Biodegradation of a few organic compounds in duckweed systems was also reported. It is assumed that duckweed does not directly contribute to the biodegradation process, but indirectly via the provision of additional oxygen for associated bacteria. Anaerobic degradation of organic xenobiotics in the water column and the sediment of duckweed treatment systems is also likely to occur.

Certain organic xenobiotics may to some extent, undergo microbial degradation in duckweed systems.

Federle and Schwab (1989) reported the efficient biodegradation of alcohol ethoxylate and mixed amino acids by the microbiota associated with *Lemna minor*. Linear alkyl benzene sulphonate was not biodegraded by the same microbial population.

Mosquito and Odour Control

The results of several studies on the effects of duckweed on mosquito breeding appear to be contradictory (Gijzen and Khondker 1997). Positive, negative and no effects were reported by the references in Landolt and Kandeler (1987). A positive effect of a duckweed cover on the decrease of mosquito larvae was reported for *S. punctata* (Furlow and Hays 1972), *L. minor* (Angerilli and Beirne 1980), *Wolffia* (Bentley 1910), and *Spirodela* (Culley and Epps 1973). The authors suggest that a complete duckweed cover acts either as physical barrier and hinders the mosquito larvae from reaching the surface for oxygen uptake, or that the plants release compounds which are toxic to the larvae (Bentley 1910, Judd and Borden 1980). A possibly reducing effect of duckweed on mosquito breeding may positively contribute to the acceptance of duckweed farming systems in areas where mosquitoes are a nuisance and a vector of serious human diseases like malaria or dengue.

There are indications that a dense mat of duckweed acts as physical and chemical barrier against mosquito larvae and odour development.

The gaseous products resulting from anaerobic decomposition in the sediment and water column are responsible for odour development. It is assumed that the aerobic duckweed mat acts as chemical and physical barrier against odours. Hydrogen sulphide (H_2S) oxidises for example to sulphuric acid (H_2SO_4) within the aerobic plant mat (Lemna Corp. 1994).

Removal Efficiencies

Reliable data on removal efficiency in full-scale duckweed treatment systems is practically inexistent.

The most relevant study on removal efficiencies in a full-scale duckweed treatment system in a low-income country was published by Alaerts *et al.* (1996). The study focused on a 0.6 ha plug-flow sewage lagoon covered with *Spirodela* for 2000-3000 inhabitants in Bangladesh. The lagoon received the effluent of an anaerobic sedimentation pond with a HRT of 1-3 days. The plug-flow's depth increased from 0.4 to 0.9 m with a HRT of about 20 days. Table 3 shows the typical loading rates, influent and effluent concentrations, including reduction in concentration of the lagoon during the study period (dry/winter season).

Table 3. *Typical wastewater parameters of a duckweed-covered plug-flow lagoon during the dry/winter season in Bangladesh. The values in parentheses are based on a 4-year monitoring (1990-1994). Influent data was corrected for dilution effect caused by groundwater supply. Concentrations of NH_4^+ and NO_3^- are expressed in mg N/l. The concentration of o-PO_4^{3-} is given in mg P/l. Values were corrected for a leakage-free lagoon (Alaerts et al. 1996).*

Parameter	*Loading rate (kg/ha·d)*	*Influent (mg/l)*	*Effluent (mg/l)*	*Reduction in concentration (%)*
BOD_5	48-60	125 (80-160)	5 (8)	96 (90-95)
Kjeldahl-N	4.2	10.5	2.7	74
Total P	0.8	1.95	0.4	77
o-PO_4^{3-}	----	0.95 (0.5-2.5)	0.05 (0.05-1)	95 (90-95)
NH_4^+	----	8 (3-20)	0.03 (0.1-1)	99 (90-99)
NO_3^-	----	0.03 (0.05-1)	0.05 (0.05-1)	----

A duckweed-covered lagoon in Bangladesh treats domestic sewage of relatively low strength to a quality meeting tertiary wastewater effluent standards.

The system performs extremely well with regard to the studied chemical wastewater parameters and meets tertiary effluent standards.
Mention should be made that the lagoon suffered from substantial leakage during the dry season with a loss of about 30 % of total nutrient input. Furthermore, the influent BOD concentration was lower than typical values encountered in most developing countries, as a significant portion of the community's BOD discharge was not captured by the collection system.

The contribution of duckweed towards total nutrient removal in the system was around 46 % for phosphorous and about 42 % for nitrogen. When corrected for leakage, the authors calculated that duckweed harvest would remove 60-80 % of the total N and P load.

About 80-90 % BOD removal and about 90 % of total nutrient uptake by the duckweed were already reached within 7.3 days actual retention time, indicating that the system could accommodate higher organic and nutrient loads.

Table 4 contains promotional information by Lemna Corp. on removal efficiencies. This data has to be interpreted with reservation as Lemna Corp. uses artificial aeration for gross BOD and TSS reduction, and nitrification reactors with fixed media for bacterial growth as modular options for their treatment facilities.

Table 4. *Reported treatment efficiencies of Lemna Corp. facilities (Lemna Corp. 1994).*

Parameter	*Influent*	*Effluent*	*Removal (%)*
BOD (mg/l)	200-600	<30-10	85-98
TSS (mg/l)	250-700	<30-10	88-98
Ntot (mg/l)	40-80	<20-5	50-93
NH_3-N (mg/l)	10-50	<10-2	0-96
Ptot (mg/l)	10-20	<5-1	50-95

Table 5 lists nitrogen and phosphorous uptake rates for duckweed as reported by different authors. The results are, however, not comparable due to differences in climate, operating conditions, incomplete mass balances, and species.

Table 5. *Nitrogen and phosphorous uptake rates ($g/m^2 \cdot d$) by duckweed (Gijzen and Khondker 1997, completed).*

Region	*Species*	*N uptake ($gN/m^2 \cdot d$)*	*P uptake ($gP/m^2 \cdot d$)*	*Reference*
Italy	*L. gibba / L. minor*	0.42	0.01	Corradi *et al.* (1981)
CSSR	Duckweed	0.2	------	Kvet *et al.* (1979)
USA	*Lemna*	1.67	0.22	Zirschky and Reed (1988)
Louisiana	Duckweed	0.47	0.16	Culley *et al.* (1978), Culley and Myers (1980)
Minnesota	*Lemna*	0.27	0.04	Lemna Corp.
Florida	*S. polyrrhiza*	------	0.015	Sutton and Ornes (1977)
Florida	*S. polyrrhiza*	0.15	0.03	Reddy and DeBusk (1985)
India	*Lemna*	0.50-0.59	0.14-0.3	Tripathi *et al.* (1991)
Bangladesh	*S. polyrrhiza*	0.26	0.05	Alaerts *et al.* (1996)

The area required for phosphorous removal is greater than for nitrogen removal. A reduction of the total phosphorous level to 1 mg/l, as proposed for strict water effluent standards in the USA, is unlikely to be achieved with duckweed alone (Culley and Myers 1980), as duckweed is unable to significantly reduce nutrient concentrations in waters with N and P levels below 4 mg/l (Rejmankova 1982). As phosphorous is mostly the limiting factor (Landolt 1996), P reduction to 1 mg/l may require a supplementary addition of N (Koles *et al.* 1987) or the use of a mixture of plants with similar climatic but different nutrient requirements (see Chapter Four, pp. 47).

Reduction of total P concentration to 1 mg/l is unlikely to be achieved without supplementary addition of nitrogen, as phosphorous is mostly the limiting factor for duckweed growth.

Comparison of Duckweed Systems with Other Treatment Systems

Duckweed treatment systems are less robust and simple to operate than waste stabilisation ponds. However, the generation of valuable biomass may offer a competitive advantage of duckweed systems over waste stabilisation ponds, and make up for their highly labour-intensive operation disadvantage.

Comparison with Waste Stabilisation Ponds

Where land is available at reasonable costs, waste stabilisation ponds are usually the wastewater treatment method of choice in warm climates (Mara 1976, Arthur 1983). They should be arranged in a series of anaerobic, facultative and maturation ponds with an overall HRT of 10-50 days, depending on temperature and required effluent quality. Simplicity, low cost and high efficiency of stabilisation pond systems compete with the generation of a net income derived from a qualitatively high feedstuff obtained from duckweed treatment systems. The disadvantage of both systems is their large land requirement. Table 6 compares the two types of pond systems.

Table 6. *Comparison between waste stabilisation ponds (WSP) and duckweed treatment systems (WHO 1989, Alaerts et al. 1996, Asano 1998).*

Criterion	*WSP*	*Duckweed treatment system*
Robustness	• Extremely robust • High ability to absorb organic and hydraulic shocks	High BOD loads need appropriate pretreatment
Capital costs	Low	25% higher than for WSP (*Source:* PRISM)
Labour requirements for operation and maintenance	• Low labour requirements • Unskilled, but supervised labour is sufficient • Extreme simplicity of O&M	• Highly labour intensive • Requires skilled labour • Sophisticated management necessary
BOD removal efficiency	>90%	>90%
Nutrient removal efficiency	Ntot: 70-90%, Ptot:30-50%	Ntot and Ptot >70%
TSS removal efficiency	Low, because of algae in the final effluent	High, due to inhibition of algae
Pathogen removal efficiency	High	Mainly unknown, but good preliminary results
Valorisation of biomass	None	• Use as animal feed • Revenue generation

Comparison with other Aquatic Macrophytes

Various aquatic macrophytes were studied as low-cost options for combined secondary (BOD removal) and tertiary (nutrient and final pathogen removal) wastewater treatment and nutrient reuse. Most of the work was done on water hyacinth (*Eichhornia crassipes*), some focused on pennyworth (*Hydrocotyle umbellata*), water lettuce (*Pistia stratiotes*) and waterfern (*Azolla sp.*).

The advantages of duckweed over other water plants are the following:

- Duckweed grows rapidly and is capable of nutrient uptake under a wide range of environmental conditions. Compared to most other aquatic plants, it is less sensitive to low temperatures, high nutrient levels, pH fluctuations, pest, and diseases (Dinges1982).
- Duckweed and its associated microorganisms are capable of absorbing and disintegrating a number of toxic compounds (Landolt and Kandeler 1987).
- Duckweed has been observed to efficiently absorb heavy metals (Landolt and Kandeler 1987). This characteristic may be detrimental if duckweed is used as feed.
- When grown on nutrient-rich waters, duckweed has a high protein and a relatively low fibre content and is, thereby, suitable for use as high-quality feed supplement.
- Harvesting of duckweed plants from the water surface is easy.
- A complete duckweed cover on the wastewater may efficiently prevent the growth of algae in the water body and result in a clear effluent of low TSS content.
- The presence of a dense duckweed mat has been reported to decrease and control the development of mosquito and odour in a wastewater body.

The reported nutrient removal rates for duckweed may be lower than for other aquatic macrophytes used in wastewater treatment.

Landolt and Kandeler (1987) report that of all aquatic macrophytes, *Lemnaceae* have the greatest capacity in assimilating the macroelements N, P, K, Ca, Na, and Mg, however, this may not be supported by other literature sources. The data presented in Table 7 suggests that nutrient removal rates for duckweed are comparatively slower than for other aquatic plants and, therefore, longer retention times will be necessary to reduce nutrient concentrations to specific discharge limits. Gijzen and Khondker (1997) state that despite of contradictory data, it is an established fact that duckweed has a high nutrient removal efficiency.

Table 7. *Nitrogen and phosphorous uptake rates by different floating aquatic macrophytes during summer and winter months in central Florida (DeBusk and Reddy 1987 and Reddy and DeBusk 1985).*

Plant	N uptake ($g/m^2 \cdot d$)		P uptake ($g/m^2 \cdot d$)	
	Summer	Winter	Summer	Winter
Water hyacinth	1.30	0.25	0.24	0.05
Water lettuce	0.99	0.26	0.22	0.07
Pennywort	0.37	0.37	0.09	0.08
Duckweed *(S. polyrrhiza)*	0.15		0.03	

Water hyacinth has been widely used for its extremely high nutrient uptake capacity (Tab. 7). However, no economically attractive application of the harvested biomass has so far been identi-

Duckweed treatment systems offer an alternative to water hyacinth systems in terms of tolerance to low temperatures, mosquito and odour problems, harvesting, nutritional value, use of biomass, and water loss through evapotranspiration. However, water hyacinth systems are more suitable for treatment of high BOD loads.

fied. In addition, water hyacinth only grows efficiently in tropical climates. Its use is restricted to regions with an even more pronounced temperate or seasonal climate than required for duckweed cultivation. A specific comparison of duckweed with water hyacinth for wastewater treatment and biomass use is presented in Table 8.

Table 8. *Comparison between duckweed and water hyacinth for wastewater treatment and biomass use as reported by various authors.*

Criterion	*Duckweed*	*Water hyacinth*
Tolerance to low temperatures	Higher	Lower, more restricted to warm climates
Nutrient uptake capacity	• High, but smaller contact area with the wastewater surface • High tolerance to high nutrient concentrations	Higher, due to greater contact area with the wastewater through root hairs
BOD removal efficiency	• Lower, because of smaller surface area for attached bacteria growth and lower oxygen supply • Lower tolerance to high BOD concentrations (<200 mg/l)	• Higher, because of larger submerged suface area for attached bacteria growth and higher oxygen supply to the root zone • Treatment of wastewater with very high BOD concentrations reported (>1000 mg/l)
Removal capacity of organic xenobiotics and heavy metals	High	High
Mosquito and odour problems	Probably positive effect on mosquito and odour control	In non-aerated and aerated aerobic systems a lesser problem. In facultative anaerobic systems a major problem
Harvesting	• Easier • Can be done manually (labour-intensive) and mechanically	• Complicated, because plants are bulky and interconnected over large distances • Mechanical harvesting equipment necessary
Nutrient profile (in % dry weight) when grown on wastewater	• Protein (30-45%) • Carbohydrate (35%) • Fiber (7-14%) • Fat (3-7%) • High vitamin and mineral content	• Protein (10-25%) • Carbohydrate (37-52%) • Fiber (17-20%) • Fat (1-3%)
Use of biomass	• High quality food supplement for fish and poultry • Land application • Composting • Methane and ethanol fermentation • Medicinal plant	• Hardly consumed at all by herbivorous fish • Technical processing feasible as animal food supplement, but unlikely because of high costs • Land application • Composting • Paper production • Biogas digestion
Water loss through evapotranspiration (ET)	Lower ET rates compared to open water (20-30% reduction)	Equal or increased ET rates compared to open water

Chapter Three

Public Health Aspects

Pathogens, heavy metals and organic toxins are the major public health aspects of concern. The, thereby, related health risks affect three main categories of people: Firstly, the workers who are in direct or indirect contact with the wastewater during operation and maintenance of a duckweed treatment system, and when handling and processing the system's outputs, such as duckweed, fish or sludge. Secondly, the consumers of the system's products, such as fish (mainly), but also chickens and ducks which are contaminated with pathogens and can contain high concentrations of toxins due to their bioaccumulation in the food chain. Thirdly, the population, especially children, living in the vicinity of the treatment ponds. Many people belong to more than one of the aforementioned categories, in some cases even to all three of them and will, thus, be at increased risk.

Particularly workers, but also the population residing near duckweed treatment systems and consumers of its products, are exposed to potential health risks through disease transmission by pathogens and toxic effects of heavy metals and organic xenobiotics accumulating in the food chain.

As it is difficult to entirely exclude direct contact with wastewater during work routine (Phots. 14 and 15), such as duckweed harvesting, dunking and transport, the pond workers belong to the highest risk category and are especially exposed to parasitic infections. Workers should be urged to adopt a high level of personal hygiene and receive basic health training to ensure that they understand the nature of risk and adopt available countermeasures. Pond design and surrounding vegetation should possibly allow operation and maintenance work to be carried out from the pond embankment (Phot. 16). Use of gloves, wellington boots and/or high-body waders is rare (Phot. 17), as they hinder

Workers should be urged to adopt a high level of personal hygiene.

Photograph 14: *Workers come into direct contact with diluted sewage of low strength during duckweed harvesting. They thoroughly wash themselves with soap and groundwater after harvesting routine is completed. So far, they have not shown any symptoms of disease transmission after 4 years of employment. Formerly, harvesting was performed from the plug-flow's embankment, but turned out to be too inconvenient and time-consuming.*

Photograph 15: *Filling of fresh duckweed into sacs using bamboo poles and wickerwork baskets. Workers come into direct contact with the organically polluted surfacewater used for duckweed cultivation (Taiwan 1977). (Photograph: Edwards et al. 1987).*

Photograph 16: *Fresh duckweed is placed into sacs and excess water squeezed out manually. Duckweed was grown on organically polluted surfacewater. The worker is using high wellington boots and gloves to protect himself from direct contact with the wastewater (City of Tainan, Taiwan). (Photograph: Edwards et al. 1987).*

Photograph 17: *Appropriate pond design and unconstrained access to the pond, allows manual harvesting of duckweed from the pond embankment, and prevents direct contact with the faecally polluted pond water (Thailand). (Photograph: Edwards et al. 1987).*

free and specific movements necessary for skilled duckweed farming, and because they are inconvenient to wear in warmer climates.

Some user groups in Bangladeshi villages have developed their own protective measures against contact with pond water: they form a kind of floating platform from bamboo poles or use a large bamboo stick for dunking (DWRP 1996). In some cases, boats are used for duckweed harvesting in larger ponds.

Viewed from a public health perspective, the limited number of health educated workers operating the system at increased risk will be of benefit to the population at large through the removal of faecal contamination. This is particularly true for community and (peri-)urban treatment systems.

To reduce the risk of pathogen transfer to consumers of animals fed on sewage-grown duckweed, removal of intestinal organs, repeated washing with safe water and thorough cooking is recommended.

Transfer of pathogens from animals fed with excreta-grown duckweed can be significantly reduced through the removal of intestinal organs, repeated washing with safe water and thorough cooking. However, traditional eating habits of raw meat or fish are very difficult to alter. The introduction of fish not eaten raw (for example tilapia) to such areas is also a possible alternative. However, even this preventive measure will not entirely eliminate customary practices, especially in small-scale subsistence aquaculture (WHO 1989). The physical separation of duckweed (grown on wastewater) and fish (raised in freshwater) cultivation in a two-pond system may lower health risks, as only indirect pathogen contamination of fish via duckweed is possible. However, due to bioaccumulation of toxic compounds, indirect wastewater use does not lower the risk of contamination.

Local residents should be informed that duckweed-covered ponds are fertilised with excreta and wastewater, in order to forbid their children from playing or swimming in them, and prohibit its use for bathing, cooking and other purposes. Warning notices should be posted by ponds adjacent to roads, especially if they are unfenced (WHO 1989).

Use of water for bathing, washing of clothes and cooking from excreta and wastewater-fertilised duckweed ponds should be prohibited.

Transfer of Pathogens

Pathogens of concern include helminths, bacteria, viruses, and protozoa. Almost no literature is available on the transfer of pathogens from duckweed farming systems (Gijzen and Khondker 1997). The few studies conducted so far have not revealed serious public health risks, however, further research is necessary and ongoing.

There is a priority research need to asses the risk of pathogen transfer in wastewater-duckweed-animal farming systems.

Feachem *et al.* (1983) mention three potential health risks associated with the aquacultural use of excreta and wastewater: a) passive transfer of excreted pathogens by fish and cultured aquatic macrophytes, b) transmission of trematodes whose life cycles involve fish and aquatic macrophytes (principally *Clonorchis sinensis* and *Fasciolopsis buski*) and c) transmission of schistosomiasis. These health risks are given for direct reuse of excreta and wastewater. In such systems, fish and aquatic macrophytes for human consumption are raised in ponds directly fertilised with excreta for which tentative microbiological pond water guidelines were set at 0 viable trematode eggs per litre and $<10^4$ faecal coliforms per 100 ml (WHO 1989). The same guideline values have to be considered when the final effluent of a duckweed treatment system is reused for irrigation purposes and fish pond topping. However, the potential health risks associated with the indirect reuse of excreta in duckweed farming systems are unknown. Microbiological quality guidelines are missing for different pathogens on excreta-grown duckweed fed to fish, poultry and mammals.

Tentative microbial guidelines for direct reuse of excreta and wastewater do exist, however, health guidelines for indirect reuse via duckweed are lacking.

Islam *et al.* (1996), who monitored faecal coliforms in a plug-flow lagoon covered with duckweed, observed a reduction from $4.57x10^4$/ml in the raw wastewater to values below 10^2/ml after treatment with duckweed (99.78 % removal). Despite these promising results, it does not provide any information on the relative contribution of duckweed on coliform removal or survival (Gijzen and Khondker 1997). Although different strains of *Vibrio cholerae,* including strains associated with cholera epidemics were isolated from duckweed, water, fish gills and intestine, and from the soil, the duckweed-wastewater-fish cultivation was considered a safe system (Kabir 1995, Islam *et al.* 1996).

Studies in Thailand and Bangladesh revealed promising results regarding faecal coliform removal in two-pond duckweed-fish systems.

Edwards *et al.* (1987) monitored aerobic bacteria (standard plate count), total and faecal coliforms, bacteriophages, *Salmonella*, and helminths in a duckweed-tilapia system using pour-flush water-sealed pit latrine effluent for duckweed culture at family/ village level (Tab. 9). The authors concluded that the system was

A hundred-fold accumulation of bacteria by duckweed from excreta-loaded pond water was observed.

safe from a health point of view. Concentrations of faecal and total coliforms were about a hundred times higher on duckweed than in duckweed pond water, thereby indicating a concentration effect of bacteria by duckweed. Although the contents of the digestive tract of fish showed relatively high concentrations of aerobic bacteria and total and faecal coliforms, most samples of fish muscle tissue were negative for all microbiological tests, and judged safe for human consumption following gutting, washing and thorough cooking. Fish and duckweed were cultivated in separate ponds.

Table 9. *Concentrations of microorganisms monitored at village level excreta-fed duckweed-fish systems in Thailand. Spirodela polyrrhiza was selected in Trial 1, whereas a mixture of Lemna perpusilla and Wolffia arrhiza was used in Trial 2 for duckweed cultivation.*

Test	*Water-sealed pit*		*Duckweed pond water*		*Duckweed*		*Fish pond water*	
	Trial 1	*Trial 2*	*Trial 1*	*Trial 2*	*Trial 1*	*Trial 2*	*Trial 1*	*Trial 2*
Stnd. plate count (number/l)	$1.8x10^8$	$1.5x10^6$	$1.9x10^4$	$2.6x10^4$	$2.1x10^7$	$1.8x10^7$	$4.0x10^3$	$4.7 x10^3$
Total coliforms (MPN index/100 ml)	$6.7x10^7$	$1.1x10^7$	$1.5x10^4$	$1.2x10^4$	$1.8x10^6$	$1.5x10^6$	$3.4x10^3$	$2.9x10^3$
Faecal coliforms (MPN index/100 ml)	$3.6x10^7$	$8.1x10^6$	$7.0x10^3$	$6.0x10^3$	$5.4x10^5$	$4.8x10^5$	$2.0x10^3$	$3.3x10^2$
Bacteriophage (MPN index/100 ml)	$1.8x10^5$	$2.8x10^6$	$2.2x10^2$	$2.7x10^3$	2.8x10	$1.5x10^3$	7.1	3.0x10

Efficient coliform removal mechanisms of sunlight (UV) and high pH values, as encountered in stabilisation ponds, are absent in duckweed-covered lagoons for lack of light and algal growth.

Efficient removal of coliforms is known from conventional lagoon treatment systems without floating aquatic macrophytes. Direct sunlight and an increase in pH due to algal growth are believed to be possible factors responsible for coliform die off in such systems. These beneficial effects are not prevalent in a pond system completely covered by duckweed which cuts off light and suppresses algal growth. A study in Egypt by Dewedar and Bahgat (1995) actually showed no decline in faecal coliforms under a dense duckweed cover over a period of (only) 5 days, whereas faecal coliforms in dialysis sacs exposed to direct sunlight decayed at a rate of 0.177/h. However, an analysis of studies on removal performance of *E. coli* in lagoons covered by various species of floating macrophytes (Alaerts *et al.* 1990) suggests that water temperature and hydraulic retention time are more determining factors. The effects of sunlight, pH and other parameters on bacterial and viral removal have to be investigated further in comparative studies using ponds with and without duckweed (Gijzen and Khondker 1997).

Helminths and their ova usually settle and die off in pond systems with long hydraulic retention times. These processes will probably be similar in duckweed-covered ponds. The quiescent conditions under a duckweed cover possibly favour the settling of helminths and TSS (Gijzen and Khondker 1997).

The quiescent conditions prevalent under a duckweed cover are believed to favour the sedimentation of helminths and their ova.

Transfer of Heavy Metals and Organic Compounds

As clearly shown, *Lemnaceae* can tolerate and accumulate high concentrations of heavy metals and organic compounds at accumulation factors ranging between multiples of 10^2 and 10^5.

Little specific information is available on the health risks associated with bioaccumulation of toxins in fish and other animals fed on duckweed grown in (industrial) wastewater. Krishnan and Smith (1987) report acceptable levels of heavy metals and pesticides in fish grown in sewage stabilisation ponds. Nevertheless, a potential health risk through bioaccumulation of toxins must be assumed even if some animals such as fish possess specific proteins which bind and eliminate certain heavy metals or metabolise toxins.

A potential health risk through the transfer of organic and inorganic toxins by animals consumed must be assumed due to high accumulation of such compounds in the duckweed feed.

From a health point of view, a strict separation of domestic and industrial wastewaters containing critical substances for duckweed culture is recommended if possible. The duckweed cover or sections of it grown on wastewater contaminated with heavy metals and organic toxins should, under no circumstances, be used anymore for food production, but rather be disposed off as safely as possible for example in bottom-sealed landfills.

Chapter Four

Particular Growth Constraints

Several problems partially limiting duckweed cultivation have emerged in practice. The major ones, as aforementioned, are drying up of ponds during the dry season and lack of water. This leads to wide seasonal variations of duckweed productivity and wastewater treatment efficiency. A second major problem is caused by the insufficient supply of nutrients required at relatively high concentrations for the rapid growth of duckweed. Other practical problems occasionally encountered are algal blooms, insect and fungal infestations and contamination of ponds by other aquatic macrophytes.

Insufficient Supply of Nutrients and Alternative Nutrient Sources

Insufficient nutrient supply was reported as a major growth constraint in two studies at rural level in Thailand (Edwards *et al.* 1987) and Bangladesh (DWRP 1996) using family latrine effluent as a nutrient source. Low nutrient concentrations are a minor problem in well-dimensioned community and peri-urban facili-

An insufficient supply of nutrients is a major problem, particularly at village level, since relatively high nutrient concentrations are required for duckweed growth.

ties where nutrient availability is higher and more regular. *Lemnaceae* need relatively high concentrations of nutrients for optimal growth (Tab. 10).

Table 10. *Range of nutrient concentrations in waters with Lemnaceae (Landolt 1996). Chemical elements in mg/l, conductivity in µS/cm.*

Parameter	*Absolute range*
pH	3.5 - 10.4
N	0.003 - 43
P	0.000 - 56
K	0.5 - 100
Conductivity	10 - 10900
Ca	0.1 - 365
Mg	0.1 - 230
Na	1.3 - >1000
HCO_3	8 - 500
Cl	0.1 - 4650
S	0.03 - 350

Phosphorous is mainly the limiting factor for duckweed growth.

Nutrient uptake is highest at relatively high concentrations of nutrients. At nitrogen and phosphorous concentrations below 4 mg/l, however, nutrient uptake strongly declines (Rejmankova 1982). Edwards *et al.* (1992) observed that pond water with less than 3 mg/l TKN and 0.3 mg/l TP did not support normal growth of *Lemna perpusilla* and *Spirodela polyrrhiza*. The limiting factor in waters for Lemnaceae growth is mainly phosphorous (Landolt 1996). Long-term growth of *Spirodela polyrrhiza* is, for example, only possible with a minimum phosphorous concentration of 0.4 mg/l (Lueoend 1983).

The reason for the comparatively high nutrient demand of duckweed resides in the fact that the nutrients are absorbed by the lower surface of the fronds which are rather small compared to that of the root hairs of other plants (Landolt and Kandeler 1987).

A mixture of aquatic plants, including different duckweed species, with similar climatic requirements but different nutrient level demands is suggested for nutrient removal at limiting phosphorous concentrations and continuous biomass production under conditions of low nutrient supply.

Landolt (1996) suggests the use of a mixture of plants with similar climatic requirements but lower nutrient level demands, such as for example different duckweed species (*L. minuta*), *Azolla*, or *Salvinia*, as a possible solution for nutrient removal at low concentrations. This, of course, would also be an option to sustain plant production during periods when nutrient supply is lower. Moreover, Zirschky and Reed (1988) assume that a mixture of different species is less susceptible to diseases and pests than a monoculture.

Natural selection generally shifts the composition of the plant community to the one best suited to the prevalent climatic and nutrient conditions. In Bangladesh for example, the growth of *Azolla* was observed in excreta-fed duckweed ponds at village level. The mixture of duckweed and *Azolla* was used as feed for a carp polyculture. However, initial stocking with *Lemna* and *Spirodela* of a wastewater lagoon receiving domestic sewage from a community in the same country gradually shifted to a monoculture of *Spirodela*.

Lemna Corp. optimises treatment efficiencies of their systems by addition of nutrients and micro-nutrients. As phosphorous is the limiting factor for duckweed growth, the addition of N was suggested for reduction of total P down to 1mg/l (Koles *et al.* 1987) to meet U.S. EPA discharge limits for tertiary treatment.

Human excreta, in particular urine, is a most suitable nutrient source for duckweed growth.

Owing to their comparatively high N, P, K, and Ca contents, human faecal matter and, particularly, urine seem a most suitable nutrient source for duckweed cultivation (Tab. 11). Rashid (1993) showed that for cultivation of duckweed in a 1000 m^2 shallow pond, human faecal matter and urine from 29-50 people are sufficient to sustain a high duckweed production rate.

Low-strength septage was reported to be an effective fertiliser for duckweed cultivation.

Edwards *et al.* (1992) used septage as a fertiliser for duckweed cultivation. The septage was pumped by municipal vacuum trucks from residential septic tanks in the city of Bangkok and transported to the experimental ponds at AIT, where it was directly loaded without further treatment at weekly intervals into four 200 m^2 (20x10m) ponds at a rate of 2 m^3 septage per 200 m^2. The municipal septage, with a mean 1.9 % dry matter, 941 mg/l TKN, and 119 mg/l TP content, was reported to be an effective fertiliser for duckweed cultivation.

The sole use or the addition of inorganic chemical fertilisers like urea (as nitrogen source), TSP (triple super phosphate as a source for both phosphorous and calcium), MP (muriated potash as a source for potassium), and unrefined sea salt (as a source for trace elements) for duckweed cultivation is practised in Bangladesh. This may be a solution for short periods of acute nutrient shortage in the waste streams, however, it increases costs significantly in the long run.

Various readily biodegradable organic and inorganic wastes, containing a high level of nutrients, are potential sources of nutrients for duckweed cultivation.

Various other readily biodegradable organic wastes with a sufficiently high content of nutrients could be potentially used in addition to human excreta for duckweed cultivation (Tab. 11). Wastes from kitchen and bathroom, food, dairy and fish processing industries, from slaughter houses, urban refuse, animal manure, biogas effluents, composted agricultural and market wastes, etc. are mentioned as potential nutrient sources (Gijzen and Khondker 1997). The same authors also suggest the use of inorganic and nutrient-rich waste streams originating from fertiliser industries (ammonium production), soap factories, pharmaceutical companies, etc.

The choice of (additional) nutrient sources is largely dependent on the local situation pertaining to available quantity, quality, degree of required pretreatment, and market value.

Table 11. *Moisture, organic and mineral content of some organic wastes expressed in % dry matter (Gijzen and Khondker 1997).*

Nutrient Source	*Moisture*	*Dry org. matter*	*C*	*N*	*P_2O_5*	*K_2O*	*CaO*	*Reference*
Human faecal matter	65-80	88-97	40-55	5-7	3-5.5	1-2.5	4-5	Rashid (1993)
Human urine	93-96	65-85	11-17	15-19	2.5-5	3-4.5	4.5-6	Rashid (1993)
Urban refuse	10-60	25-35	12-17	0.4-0.8	0.2-0.5	0.8-1.5	4-7.5	Rashid (1993)
Water hyacinth compost	85-95	_	_	1.9	1	2.9	4.6	Haider *et al.* (1984)
Cow dung (fresh)	85	_	_	0.4	0.02	0.1	_	Quddus and Talukder (1981)
Cow dung (compost)	_	_	_	0.5	0.3	0.2	0.3	Haider *et al.* (1984)
Pig manure (fresh)	80	_	_	0.55	0.5	0.45	_	Quddus and Talukder (1981)
Poultry (fresh)	_	_	_	1.6	1.5	0.85	_	Quddus and Talukder (1981)
Digester effluent (charged with pig manure)	_	6.5	_	3.4	_	_	_	Rodriguez and Preston (1996)

Ammonium concentrations above 50 mgN/l combined with pH values above 8 were reported to inhibit duckweed growth.

Not only the shortage of nutrients can limit duckweed growth, but also an oversupply of nitrogen at higher pHs. Koles *et al.* (1987) observed an important duckweed die off at ammonium-N concentrations above 50 mg/l, especially at pHs above 8. At high pHs, ammonium is transformed into the gaseous ammonia (NH_3) which is toxic to duckweed. Therefore, high concentrations of NH_4^+ at high pHs should preferably be avoided by dilution and pH buffering.

Algal Blooms

Algal blooms resulting from an incomplete duckweed cover and allowing penetration of sunlight into the water column, may cause severe damage and even duckweed die off.

Light penetration in the water column and subsequent competition of nutrients and space by algae can become a nuisance when the duckweed mat is incomplete due to disturbances or poor growth. The amount of duckweed harvested is an important factor in algal blooms. If too much duckweed is harvested, algae may start to grow. Refer to Chapter Two, pp. 30, for more detailed information on harvesting frequency and quantity.

Edwards *et al.* (1987) reported that the filamentous green alga *Spirogyza* bloomed in duckweed ponds fed with family latrine effluent. The farmers removed the filamentous algae manually, but the algae grew rapidly, became entangled with the duckweed roots and the duckweed fronds turned in colour from green to yellow. In several ponds, duckweed stopped growing and died. Although the ponds were cleaned from dead duckweed and algae and restocked with healthy duckweed, algal blooms reoccurred in most cases.

In another study (Edwards *et al.* 1992), algal blooms of both filamentous algae (mostly the blue-green alga *Oscillatoria* and the green alga *Oedogonium*) and phytoplankton (mostly the blue-green alga *Microcystis*) were reported as one of the most important factors constraining growth of duckweed with septage. The former was more harmful to duckweed as it clogged and wrapped itself around plant roots, causing the fronds of duckweed to shrivel and finally die. Attempts were made to kill algae by the algicide copper sulphate at a concentration of 2 mg/l. Algal growth was inhibited, but duckweed turned yellowish in colour. By changing the harvesting strategy, to maintain an almost complete duckweed cover on the pond surface, algal blooms did not reoccur. However, when algal infestation became severe, it was necessary to clear the pond and restock it with fresh duckweed.

Similar problems with filamentous algae were reported by DeBusk *et al.* (1976) and Lin (1982).

Insect and Fungal Infestation

Though duckweed growth is reported to be less sensitive to pests and diseases compared to most other aquatic plants (Dinges 1982), insect infestation can cause severe damage and even death of the plants. Fungal infestation inhibits growth.

Insect larvae and fungal infestation may cause severe damage and even death of duckweed.

A study in Thailand revealed that occasional insect infestation by larvae of *Nymphula* (Order Lepidoptera, Family Pyralidae) or/and by the waterlily aphid *Rhopalosiphum nymphaeae* (Order Homoptera, Family Aphididae) caused heavy damage to duckweed. Infestation by *Nymphula* was more frequent than by aphids. In one case, *Nymphula* infestation caused the death of plants within two weeks. Insecticide was applied to duckweed whenever insect infestation was observed and carried out weekly until the infestation was under control. Sevin-85 (carbaryl) at 5 g/5 l, dimethoate at 7.5 ml/5 l, ambush-100 (pyrethroid) at 5 ml/5 l water were alternately used to prevent insect resistance (Edwards *et al.* 1987).

In the same study, fungal infestation occurred in many ponds and inhibited the growth of duckweed. The fungal infestation resulted in a leaf spot disease and was probably caused by *Mylothecium,* which is also a parasite of the aquatic mosquito fern, *Azolla*. Infestation was brought under control by a weekly application of the fungicide Thane-45 (carbamate) at a concentration of 7.5 g/5 l water.

Insect (and possibly fungal) infestation by lepidoptera larvae (summer) and aphids (winter) was reported to affect duckweed yields at irregular intervals, causing decreased duckweed production in Bangladesh. At demo farm level, insect infestation was controlled by alternate application of different insecticides like Malathion and Nogos. At rural level, farming groups mentioned insect damage and diseases as the third reason for seasonal variations in duckweed production after lack of water and high temperatures (DWRP 1996).

Farmers, who commercially cultivated duckweed in Taiwan, reported that insects cause no problems to the crops and regarded insect damage as unimportant (Edwards *et al.* 1987).

Application of biocides to control insect and fungal infestation of duckweed is critical due to their extremely high and rapid uptake by duckweed and possible transfer into the food chain. Pesticides designed for agricultural use may behave differently in aquatic systems.

Application of insecticide and fungicide does indeed represent a health risk, since lipophilic organic compounds are known to bioaccumulate in the lipids of the cell membranes of duckweed and to excrete inside the cells. *Lemna minor,* for example, accumulates DDT up to 800 times (Vrochinski *et al.* 1970 in Landolt and Kandeler 1987). Studies of other pesticides revealed that the concentrations were about 1000 times higher in duckweed than in water (Landolt and Kandeler 1987). When fed to animals like fish, the residual pesticide can penetrate the food chain.

Regular residue analyses of duckweed and fish are recommended, yet they are often not always feasible in low-income countries for lack of necessary sophisticated analytical equipment. Biocides should be correctly applied (dosage, protective measures during application) and plants harvested several days after biocide application.

Although no alternative strategies for duckweed pest control have been developed so far, entomological research is regarded as an important element in research proposals by scientific groups in the Netherlands and Bangladesh for example. A mixture of several duckweed species, as recommended by Zirschky and Reed (1988), would be less susceptible to infestations and diseases than a monoculture.

Chapter Five

Use of Biomass

The low fibre content and high nutritional value of duckweed makes it a quality feed or feed component for animals and possibly also for humans. On account of its high moisture and nitrogen content, it can also be used as organic fertiliser in agriculture by direct land application or via composting.

Application of duckweed as fish feed is the most frequent and best studied use of duckweed. Moreover, duckweed is also known as a feed for ducks, chickens, freshwater prawns, pigs, edible snails, horses, and ruminants like cattle and sheep, however, information on these applications is scarce.

Duckweed is mainly known as fish feed, but also as feed for ducks, chickens, prawns, pigs, snails, horses, and ruminants.

Nevertheless, the following factors restrict the use of sewage-grown duckweed for feeding and fertilising purposes (Gijzen and Khondker 1997):

- Due to efficient absorption of heavy metals and other toxic compounds, duckweed should be cultivated on wastewaters with extremely low concentrations of such compounds.
- Its high moisture content (about 95 %) increases its handling, transport (Phot. 18) and drying costs. This fact is less important in integrated systems where fresh duckweed is used on site.
- The genera *Lemna* and *Spirodela* may contain high amounts of calcium oxalate which may limit the use of certain species for non-ruminant or for human consumption.

Photograph 18: *Freshly harvested duckweed filled into 60 kg sacs awaiting collection by truck for transport to fish and duck farms (City of Chiai, Taiwan). (Photograph: Edwards et al. 1987).*

Due to preservation, storage and transport constraints the current use of fresh duckweed is often restricted to areas located near the farm. Depending on the target animal, duckweed can be fed fresh as the only feed or, as in the case of most animals, in combination with other feed components. Almost all the animals mentioned in the following chapters feed on fresh duckweed with the exception of poultry, such as chickens, which probably have to be offered dried duckweed.

Due to preservation and storage constraints, duckweed is mainly fed to animals in its fresh state, mostly as feed component of a mixed diet. Poultry will probably, have to be fed on dried duckweed.

Fresh duckweed can be stored temporarily in a cool, humid place, such as in a small tank or pool. The fresh material, which will begin to ferment at high temperatures after a few hours, can be preserved for several days if kept cool and damp (Skillicorn *et al.* 1993).

Small-scale solar drying is feasible, UV light, however, degrades the valuable pigments in duckweed.

Small-scale solar drying is possible by spreading the fresh material on the ground and exposing it to sunlight. UV light, however, degrades the valuable pigments in duckweed. Pigment losses of about one-third to one-half may be expected after two days in the sun (Skillicorn *et al.* 1993).

Lemnaceae have a very high moisture content. Therefore, desiccating duckweed with purchased energy is economically not feasible as large amounts of energy are required.

Developments of feasible procedures for large and medium-scale solar drying and pelleting are lagging behind. According to some critics, drying of duckweed, as component part of dry pelleted feed, is not economically possible. However, its use in moist pelleted feed should be studied (Edwards *et al.* 1987). Desiccating duckweed, whose moisture content amounts to about 92 to 94 %, with purchased energy, such as gas, oil, electricity or biomass, is not economically feasible as large amounts of expensive energy are required. The economic potential of the plant may not be fully realised until it can be economically reduced to a dried, compact commodity (Skillicorn *et al.* 1993). This requires solar drying and either pelleting, powdering or other potential preservation methods like ensilaging.

Duckweed is potentially suitable for pelleting.

The waxy coating on the upper surface of duckweed plants is a good binding agent for pelleting. It can be stored for five or more years in the form of dried pellets. Sealable, opaque plastic bags are recommended for long-term storage to protect dried pellets from humidity, insects, vermin, and direct sunlight (Skillicorn *et al.* 1993).

Nutritive Value and Productivity

In comparison with the FAO amino acid reference pattern, duckweed protein is of high quality and could improve the protein-supply in countries where people suffer from protein malnutrition.

The amino acid profile of duckweed compares favourably with the FAO reference pattern with the exception of methionine, which reaches only half of the percentage of the reference pattern, and tryptophane of which only traces can be detected (Russoff *et al.* 1980). Since duckweed protein resembles more closely animal protein (as found in meat, fish, eggs, and dairy products), it offers an effective supplement to grains for animal and human consumption, especially in countries where people suffer from protein malnutrition.

Duckweed contains valuable vitamins, pigments and minerals.

Other important components like minerals and vitamins are also found in *Lemnaceae*. Landolt and Kandeler (1987) reported that duckweed contains about 40 different minerals, including vitamins A, B_1, B_2, B_6, C, E, and PP. Especially the contents of vitamin E (20-40 ppm) and PP (40-60 ppm) are remarkably high (Muzaffarov *et al.* 1971). The fairly high concentrations of the pigments xanthophyll and carotene (Truax *et al.* 1972) deepen the yolk colour of chicken eggs and the skin colour of red tilapia.

Grown under nutrient-rich conditions, protein makes up between 30 and 40 % of the dry matter content, with average yields under real-scale conditions ranging somewhere between 10 to 30 t dry wt/ha·y (Tab. 12).

Table 12. *Duckweed productivity and protein content as reported by various authors in different parts of the world (Gijzen and Khondker 1997).*

Species	*Nutrient Source*	*Productivity (t dry wt/ha·y)*	*Protein (% dry wt)*	*Reference*
S. polyrrhiza	Domestic wastewater	35.5	_	Robson (1996)
S. polyrrhiza	Domestic wastewater	17-32	_	Alaerts *et al.* (1996)
L. minor	UASB - effluent	10.7	28.9	Vroon and Weller (1995)
L. gibba	Municipal waste	_	11.5-23	Oron *et al.* (1987)
L. gibba	Pretreated raw domestic sewage	55	30	Oron and Wildschut (1994)
L. gibba *S. polyrrhiza*	Domestic wastewater	10.9-54.8	30-40	Oron (1986)
S. polyrrhiza *L. perpusilla* *W. arrhiza*	Septage from septic tank	9.2-21.4	24-28	Edwards *et al.* (1992)
L. perpusilla	Septage from septic tank	11.2	_	Edwards *et al.* (1990)
Lemna	Domestic wastewater	26.9	37	Zirschky and Reed (1988)
Lemna	Domestic wastewater	_	40	Logsdon (1989)
S. polyrrhiza	Sewage effluent	14.6	29.6	Sutton and Ornes (1975)
S. polyrrhiza	Domestic sewage	17.6-31.5	30	PRISM valid. report
	Inorganic fertiliser	12.2-21.1	27	PRISM valid. report

Productivity reported by various authors in different parts of the world varies from values as low as 2 t dry wt/ha·y to values over 50 t dry wt/ha·y. The wide variations are due to differences in species, climatic conditions, size of cultivation area, nutrient supply, and management. Some of the higher yield values are extrapolated from short-term and small-scale experimental systems operated under controlled growth conditions. These are not representative of real-scale conditions prevailing throughout the year. As aforementioned, by assuming a sufficient nutrient and water

Annual dry matter yields of duckweed under real-scale conditions in warmer climates range between 10 and 30 tons per hectare.

supply, an annual dry matter yield of about 10-30 t/ha, therefore, seems more realistic. Culley *et al.* (1978) report that best long-term productivities under natural conditions and in warm climate do not exceed 25 t dry wt/ha·y. Edwards *et al.* (1992) report that a productivity as high as 20 t dry wt/ha·y is perhaps a more realistic value for well-managed systems in the tropics.

Duckweed can yield about ten times more protein per hectare and year than soybean!

Assuming a mean annual yield of 17.6 t dry wt/ha·y, with a protein content of 37 % dry weight, a protein production of about 6.5 t/ha·y can be obtained. This per hectare protein yield is far higher than for most other crop plants, and about 10 times that of soybean (Tab. 13). This remarkable value for duckweed is not only attributed to its high growth rate and high protein content, but also to the fact that the entire biomass of duckweed is used as compared to only the seeds for most crops (Gijzen and Khondker 1997).

Table 13. *Comparison of annual and per hectare protein yields of duckweed and selected crops (adapted from Hillman and Culley 1978 in Gijzen and Khondker 1997).*

Plant/Crop	*Yield (t dry wt/ha·y)*	*Crude Protein (% dry wt)*	*Relative protein production**
Duckweed	17.6	37	100
Soybean	1.59	41.7	10.2
Alfalfa hay	4.37-15.69	15.9-17	11.4-38.3
Peanuts	1.6-3.12	23.6	5.7-11.3
Cottonseed	0.76	24.9	2.9

*Relative protein production: duckweed set at 100 units = 6.51 t dry wt/ha·y

Duckweed for Human Consumption

Wolffia arrhiza has traditionally been eaten in Myanmar, Laos, and northern Thailand (Bhanthumnavin and McCarry 1971). The duckweed cultivated in these areas is sold on local markets, however, since it is regarded as the “poor man’s food”, interest is apparently declining.

Use of duckweed for human consumption is not very popular as (pathogenic) organisms associated with duckweed are difficult to separate from the plants.

The use of *Lemnaceae* for human consumption has surprisingly not spread to other regions of the world. A possible explanation could be its high content of crystallised oxalic acid which has a negative effect on the taste. Another factor contributing to the low interest in duckweed as a potential food product for human consumption could be attributed to the fact that it is difficult to separate associated (pathogenic) organisms such as worms, snails, protozoa, and bacteria from the plant (Gijzen and Khondker 1997).

Duckweed as Fish Feed

Use of duckweed as fish feed is by far the most widespread application. Duckweed can be fed fresh as the only feed, or in combination with other feed components to a polyculture of Chinese and Indian carp species (Phot. 19) and tilapias (Phot. 20). Especially herbivorous and omnivorous fish such as grass carp (*Ctenopharyngodon idella*), silver barb (*Puntius gonionotus*) and tilapias (*Oreochromis sp*.) readily feed on duckweed.

Fresh duckweed is readily consumed by grass carp and tilapia.

Photograph 19: *Harvested Indian carp (Catla catla), 1.5 kg each, fed exclusively on duckweed. (Photograph: PRISM).*

Photograph 20: *Harvested tilapia (Oreochromis sp.) fed on sewage-grown duckweed and supplementary feed (Bangladesh).*

However, successful pisciculture on its own requires a high degree of skill, combining both know-how and experience. A delicate balance between fish density, feed and fertiliser inputs, and sufficient amounts of dissolved oxygen have to be maintained to reach high fish yields. The combination of duckweed and fish cultivation makes the system even more complex with strong interdependencies for example between availability and quality of duckweed feed and fish growth.

Combined wastewater-based duckweed-fish cultivation requires a high degree of skill.

Conversion efficiency of duckweed biomass into fish is represented by the feed conversion ratio FCR (g dry duckweed per g fish fresh weight). Table 14 contains an overview of FCRs as reported by various authors.

Table 14. *Duckweed to fish feed conversion ratios (in Gijzen and Khondker 1997).*

Duckweed species	*Fish species*	*FCR*	*Reference*
Lemna	Tilapia	1.6 to 3.3	Hassan and Edwards (1992)
Unknown	Grass carp 3g	1.6	Shireman *et al.* (1978)
Unknown	Grass carp 63g	2.7	Shireman *et al.* (1978)
Unknown	Unknown	1.1 to 5.3	Sutton (1976)
Unknown	Unknown	1.55 to 4.07	Baur and Buck (1980)
Unknown	Unknown	3.1 to 3.15	Hajra and Tripathy (1985)
Spirodela	Carp polyculture	1.2 to 3.3	PRISM, Bangladesh

Pisciculture using duckweed as the only feed was reported to be feasible, however, duckweed as a sole feed for fish tends to be a diet too low in fats and carbohydrates. Good results were obtained with a dry weight feed mixture of 50-60 % duckweed and 40-50 % supplementary carbohydrate-rich feed.

The reason for the very low values obtained by PRISM Bangladesh can be attributed to the addition of inorganic fertiliser to the fish ponds. Moreover, duckweed was not applied as a sole feed, but added to conventional feeds like oil cake and wheat bran. Though carp polyculture using duckweed as the only feed input was reported to be feasible (Phot. 21), there is some evidence that duckweed as a sole feed for fish is a diet too low in fats and carbohydrates. Recent findings for a balanced diet suggest a mixture of 50-60 % (dry weight) duckweed and 40-50 % (dry weight) fat and carbohydrate-rich feed (Gijzen, personal communication). Also Hassan and Edwards (1992) reported a decrease in crude lipid content of tilapia carcass, possibly attributed to the low fat content of fed duckweed (3-5 % of dry wt). They suggested energy-rich supplementary feed, such as rice

Photograph 21: *Harvesting of various carp species fed exclusively on duckweed. The vigorously jumping fish indicate healthy fish and good pond water quality. (Photograph: PRISM).*

bran, to avoid body lipid degradation as an energy source for metabolism.

With an average FCR value of 2.5 and a duckweed yield of 20 t(dry wt)/ha·y, a production of 8 t/ha·y of fish may be expected (Gijzen and Khondker 1997). This compares favourably with typical carp yields of 2 to 8 t/ha·y from well-managed, semi-intensive carp farms in Asia (Skillicorn *et al.* 1993).

Potential fish yields from carp polycultures fed on duckweed as feed supplement, compare favourably with carp yields obtained in Asia.

The smaller duckweed species like *Wolffia, Wolffiella* and *Lemna* were reported to serve as feed for fry and fingerlings. In China for example, excreta-grown *Wolffia* and *Lemna* are mainly used as feed for grass carp fingerlings (Edwards 1990).

Production of duckweed and fish in the same pond seems attractive in areas where land availability is low or competition for water bodies is high. Since a dense duckweed cover may reduce the oxygen supply to the water, this application should be tested with fish species tolerating low oxygen concentrations (Gijzen and Khondker 1997). The possible reducing effect on pathogen transfer in a two-pond system would be excluded in a one-pond system. The health hazards from a one-pond system are likely to be similar to those encountered with direct excreta reuse piscicultural systems.

Duckweed as Pig Feed

The limited information available on the application of duckweed as feed for pigs is contradictory. Haustein *et al.* (1992) reported a reduced meat production and lower FCRs for pigs fed on duckweed whose protein content amounted to 23 % and fibre content to 7.5 % dry matter. Schulz (1962) and Galkina *et al.* (1965), however, demonstrated a clearly positive effect on the weight gain of pigs when duckweed was added as a supplement to the normal diet. Comparative experiments using conventional diets and diets supplemented with high-quality duckweed are imperative (Gijzen and Khondker 1997).

Whether duckweed is a suitable feed for pigs is currently unknown.

Duckweed as Poultry Feed

As aforementioned, chickens are preferably fed on dried duckweed. The effect of the addition of duckweed to the feed of chickens has been studied by various authors with conflicting results. The overall tendency seems to be that small amounts (2-25 % of total dry matter fed) of duckweed in the diet stimulate the growth of chickens, while higher additions (> 40 %) of duckweed tend to decrease weight gain (Haustein *et al.* 1988). Several authors reported an increase in weight by 10 to 32 % for chicken fed with small amounts of duckweed (2-5 %) in addition to their regular diet (Mueller and Lautner 1954, Muzaffarov *et al.* 1968, Naphade and Mithuji 1969, Taubaev and Abdiev 1973). Shahjahan *et al.* (1981) obtained very good results with a 10 % addition of *Spirodela* to a mixed chicken diet. Other authors, however, did not observe an increase in weight by the addition of duckweed

Small amounts of dried duckweed are a suitable feed supplement for chickens.

to the chicken diet. When high portions of the diet were replaced by duckweed (50 %), even negative effects were observed (Muztar *et al.* 1976, Johri and Sharma 1980). Further studies comparing the effects of different *Lemnaceae* species at different feeding levels are necessary to draw definite conclusion of the nutritional value of duckweed for chickens (Gijzen and Khondker 1997).

Observations in Bangladesh and reports from Taiwan (Edwards *et al.* 1987) clearly revealed that ducks readily feed on fresh duckweed, often directly from the pond surface (Phot. 22). Application of duckweed as feed for ducks is practised at least to some extent in rural areas (Gijzen and Khondker 1997).

Photograph 22: *Excreta-fertilised duckweed pond at village level in Bangladesh showing dense duckweed cover with ducks feeding on duckweed from the pond surface.*

Duckweed as Ruminant Feed

Duckweed was reported to be a suitable feed for ruminants, however, the contribution of duckweed protein in ruminant nutrition is doubtful, as it is readily fermented by microorganisms in the rumen.

Several feeding experiments with duckweed as feed additive in regular diets for both cattle and sheep have been conducted by various authors. Russoff *et al.* (1977, 1978) reported that up to 75 % of duckweed could be fed to Holstein cattle without affecting the taste of milk. The weight gain of calves fed with a mixture of duckweed (67 %) and silage of corn (33 %) showed a daily weight gain of 0.95 kg, compared to only 0.5 kg weight gain when fed on a concentrate/corn silage diet. Culley *et al.* (1981) calculated that a 3.1 ha surface area of duckweed cultivation could provide sufficient protein to feed 100 dairy cattle.

Taubaev and Abdiev (1973) reported an additional weight gain of up to 27 % and 14 % for ram and sheep, respectively, upon feeding the animals 0.5 kg/day *Lemnaceae* in addition to their regular diet.

Leng *et al.* (1995) mentioned that the contribution of duckweed protein in ruminant nutrition is doubtful, as the duckweed protein is readily fermented by microorganisms in the rumen, and the amino acid supply to the animal, thereby, minimised. Preliminary tests showed that it may be difficult to protect duckweed protein from digestion in the rumen.

Duckweed as Agricultural Fertiliser

Duckweed can be used as an organic fertiliser in agriculture by direct land application or via composting.

Use of *Lemnaceae* as fertiliser and soil improver on fields and gardens was reported for Angola (Welwitsch 1859), China (Tai-Hsingh *et al.* 1975) and Mexico (Lot *et al.* 1979). According to Lot *et al.* (1979), application of duckweed eventually contributed to a superior soil texture, including an improved water and cation exchange, and resulted in an annual harvest of 4 crops of vegetables or corn.

Chapter Six

Sociocultural Aspects

Besides skilful management, the feasibility and successful introduction of duckweed wastewater treatment/farming systems depends mainly on the acceptance and understanding of the technology by the user groups within a given sociocultural context. This chapter presents some country-specific experience with dissemination of duckweed aquaculture, and draws general conclusions where permissible. These general conclusions should be interpreted with caution, as cultural beliefs vary so widely in different parts of the world. Therefore, it is not possible to assume that existing practices of duckweed aquaculture can be readily transferred elsewhere.

Duckweed as a Novel Crop

Introduction of duckweed aquaculture as a novel farming method is likely to be initially rejected due to its labour-intensive, on-going and aquacultural nature.

With the exception of countries like Taiwan and China, where duckweed cultivation is traditional and has been carried out over decades, the introduction of duckweed as a novel and unknown crop is likely to be rejected at first. Duckweed farming is not only a novel farming method, but also a highly intensive one. Unlike traditional terrestrial crops, duckweed is an aquacultural crop. And unlike traditional crops requiring only sporadic attention, duckweed farming is a continuous process. The conventional agricultural cycle of planting, fertilising/crop maintenance, harvesting, processing, storage, and sale, spread over a growing season of a few months to two years, is compressed into a daily cycle in duckweed farming (Skillicorn *et al.* 1993). The initial rejection is likely to decrease with time. After about ten years of duckweed propagation in Bangladesh, the plant is now known throughout the country and accepted by rural farmers as a fresh feed component for pisciculture (PRISM unpublished).

Contact with Excreta and Wastewater

Human society has evolved very different sociocultural responses to the use of excreta, ranging from abhorrence through disaffection and indifference to predilection (WHO 1989).

In societies where excreta reuse is regarded as cultural or religious taboo, wastewater-based duckweed-animal farming is likely to be rejected.

In several African, American and European societies, human excreta is regarded as repugnant substances best kept away from the sense of sight and smell. Therefore, products which come into direct or indirect contact with excreta are likely to be considered as tainted or defiled in some way (WHO 1989). In such societies where excreta use is regarded as cultural or/and religious taboo, wastewater-based duckweed-fish farming is likely to meet with strong rejection.

In countries where excreta reuse is traditional, wastewater-based duckweed-animal farming may meet with less social resistance, however, farmers have to experience its advantages in order to give duckweed farming preference over established aquacultural techniques.

In contrast, both human and animal wastes have been used in aquaculture in countries like China, Japan and Indonesia. In such societies, intensive cultivation practices have evolved in response to the need of feeding a large number of people living in an area of limited land availability, and calling for the careful use of all resources available to the community, including excreta (WHO 1989). In such countries, excreta reuse through wastewater-based duckweed-fish farming will probably face less problems of social acceptance. However, the introduction of duckweed aquaculture as a novel farming method in societies where other (piscicultural) techniques have a long-lasting tradition, will probably be met with scepticism.

Indirect Excreta Reuse

Indirect reuse of excreta via duckweed may be of relevance to societies where direct reuse is socially unacceptable.

Edwards (1990) suggests that indirect reuse of excreta for food production could become of relevance to societies where direct reuse is socially unacceptable. Unlike direct excreta reuse, where fish is raised directly on human and animal wastes as practised for thousands of years in China for example, duckweed-fish production is physically separated by a two-pond system. As opposed to duckweed, fish raised for human consumption does not come into direct contact with the excreta. Therefore, duckweed acts as an intermediate in a lengthened food chain. Generally speaking, indirect excreta reuse involves two separate sequential processes; i.e., resource recovery using excreta and wastewater as fertiliser to cultivate duckweed, and resource use of the aquatic biomass in a separate system as animal feed to grow food for human consumption.

In Islamic societies, direct contact with excreta is abhorred since it is regarded as containing impurities (*najassa*) by Koranic edict. Its use is permitted only when the *najassa* have been removed (WHO 1989). Thus, it is possible that indirect use of excreta after treatment with duckweed will be met with less opposition. Of course, this cannot be generalised for all Islamic countries. The local sociocultural context will be the determining factor regarding acceptance or rejection of indirect excreta reuse through duckweed.

Village farmers in Bangladesh initially did not eat the fish, fed on excreta-grown duckweed which they produced.

The mainly Islamic villagers in Bangladesh initially rejected fish fed on duckweed-grown ponds fertilised with latrine effluents. Although the fish is raised indirectly on excreta, some farmers still do not eat the fish they produce themselves. Resistance decreased with time, however, it is likely to reappear when latrine-based duckweed-fish farming is introduced to villages where this farming method is unknown.

Positive Influence of Duckweed Farming on its Social Acceptance

Social acceptance of wastewater-based duckweed farming and its products may benefit from the potential advantages of the technology, such as income generation, improved nutrition and water quality, reduced odour problems, and possibly reduced mosquito breeding. Of course the opposite could also be true if for example a badly designed or operated system turns into a stinking and unpleasant site. Especially open sedimentation lagoons may produce bad odours and are likely to be met with the objection of those who live or work nearby.

Income generation, improved nutrition and water quality, and reduced mosquito breeding may have a positive effect on social acceptance of wastewater-based duckweed farming.

In this context, it is interesting to note that a duckweed treatment system in Mirzapur (Bangladesh) has become a meeting place for the local population who enjoys its pleasant and park-like atmosphere (Skillicorn *et al.* 1993).

Chapter Seven

Economic Aspects

Literature on reliable economic data analyses of real-scale duckweed farming is very scarce. Only a few economically feasible examples of sewage and excreta-based duckweed farming systems used at urban, demo farm and rural level were reported from Taiwan (Edwards *et al.* 1987) and Bangladesh (DWRP 1996/97).

Economically feasible duckweed farming systems were reported from Taiwan and Bangladesh.

Since fish production is the most widespread and well-documented application, it was chosen to exemplify animal production.

Integrated and Separate Duckweed-Fish Production

Until adequate storage technologies are developed, such as drying, pelleting, cold storage, ensilaging or others, the fresh duckweed has to be used within two to three days after harvesting. Therefore, duckweed cultivation is physically and geographically limited to the vicinity of the fish production area. Two approaches are known; i.e., the integrated production of duckweed and fish on the same premise by a single owner or group of owners, and the separate production of duckweed and fish by different owners with an intermediate market for the sale of duckweed.

Lack of storage technologies, such as pelleting or ensilaging limit the use of duckweed to its fresh form in the vicinity of cultivation area.

Integrated duckweed-fish production by a single owner group has the following advantages and disadvantages over separate production of duckweed and its subsequent sale to fish producers (Tab. 15):

Integrated duckweed-fish production yields higher profits in the long-term and is not dependent on market uncertainties of duckweed demand and supply in comparison with separate duckweed cultivation. The latter production system, however, is less complex to manage, requires less land, infrastructure and working capital, and is, therefore, exposed to a lower risk of capital loss through natural calamities, diseases and pests.

Integrated duckweed-fish farming requires sufficient land, an appropriate infrastructure and large sums of working capital, thereby, increasing the risk of capital loss through natural disasters like floods and droughts, diseases and pests. However, supply and demand of duckweed do not depend on market uncertainties. Although a market infrastructure for preservation and storage is necessary for both separate and integrated duckweed-fish production, it is less sophisticated for the sale of fresh duckweed. For integrated duckweed-fish production, access to urban and small-town markets for fish sale is desirable, while separate duckweed production only relies on local buyers of duckweed. Efforts and costs for duckweed transport are reduced in an integrated system. However, the complexity of the whole system, with two highly sensitive subsystems for maintenance and management of optimum growth conditions and strong system interdependencies are naturally higher in the case of integrated duckweed-fish farming. The greater risk of managing a more complex system at higher capital investment is set off by a substantial higher net return from the sale of fish produced by integrated duckweed-fish farming.

Physically separated production of duckweed and fish by different groups is a feasible option requiring, however, a good marketing infrastructure for storage and preservation of duckweed, transport of duckweed to the fish farms and protective trade agreements between the different production groups as described hereafter.

Formal short-term agreements between duckweed and fish producers on minimum price, supply guarantees and minimum purchase quantities are necessary to protect the interests of both sides in separate duckweed-fish production.

The current lack of storage technologies prevents the formation of a conventional duckweed market where supply and demand determine an equilibrium price. Protection of the interests of duckweed and fish producers through short-term agreements on duckweed minimum price over defined periods, including guarantees on supply and minimum purchased quantity, are necessary formal forms of linkage. Without price and supply guarantees on either side, duckweed producers retain little pricing leverage and remain vulnerable to arbitrary termination, while fish farmers are vulnerable to supply uncertainties (Skillicorn *et al.* 1993).

The presence of several groups of duckweed suppliers and buyers may create a more dynamic market and provide a buffer against fluctuations in duckweed supply and demand.

However, linked production between one duckweed and one fish producer may not provide a buffer against fluctuations in duckweed supply and demand. Linkage between groups of duckweed and fish producers appears to provide better conditions for duckweed-fish production. Supply shortage can also be buffered by guaranteeing adequate substitution and supplements for duckweed feed, like for example *Azolla,* water hyacinth, oil cake, or wheat bran. A market with several groups of duckweed suppliers and fish producers creates more dynamics with regard to price negotiations and eventually higher returns for duckweed producers, compared to a single fish producer's demand (Skillicorn *et al.* 1993).

As aforementioned, duckweed cultivation has significantly lower net returns than pisciculture. For example, at a price of US$ 0.03 per kg of fresh duckweed, a farmer in Bangladesh producing only duckweed can expect to net less than one-third of what the fish farmer to whom he sells the duckweed can earn from the same amount of land (Skillicorn *et al.* 1993).

Table 15. *Advantages and disadvantages of integrated and separate duckweed-fish culture (after Skillicorn et al. 1993).*

	Separate duckweed production	*Integrated duckweed-fish production*
Market dependencies of duckweed demand and supply	Formal agreements with fish producers are necessary on minimum price, supply guarantees and minimum purchase quantities	Not dependent on duckweed market uncertainties
Market infrastructure requirements for preservation, storage and transport	High, but no requirements for fish marketing Lower when fresh duckweed is traded	High, especially for fish marketing
Net financial return	Significantly lower, but more immediate	Higher, but profit only after 2-4 years
Risk of capital loss through natural disasters, diseases and pests	Lower	Higher
Complexity of the system, requirement of labour and management efforts	Lower	Higher
Requirements of land, infrastructure and working capital	Lower	Higher

The question of suitability between the integrated and separate farming model cannot be answered at this point. Both models are known to be practised. The prevalent local institutional, agricultural and socio-economical conditions will be the determining factor.

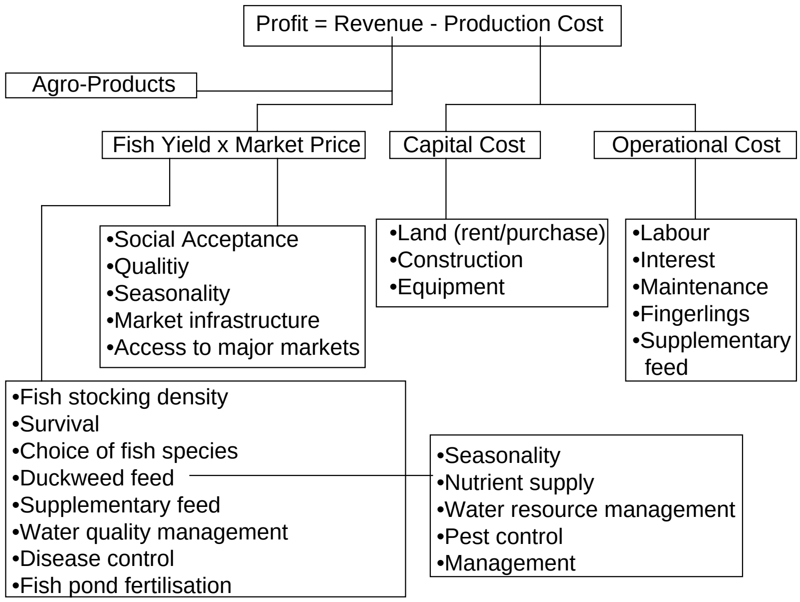
Separate production of duckweed was reported to be practised in Taiwan. Harvested duckweed was sold as feed for grass carps in sacs at 50 to 60 TwD per 60 kg sac, but also as a feed for chickens, ducks and edible snails. This was equivalent to about US$ 0.04/wet kg or US$ 1/dry kg duckweed in 1985. The sacs were transported by truck.

Integrated sewage/excreta-duckweed-fish production is practised in Bangladesh at demo farm and village level.

Economics of Integrated Wastewater-Duckweed-Fish Production

The major factors influencing the economics of integrated wastewater-duckweed-fish farming are summarised in Fig. 6.

Figure 6. *Major factors influencing the economics of integrated duckweed-fish production (adapted from Shang 1981, in Edwards et al. 1987)*



Based on the operating costs, sewage-duckweed-fish production at demo farm level proved to be profitable .

Based on the operating costs of 1994 and 1995, respectively, an economic analysis of the Mirzapur sewage-duckweed-fish system revealed that the system, covering a total area of 2 ha, earned a gross margin of 34,958 BdT and 62,597 BdT (Tab. 16). Interest fees on capital costs were not taken into consideration. The gross earnings do not include the revenue created by the sale of vegetables and fruit from the co-cropping vegetation. Besides, the value created by treating wastewater to an effluent quality meeting western standards was not taken into account either.

Table 16. *Operating costs for sewage-duckweed-fish production at Mirzapur demo farm of PRISM Bangladesh in the years 1994 and 1995 (DWRP 1996).*

Item	*1994*	*1995*
Duckweed production:		
Labour	31,200	31,200
Bamboo grids	3,500	3,500
Water supply	14,200	14,625
Others	34,200	37,800
Total operating cost (1)	83,100 BdT	87,125 BdT
Absolute production (0.6 ha)	149 t(wet wt)	182 t(wet wt)
Per kg operating cost	0.56 BdT/kg	0.48 BdT/kg
Per ha operating cost	138,113 BdT/ha	144, 803 BdT/ha
Fish production:		
Total operating cost (2) including (1)	216,700	244,670 BdT
Absolute production (3x0.2 ha)	6.2 t	7.57 t
Per ha production	10.3 t/ha	12.62 t/ha
Per kg operating cost	34.95 BdT/kg	32.32 BdT/kg
Gross earnings from fish sale (3)	251,658 (*)	307,267 BdT
Gross margin (3)-(2)	**34,958**	**62,597**

(*) calculated value, assuming same average price/kg fish as in 1995.
(2) in addition, total operating costs for fish production include costs for labour, lime, chemicals, fish pond fertiliser (urea), supplementary feed (mustard oil cake), fingerlings, and water supply.

The positive operating gross margin is remarkable, especially since wastewater treatment plants worldwide are generally never operated at a profit, as they rely on user-fees, contract revenues or on the sale of water to cover their costs. The Mirzapur sewage-duckweed-fish system is perhaps the only flow through sewage treatment plant in the world that is making a profit from its operation.

The Mirzapur sewage-duckweed-fish system is perhaps the only flow through sewage treatment plant in the world that is making a profit from its operation.

Chapter Eight

Institutional Aspects

Skillicorn *et al.* (1993) suggest the following institutional concept for propagation of duckweed aquaculture:

A first step for introduction and dissemination of duckweed farming in tropical and semitropical developing countries is to create institutional demo centres. During the first years, their task is to assimilate the existing knowledge about duckweed cultivation, to adapt this knowledge to the specific local conditions and increase it through research at demo farm level. In a second phase, when locally adapted farming protocols, design guidelines and end-use applications of the biomass are developed, the difficult process of introducing and disseminating the farming method to a wider audience can be initiated. The demo farms will then serve as training and know-how centres where individual farmers, farming cooperatives, government and NGO staff, as well as officials

An institutional concept to introduce and disseminate duckweed aquaculture is the creation of demo centres. These will in a first phase adapt the existing knowledge on duckweed aquaculture to the specific local conditions and, in a second phase, provide training, supervision, technical assistance, and credit support.

from other institutions will receive practical training and gain knowledge in duckweed aquaculture. Furthermore, they will provide continuous supervision, technical assistance and financial reinforcement to groups who are willing to adopt the technology with the support of extension workers. These demonstration centres should naturally receive financial aid from credit institutions capable of providing their credits directly to the duckweed and duckweed-fish (or other animals) farmers at low interest rates.

The role of the village extension worker for example is to ensure (1) that each participating farmer is trained in the latest farming techniques, (2) that he understands the continuous nature of the production process, (3) that he carries on with the good practice, and (4) that he continues to receive immediate payment for his daily product.
Receiving daily payment for daily production is a strong incentive for good practice. A farmer who fails to manage his crop adequately will experience an immediate drop in production and, hence, in income. He will not have to wait for months before facing the consequences of his action. Feedback is immediate and has a reinforcing effect on quality and level of effort.

Baseline Survey

A baseline study prior to introduction of duckweed farming technology should include evaluation of available land, water and human resources, existing farming systems, and identification of target groups.

Prior to introduction and dissemination of wastewater-based duckweed farming technology at rural and urban level, a baseline survey should evaluate if the specific local conditions provide an appropriate setting for duckweed farming. The following aspects should be considered in a baseline survey (DWRP 1997b):

Availability of resources

- Water bodies (ponds, river, wells, ditches, etc.)
- Water availability, quality and usage (annual fluctuations)
- Nutrients, their sources and availability
- Locally available animal and fish feeds
- Labour resources
- Domestic animals (fish, ducks, chickens, goats, etc.)

Existing farming systems

- Agricultural practices
- Animal production and animal products
- Nutrients, their sources and availability
- Flow of nutrients
- Use of existing resources
- Availability, cost and need of nutrients and feed
- Relative importance (time, economy) of different activities

Identification of target groups

- Present source of income
- Interest to participate in project activities
- Indication by the beneficiaries of their specific needs or interests

Credit Requirements

It seems obvious that credit support for wastewater-based duckweed-fish farming is essential. The intensive and continuous process needs a steady flow of investment. Skillicorn *et al.* (1993) report that credit for this kind of farming method is characterised by two features: (1) it is best disbursed continuously in small, productivity-based increments and (2) it is comparatively higher than the credit required for comparable conventional farming processes, especially when insufficient nutrient supply from the wastewater is compensated by applying costly inorganic fertilisers.

Credit requirements for wastewater-based duckweed-fish farming are comparatively higher than for comparable conventional farming processes.

The performance of credit programmes to support small farmers worldwide is poor. Loans seldom match real requirements, disbursements are slow, interests are exorbitant, and recovery rates are low. Beyond the more frequently cited structural deficiencies of the credit institutions themselves, common belief holds that a primary failing of agricultural credit programmes is the inability of farmers to manage their credit. Experience shows that farmers are likely to directly use the greater part of the credit received. Consequently, the higher the credit, the greater the amount used.

In the case of duckweed-fish production, the risk for farmers can be reduced through close technical and managerial involvement by the credit institution. Income from fish sales should flow through the credit institution before net payments are made to fish producers in order to add value to the production process by improving both production and marketing, and by continuously reinforcing good practice.

Promotion of Excreta-Based Duckweed-Fish Production in Rural Bangladesh

The aforementioned concept for duckweed propagation was derived from PRISM, a Bengali NGO. The institution is promoting integrated duckweed-fish production in the surrounding villages of their demo farms. Rural farming groups received credit, technical assistance and supervision by PRISM, and their extension workers resided in the assigned villages. Despite impressive achievements from the over 120 duckweed farming groups, a recent study (DWRP 1996) revealed some weaknesses of the chosen, so-called, “joint stock company” approach; i.e., it led to its abandonment and development of new group organisation models. The experience gained with the joint stock company approach can be of great benefit to rural duckweed propagation programmes. DWRP (1996) describes it as follows:

Through the formation of officially registered, so-called, “joint-stock companies”, PRISM, a Bengali NGO, developed an institutional model for promotion of excreta-based duckweed-fish cultivation at village level.

Shares were obtained by the company members through labour or land contribution.

Joint stock companies, comprising 10-15 members or shareholders, were formed and officially registered. Shares were obtained through land, labour or cash contributions. Labour contributions were compensated in cash or shares, land contribution was compensated in shares. One share was equivalent to one decimal of land (40 m^2) or 500 BdT. The net profit was distributed according to the respective number of shares held by the shareholders. PRISM received 10 % of the shares for their technical assistance.

Since land assigned to the company was registered under permanent ownership and taken as collateral security through power of attorney by PRISM for the disbursed loan, some members feared to lose control over their land.

The land assigned to the company was registered under permanent ownership and taken as collateral security through power of attorney by PRISM for the disbursed loan. Land and company registration required approx. 20,000 BdT. The amount was borne by and given to the company by PRISM in the form of a loan.

Most of the interviewed shareholders were not satisfied with the company concept. Since individual land transfer was made in the name of the company, members feared to lose their land forever.

As pond ownership was an initial criterion for selection of beneficiaries, participation of landless and marginal farmers was below target.

Selection of beneficiaries was initially based on pond ownership, particularly fish ponds which are usually larger than duckweed ponds and considered more valuable. This reduced participation of all those who do not own land or who own only a very small homestead like landless poor and women. For reasons of cultural and religious discrimination, women in Bangladesh usually do not own land or have little control over it.

Heterogeneous socio-economic background of company members caused decision-making power to lie with the rich members and favoured further build up of hierarchical structures.

The heterogeneous socio-economic situation of the company members caused decision-making power to lie completely with the rich members and favoured further build up of hierarchical structures. This led to a serious lack of coordination between the rich on one side and the poor and women on the other. The latter often had no idea about their savings, their actual number of shares, about the company's current economic condition, activities, and even about its actual concept.

High capital investment and high interest rates to be paid to PRISM exposed the members to high financial risk.

The high capital investment (approx. 280,000 BdT for a company formed by 10 farming members) and high interest rate (15 %) to be paid to PRISM put the members at great financial risk. As a result of this financial burden and damage caused by annual floods, several companies were not convinced of the company's profitability. Most of the interviewed members revealed that they had not yet received any cash benefits. If any profit was made, it was directly used to repay the loan. The members were not told that profit could be made only 3-4 years later. This was extremely disappointing for the poorer members, as they dispose of few other sources of income and require immediate returns on their contributions.

Some members continued to produce fish in their ponds but stopped sharing their yield with the companies. Some duckweed pond owners discontinued production of duckweed and started growing fish in their ponds. However, their waterbody was still owned by the company.

Quality of bookkeeping was often insufficient, as figures were not updated or inconsistent.

The company was managed by a board of directors composed of a chairperson, managing director, treasurer, and two general members. The managing director received a monthly salary from the company (800-1,000 BdT) and was responsible for record keeping and coordinating the company's activities. The quality of bookkeeping was often insufficient, as the figures were not updated and/or inconsistent in most companies. The extension workers were supposed to provide detailed accounts to the managing directors. Moreover, the record books were not understood by the poor members. Since company law required every company to be audited once a year by a qualified firm, an additional sum of about 3,000 BdT was required. In most cases, the management of the company was unable to prepare the accounts for the auditing firm.

Most companies contracted poor members as full-time labourers at a monthly salary of 1,000-1,200 BdT. Casual labourers were also employed at 35 BdT per working day. Sometimes, the wage labourers were not members of the company. Engagement of wage labourers was a good initiative to generate employment, although it increased production costs. The salary of a wage labourer was by far not sufficient to maintain his family, let alone save money to buy shares. Provision of employment to wage labourers to allow them to increase their shares failed its objective.

Demo farms served as training centres to the company and to the extension workers. Training was also given to NGO and government staff. A refresher course was also conducted for company members. Shareholders received training free of charge and also travelling allowances. The chairperson and the managing director were given first preference in the selection of trainees, while the daily activities were conducted by the untrained members or hired labourers. Most female members did not receive training as they are overburdened by a multitude of duties (raising of children, farming and domestic chores) and cannot leave home for a longer period of time.

The staff at the demo/training centres comprised one project director, one credit manager, three training officers, four area coordinators, and a number of village coordinators. Support staff like drivers, a cook and guards were also recruited. Employment of female staff in the demo centres was below 10 %.

In comparison with the sewage-duckweed-fish production system at Mirzapur demo farm, the village companies obtained lower duckweed and fish yields (Tab. 17).

Table 17. *Comparison of duckweed and fish production between PRISM joint stock companies and Mirzapur demo farm (DWRP 1996 and 1997a).*

	Duckweed production daily kg(wet wt)/ha·d		*Duckweed production* yearly t(wet wt)/ha·y		*Fish production* yearly t/ha·y	
	range	*average*	*range*	*average*	*range*	*average*
Village companies	7-444	162	2.5-162	59 (4.6)*	0.4-6.6	3.8
Mirzapur demo farm	<1200	>600	<260	>200 (15.6)*	5.6-12.6	>10
Fish production in Bangladesh	____	____	____	____	<3.6	2.1

*t(dry wt)/ha·y, assuming 7.8% dry matter content.

In comparison with other piscicultural projects in Bangladesh, joint stock companies obtained higher fish yields at higher production costs and, therefore, significantly lower rates of return on investment.

Even if fish yields were somewhat higher than those of the other aquacultural projects in Bangladesh applying lower quantum of inputs and capital, the rates of return of joint stock companies were generally much lower. This indicates high fish production costs of joint stock companies.

It should be noted that the production system at the demo farms is based on high capital investment from external donors and high labour input. It performs well, but it rather demonstrates what can be achieved under sophisticated management, maximum financial input, sufficient nutrient and water supply and high input of skilled labour than what is feasible on village level. Duckweed could not be grown year-round in the ponds of the village companies. Apart from poor management, several constraints also had a negative effect on duckweed-fish production at village level. The major ones include:

- Lack of water and duckweed (ponds dried up during the dry season, insufficient duckweed pond area)
- Floods
- Low nutrient supply

Others:

- Temperature extremes
- Insect damage/diseases (duckweed)
- High costs of supplementary fish feed
- Low fish prices (marketing problems)
- Fish diseases
- Poor quality of fingerlings
- Stealing of fish
- Shortage of oxygen in fish ponds

One of the major positive impacts of the project is the fact that people within the project area have now come to realise the importance of duckweed as a fish feed.

Interviews with villagers who were not members of a company revealed that most of them were familiar with the duckweed-fish culture activity and thought that it could yield a profit if applied correctly. One of the major positive impacts of the project is the fact that people within the project area have now come to realise the importance of duckweed as a fish feed. However, others indicated that they did not believe profits could be yielded in spite of the numerous efforts made. They were hesitant to apply the technology themselves. Some objected to the control of the rich shareholders over the poor members.

The study revealed that the households highly appreciate the installation of pour-flush-type latrines connected to the duckweed ponds, as they inhibit bad smells and reduce mosquitos and flies. However, they complained about pollution when duckweed ponds dry up.

The households highly appreciated the installation of pour-flush latrines connected to the duckweed ponds.

The fish production cycle did not coincide with the duckweed growing season; i.e., duckweed production was low when demand was high.

Interviews and observations indicated that marketing infrastructure for storage and preservation of fish was almost non-existent. Besides, the producers had little or no access to the major urban markets. Fish was either sold at the pond site to middlemen who mostly dictated prices or at local markets. A main weakness of the fish marketing system is the short period between harvesting and marketing during the winter months when most of the fish ponds dry up and, consequently, lower fish prices. Another weakness is the lack of a uniform weighing system.

Appropriate marketing infrastructure for storage and preservation of fish was practically non-existent.

An economic study revealed that only 7 of 44 companies yielded some net profit, the rest incurred losses on the basis of total costs. The fact that no dividends could be paid to the shareholders was particularly disappointing to the poor households, which not only lost control over their land, but were also left without an income. On the basis of operating costs, however, several companies showed substantial positive gross margins (operating profit). The major factors contributing to the net losses were: heavy investment costs per ha and company resulting in high interest and repayment charges, high expenses for supplementary feed inputs and fertilisers, low contribution of duckweed as a feed, and high company-related expenditures.

Only 7 of 44 companies proved that excreta-based duckweed-fish farming can be practised with a net profit. Financial loss of companies was attributed to high interest repayment charges and high expenses for supplementary fish feed and company-related issues.

The quantum of credit disbursed was quite high and surpassed the projected levels. The average loans per ha of fish pond exceeded 400,000 BdT. Such high investments against uncertain yields of fish and duckweed, and uncertain performances of newly-formed companies did not seem to be quite justified. Besides, recovery of credits was low (approx. 70 %).

It can be concluded that the high investment-driven, technology-oriented and top-down approach of the joint stock company concept as a group organisation model had to be abandoned because it did not correspond to the cultural and social reality of the beneficiary groups.

PRISM Bangladesh is currently developing new group organisation models based on the following study recommendations:

- People of a more or less homogeneous socio-economic status should be selected for group formation.
- Creation of formal (legal registration as a company) and also informal groups.
- No transfer of land owned by members to the company.
- Equal distribution of shares.
- Leasing of land from private owners or the government to allow landless poor and women groups to practise duckweed aquaculture.
- Reduction of credit investments.

Further recommendations include:

- Recruitment of female trainers to assist and supervise female groups.
- Provision of training at village level.
- Assuring detailed bookkeeping by close assistance.
- Regular village visits by demo farm staff for supervision and problem solving at field level.
- Lowering of fish production costs by increased reliance on duckweed as cheap fish feed. Reduction of expensive supplementary fish feed inputs. Replacement of costly inorganic fertilisers by cheaper organic waste as nutrient sources for duckweed production.
- Integration of duckweed aquaculture in existing farming systems.
- Development of marketing infrastructure for storage and preservation of fish to facilitate access of fish producers to the rural and urban markets.

Moreover, the following new technology approaches are being field-tested:

- Cultivation of both duckweed and non-duckweed-eating fish species like catfish and silver carp, in the same pond. Floating bamboo poles confine duckweed cultivation to one side of the pond leaving the other side uncovered for oxygen and light input.
- Use of cowdung as nutrient source.
- Only duckweed production (no fish production).

Individual farmers, family-based groups (consisting of two families), groups of landless people and groups with only female members, so-called “sister companies”, are being tested. Individual farmers and pond owners receive a loan only for latrine construction and material (about 900 BdT per latrine). The members of the sister companies in Khulna produce only duckweed which they sell to the neighbour company. A mutually signed contract fixes amount and price (0.7 BdT/kg(wet wt)) of duckweed to be sold. The companies are currently leasing low-lying retaining water throughout the year which the owners are willing to lease as severe weed and salinity problems have rendered agricultural crop production impossible. Capital costs for pond excavation of 72,000 to 83,000 BdT per ha still require a high degree of investment. Another recommendation was to lease perennial/seasonal waterbodies, so-called «kash» lands from the Land Ministry or to use borrowpits under roads.

Chapter Nine

Past and Present Duckweed Activities Around the World

Taiwan

Small-scale duckweed cultivation is traditional in Taiwan and has been practised for a long time in ditches and ponds developed from paddy fields.

Edwards *et al.* (1987) reported the following duckweed cultivation practices in urban areas of Taiwan:

Commercial duckweed cultivation has been practised on a large scale in two Taiwanese cities for nearly 30 to 40 years.

Commercial duckweed cultivation has been practised on a large scale in the cities of Tainan and Chiai for nearly 30 to 40 years. Duckweed in Tainan was cultivated in several areas over a total surface area of about 100 ha, the largest site covering 15 to 20 ha. In Chiai, duckweed was cultivated in two areas covering a total surface of about 20 ha. Since August 1985 the cultivated area has most likely decreased due to urbanisation. Whether duckweed is still cultivated today in Tainan and Chiai is unknown to the author.

The ponds were fertilised once a week by lowering the water surface by about 7.5 cm and replacing the outflow with organically polluted grey to black surfacewaters. Ponds and water distribution channels were earthen structures. The ponds were drained and fed by gravity or/and pumps. The farmers reported that nightsoil had never been used. Concern was also expressed about contamination of surfacewater by factory effluents.

Paddy fields were turned into shallow ponds to cultivate *Lemna* and *Wolffia* throughout the year. The initial culture of *Spirodela* was replaced by *Lemna* and *Wolffia,* as fish and ducks were reported to prefer these species. Floating bamboo poles were used to divide the pond surface into small square or rectangular cells of 2 to 3 by 4 to 6 m.

Duckweed was harvested at weekly intervals by moving the floating plants to one corner of the pond with a bamboo pole. 80 % of the standing crop was harvested. If too much duckweed was harvested, the water turned green and the plants did not grow well. Two people were reported to require 3.5 hours to harvest 0.3 ha. The harvested duckweed was filled into wickerwork baskets to allow some drainage of water. It was packed in sacs holding 60 kg of wet duckweed. Water was periodically squeezed out by manually pressing down the top of the plants in the sac during harvesting.

The duckweed was sold fresh for 50-60 TwD per sac and used mainly as feed for small and large grass carp, but also as feed for chickens, ducks and edible snails. It was reportedly not fed to tilapia as it was too expensive. *Wolffia* was used as a first feed for grass carp fry, followed by *Lemna* when the fish were larger. The same practice is also reported from mainland China.

The data extrapolated from reported yields varied widely from 2.5 to 12.5 to 25.9 t dry wt/ha·y on the basis of a dry matter content of 4 % and year-round cultivation. Due to seasonal effects on duckweed growth, the winter yields made up only about 40 % of the summer harvest. Production was also reduced in the rainy season due to dilution of the organically polluted surfacewater. Insect damage was reported to be unimportant.

Mainland China

Almost no information was found on duckweed application in mainland China. China's long-standing tradition of direct and indirect reuse of waste for food production probably also includes the cultivation of duckweed.

In the Provinces of Kiangsi and Chekiang, *Wolffia* was reported to be cultivated from April to September, with an extrapolated annual yield of 14 t dry wt/ha (Gijzen and Khondker 1997).

Vietnam

A research group in Vietnam is studying the use of biogas digester effluents for duckweed cultivation.

Dr Preston's group at the University of Agriculture and Agroforestry in Ho Chi Minh City is studying duckweed applications on a research level as part of its M.Sc. programme on "Integrated Farming Systems for Sustainable Use of Renewable Natural Resources". The group's very interesting work focuses on the use of biogas digester effluents for duckweed cultivation. The biogas digester was charged with pig manure containing 6.5 % solids and 3.4 % nitrogen in the solids. Optimal levels of nitrogen in the duckweed pond water between 40 and 60 mg/l were surprisingly high. Duckweed production in the pilot pond (10 m^2) was reported to be 100 $g/m^2 \cdot d$ with a crude protein content of 35%.

Thailand

Research at AIT focused on the use of septage and excreta for duck-

The Asian Institute of Technology (AIT) in Bangkok has been involved in pilot-scale duckweed research for more than 15 years.

Activities started in 1981 with funds from ODA (1981-1984). Research continued under the project "Resource Recovery and Health Aspects of Sanitation" funded by the European Union's Science and Technology for Development Programme (1984-1986). The main objective of this project was to study the direct and indirect use of septage and excreta in aquaculture. The overall results showed that neither direct feeding of septage to fish, nor the combined system with duckweed production resulted in an economically attractive fish production system. However, septage reuse in aquaculture may be economically more attractive in countries with low labour costs and high fish market prices. The use of a duckweed-fish wastewater treatment system could result in substantial savings compared to an activated sludge system. The studied village/family excreta reuse duckweed/tilapia system may have a greater relevance if integrated in an urban excreta reuse system. Currently, AIT is not pursuing duckweed-related research as most of its questions have been answered (Edwards personal communication 1998).

weed cultivation.

Excreta-based duckweed-fish treatment systems may have greater relevance if integrated in urban excreta reuse systems than if used at village level.

PRISM Bangladesh

The NGO, PRISM Bangladesh, has set up since 1989 an impressive programme to develop and disseminate duckweed aquaculture in Bangladesh. A great deal of information cited in this report is based on conclusions from research studies at PRISM's project locations. PRISM has so far developed three so-called Shobuj Shona (Green Gold) Centres located in Mirzapur, Manikganj and Khulna. The centres serve as demonstration farms and training institutions for the promotion of integrated duckweed-fish production in the surrounding villages. The information cited in this chapter is taken from Gijzen and Khondker (1997), Alaerts *et al.* (1996), Iqbal (1995), and DWRP (1996 and 1997a).

Considerable experience with real-scale excreta and sewage-based duckweed-fish production at rural and community level was gained by the projects of PRISM Bangladesh.

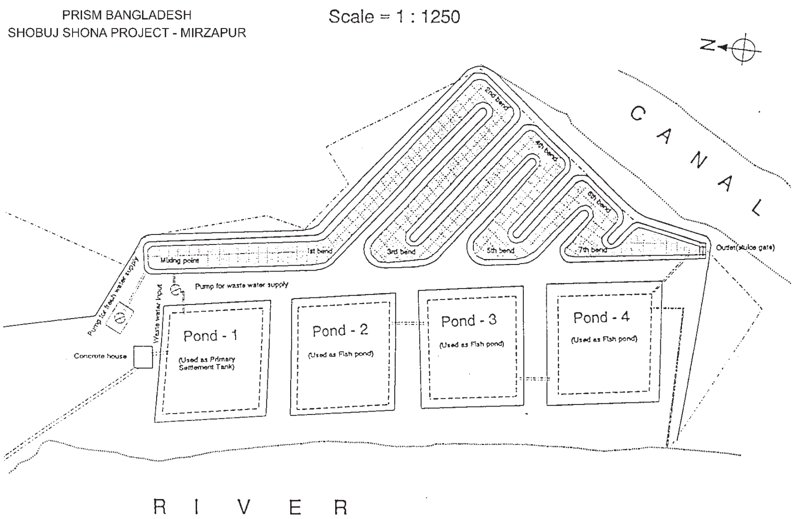
Mirzapur demo farm consists of one duckweed-covered sewage lagoon (0.6 ha), 17 fish culture ponds (total area 6.9 ha) and 66 small hydroponic duckweed ponds (total area 3.2 ha) fertilised by inorganic nutrients (Phot. 23). Manikganj demo farm operates 64 duckweed ponds (total area 1.97 ha) and 12 fish ponds (total area 2.93 ha). The duckweed ponds at Manikganj are fertilised mainly by inorganic fertilisers, however, some latrines are also directly connected to the ponds. Average daily production of duckweed in Manikganj amounts to about 535 kg/ha·d (about 10 t(dry wt)/ha·y), and fish production ranges between 4.92 to 9.88 t/ha·y.

Fig. 7 illustrates the duckweed-covered sewage lagoon preceded by a 0.2 ha sedimentation pond for removal of suspended solids, and adjacent 3 fish ponds (0.2 ha each) at Mirzapur demo farm. The fish ponds are fed by groundwater and by the final effluent of the plug-flow. The lagoon is designed as a serpentine plug-flow of 500 m length and 12.6 to 13 m width (Phots. 24 and 25). Its water surface covers an area of 0.6 ha. Depth increases gradually from 0.4 to 0.9 m at the outflow. The system

Photograph 23: *Groundwater/chemical fertiliser-based duckweed cultivation of PRISM Bangladesh at Mirzapur demo farm complex. Duckweed ponds with floating bamboo grids and co-crops on the embankments in the foreground, and main fish production pond in the background.*

treats 125 to 270 m^3/d of hospital, school and residential sewage produced by 2000 to 3000 people residing at the Kumudini hospital complex. The plug-flow is fed semi-continuously with the effluent of the sedimentation pond.

Figure 7. *Layout of duckweed-covered serpentine plug-flow lagoon, anaerobic sedimentation pond (Pond-1), and fish ponds (Pond-2, Pond-3, Pond-4) at Mirzapur demo farm of PRISM Bangladesh.*



As aforementioned, the lagoon not only suffers from substantial leakage during the dry season, with a loss of about 30 % of total nutrient input, but also from low influent BOD concentrations, as a significant amount of the community's BOD discharge is not collected. Since the plug-flow is over-dimensioned, intensive duckweed production is restricted to only about 60 % of the total surface area. On an average, 656±177 kg (wet wt)/ha·d

Photograph 24: *Duckweed-based sewage treatment lagoon of PRISM Bangladesh at Mirzapur showing one reach of the plug-flow channel under construction. (Photograph: PRISM).*

Photograph 25: *Inlet section of duckweed-covered plug-flow lagoon showing dense duckweed mat stabilised by a floating bamboo grid system and banana co-crops on the right pond embankment.*

could be harvested from February 1993 to March 1994. During the wet season, plant harvest can increase to 1000-1200 kg (wet wt)/ha·d. Annual duckweed production in 1994 and 1995 was reported at 213 t(wet wt)/ha·y and 260 t(wet wt)/ha·y, respectively. At a dry weight fraction of 7.8 %, this is equivalent to 16.6 and 20.3 t(dry wt)/ha·y.

PRISM obtained comparatively high fish yields with a carp polyculture comprising Indian and Chinese carp species, and Tilapia fed on about 60 % sewage-grown duckweed and 40 % mustard oil cake (% dry matter).

PRISM adopted the old traditional Chinese carp polyculture concept, combining species with complementary feeding habits and living zones, to take advantage of all the feeding zones and food resources in a fish pond. A polyculture of different Indian (rohu, catla, mrigal) and Chinese (common, silver and grass carp) species is stocked at a density of 18,000-20,000 fish/ha. This combination of herbivorous, planktivorous and omnivorous fish makes efficient use of pond trophic zones. The polyculture can be divided into top, mid and bottom-feeding species. Distribution of the species is given in Table 18. Tilapia is not added to the ponds but enters the system by contamination and may contribute to about 40 % of the total fish production. PRISM has currently over eight years experience with duckweed-based carp polyculture. At Mirzapur demo farm, 60 % of all fish is directly sold at a discount to the Kumudini hospital and the remaining part is sold at the local market. Market prices are dependent on fish species: Rohu (58 BdT/kg) and mrigal (51 BdT/kg) seem more attractive, however, despite high stocking densities, the relative production of the two species tends to be low. Silver carp (34 BdT/kg) and tilapia (29 BdT/kg) seem to do very well but fetch a relatively low market price. Catla, grass carp, and common carp are sold at 48, 42, and 55 BdT/kg, respectively.

Table 18. *Species distribution of carp polyculture for fish pond stocking as practised by PRISM Bangladesh.*

Species	*% of total stocking*
Catla catla (Catla)	20
Labeo rohita (Rohu)	20
Cirrhina mrigala (Mrigal)	20
Hypophthalmichthys molitrix (Siver carp)	15
Ctenopharyngodon idella (Grass carp)	20
Cyprinus carpio (Mirror carp)	5

Fish is produced in an annual cycle, with stocking in July and maximum harvesting from May to July. Harvesting is conducted throughout the year at irregular intervals varying between once a month to eight times a month. The experiments conducted only in 1990, using duckweed as sole fish feed, indicated that a fish yield of 6.6 t/ha·y could be obtained. Annual fish production using sewage-grown duckweed as a fish feed was reported at 10.58 t/ha·y in 1994 and 12.62 t/ha·y in 1995. These figures are high compared to Bangladesh or even international standards. However, these values were obtained with a mixed feed of sewage-grown duckweed and mustard oil cake at a dry weight ratio of 56-67 % and 44-33 %, respectively. Based on the total feed inputs (dry weight) and total fish production, FCR values of 2.8 (1994) and 3.3 (1995) were obtained. The reasons for these comparatively high FCR values were attributed to the non-addition of wheat bran - a good source of carbohydrates - to the feed mix, to overfeeding, loss of feed to the sediment, low water quality (oxygen, ammonia), theft of fish, and to the comparativley small size of fish ponds.

A Duckweed Research Project (DWRP) was initiated as a joint effort by the Governments of The Netherlands and Bangladesh in collaboration with PRISM and other institutions to test the technical and socio-economical feasibility of a wide range of duckweed-based production systems. Unfortunately, the DWRP was discontinued in 1997 due to structural and management problems.

The Ministry of Local Government and Rural Development is developing a “Bangladesh School and Community Sanitation Project” (SCSP) in partnership with the World Bank. The project includes a “Prefeasibility Study on Duckweed-Based Wastewater Treatment and Reuse” which is implemented by the International Institute for Hydraulic, Infrastructural and Environmental Engineering (IHE Delft, The Netherlands) in collaboration with PRISM Bangladesh. The objective of the prefeasibility study is to assess the possibility of introducing, on a demonstration basis, duckweed-based environmental sanitation into the SCSP design. The final report is expected to appear in March 1999.

India

The Indian NGO, Sulabh International, is involved in duckweed application in cooperation with the All India Institute of Hygiene and Public Health in Calcutta.

In April 1995, Sulabh started a demonstration project in Wazirabad (northern part of New Delhi), where Delhi Water Supply and Sewage Disposal Undertaking is operating 17 oxidation ponds (150 x 60 m each) for treatment of part of New Delhi's sewage. Of these 17 ponds, Sulabh is operating 4 ponds in series, using the first one for settling, the second and third for duckweed cultivation and pond four for fish production. Total HRT in the series of the four ponds amounts to 27-28 days. The aim of the project is to assess the economic feasibility of duckweed-based wastewater treatment. BOD of the influent ranges from 150 to 190 mg/l, whereas effluent levels after pond 3 are around 30 to 40 mg/l. The growth rate of duckweed is about 130 $g/m^2 \cdot d$, however, the presence of cyanobacteria as well as heavy oil and grease concentrations (>10 mg/l) were reported to seriously hamper duckweed growth. The duckweed ponds are covered mainly with *Spirodela*, as *Lemna* showed to be more sensitive to high light intensities. Another urban project is located at Halisahar in West Bengal. Both urban projects are funded by the Central Pollution Control Board.

Two Sulabh duckweed-fish production projects in rural areas are conducted in the states of Haryana and Orissa. The project in Orissa was funded by the Royal Danish Embassy (Rs. 1,943,480), the one in Haryana by the Ministry of Rural Areas and Employment (Rs. 1,246,000). The Haryana project was started in April 1996 in Gurgaon and Faridabad. The Orissa project was initiated in September 1996 in the villages of Budhalo, Indrapal, Brahmapur, and Srirampur. All the ponds used in the project are rain-fed and owned by local farmers.

UNDP/World Bank Regional Office in New Delhi compared different treatment options, including UASB, activated sludge and a duckweed-based treatment system for treatment of sewage from the city of Pondicherry. Due to additional household connections, the sewage flow is expected to increase about three times in the near future. The study concluded that a combined UASB, duckweed and fish production system can be installed at about 70 % of the costs of an activated sludge plant. Moreover, the duckweed-based system has the potential to generate, within a period of ten years, a net revenue equivalent to the initial investment costs. Operation and maintenance of the activated sludge process are also expected to be more expensive. In 1994, implementation had not yet started due to a lack of funds.

Another interesting wastewater treatment system is the Calcutta wetland system. According to Mara *et al.* (1993), the current fish yields may be increased 2-3 times if management is improved.

One of the options here could be the cultivation of duckweed in the initial stages of the wetland where high sewage concentrations are prevalent, and where the use of duckweed could sustain high fish yields in the rest of the wetland (Gijzen and Khondker 1997).

Lemna Corporation

The US-based company Lemna Corporation has been involved since the late eigthies in development and marketing of full-scale wastewater treatment plants and modules, using duckweed for tertiary post-treatment of aerated and non-aerated lagoon effluents. Lemna Corporation is divided into the two branches Lemna USA and Lemna International Inc. By February 1998, the company had installed over 125 treatment systems worldwide, with over 60 systems in the USA, of which 30 in Louisiana and over 40 outside the USA, of which 22 in Poland and others in Siberia (!), Sweden, China, and Mexico.

These facilities treat domestic and industrial wastewaters from small to medium-sized communities with daily flow rates ranging between 150 and 7000 m^3. Application of large-scale duckweed systems receiving peak wastewater flows of over 30,000 m^3/day from cities with a few 100,000 inhabitants are also reported. U.S. EPA has categorised the Lemna treatment system as an innovative/alternative technology.

The biomass produced in these treatment systems is generally not used as animal feed, but rather considered an undesirable by-product which is composted. This approach clearly focuses on duckweed as a wastewater purifier whose production is kept minimal, while allowing optimum treatment efficiencies. To minimise duckweed production, harvesting frequency is reduced to monthly intervals for secondary treatment, and weekly intervals for nutrient removal. Floating, mechanical harvesting machines are generally used for harvesting.

The company's projects in Eastern Europe and China suggest that the medium-tech approach of Lemna Corporation seems to be a feasible option for wastewater treatment in middle-income countries. The technical requirements, such as aeration pumps, high density polyethylene grids and mechanical harvesting devices, however, do not seem an appropriate solution for low-income countries as regards operation, maintenance and energy supply costs. To combine sanitation and the nutritional potential of duckweed, an optimum duckweed production allowing for acceptable treatment efficiency should be promoted rather than a minimum duckweed production as practised by Lemna Corp.

Chapter Ten

Priority Research Needs

A number of institutions in Bangladesh and elsewhere in the world have revealed the potential of duckweed aquaculture as a technology combining both wastewater treatment and fish production and, to a lesser extent, poultry, pig and livestock production. However, several key questions as regards the technical, institutional and socio-economical feasibility of duckweed-based treatment/farming systems remain to be answered before embarking on dissemination of the technology at rural and (peri-) urban level where prevalent local conditions provide the appropriate setting in developing countries.

The Duckweed Research Project (DWRP), a joint project of the governments of The Netherlands and Bangladesh, provides a comprehensive overview of the needs for applied research in development and testing of the technical and socio-economical feasibility of duckweed-based technologies in a developing country. Though the project was discontinued, the rationale and justifications which led to the identification of research topics are still valid. The priority research fields mentioned hereafter are to a major extent based on the research fields identified by the DWRP.

- Public health and environmental effects of duckweed treatment/farming systems
- Design and operation of duckweed-based pond systems for combined wastewater treatment and biomass production
- Economic assessment of wastewater-based duckweed farming models
- Sociocultural and institutional aspects of wastewater-based duckweed farming
- Duckweed production and feeding applications.

Public Health and Environmental Effects of Duckweed Treatment/Farming Systems

The key questions in this research field are:

- What are the public health and environmental effects of the introduction of duckweed-based systems?
- How can duckweed aquaculture be optimally combined with rural and (peri-)urban sanitation measures?

The research objectives should include:

- Assessment of the public health hazards of wastewater-duckweed-animal production systems with respect to pathogen transfer and accumulation of toxic compounds for different types of wastewater (domestic, industrial), animals (fish, poultry, livestock), products consumed (milk, eggs), and categories of people at risk (workers, consumers, residents). The contaminants of primary concern include pathogenic bacteria, parasites such as helminths, toxic compounds such as pesticides, and heavy metals such as chromium, nickel, led, zinc, copper, and arsenic accumulated in duckweed and possibly transferred to different organs and products of animals fed on it.

- Assessment of the effect of a duckweed cover on mosquito development in polluted still water bodies.
- Assessment of the relative contribution of duckweed to the survival or die-off of pathogens and parasites in duckweed-covered pond systems receiving domestic wastewater or latrine effluents, and comparison of the die-off rates in presence and absence of a duckweed cover.
- Assessment of the effects of duckweed on surface and groundwater quality in villages and other (urban) areas where ponds are polluted in a controlled (e.g. latrines connected to duckweed ponds) or uncontrolled way (waste dumping and indiscriminate defecation) through a combination of water quality analyses (dissolved oxygen, BOD, nutrients, pathogens, turbidity) and direct observations (algal blooms, odours, visual aspect).

Design and Operation of Duckweed-Based Pond Systems for Combined Wastewater Treatment and Biomass Production

The key questions in this research field are:

- How should a duckweed-covered pond system be designed and operated as regards quantity and strength of wastewater, to combine efficient treatment with optimum biomass production in rural and (peri-)urban systems?
- How can existing systems be further optimised?

The research objectives should include:

- Assessment and optimisation of existing duckweed-covered sewage and excreta treatment lagoons at rural and (peri-) urban level as regards efficient removal of contaminants (pathogens, BOD, nutrients, TSS, toxic compounds, etc.).
- Development of reliable plug-flow design and operation guidelines for wastewater treatment in peri-urban areas as regards maximum and minimum loading rates for BOD and nutrients, multiple wastewater input points, recirculation of final effluent, harvesting strategies, and duckweed productivity, including yield and quality as a function of hydraulic retention time.

Economic Assessment of Wastewater-Based Duckweed Farming Models

The key question in this research field is:

- What is the economic feasibility of different duckweed-based farming models under different realistic scenarios at village and (peri-)urban level?

The research objectives should include:

- Assessment of the profitability of different duckweed-based farming systems/models using methods like net present value, internal rate of return, and cost/benefit ratio. Environmental costs and benefits should possibly be incorporated in a profitability analysis.
- Provision of a sensitivity analysis of factors affecting the economic potential of duckweed-based systems.
- Assessment of the economic benefits for the target groups.

Sociocultural and Institutional Aspects of Wastewater-Based Duckweed Farming

The key questions in this research field are:

- Which institutional approaches are most suitable for dissemination of duckweed-based food production in a specific sociocultural context?
- Which target group structures or organisation models are most suitable for dissemination?
- Which sociocultural constraints influence the acceptance of duckweed systems and how can they be bypassed?

The research objectives should include:

- Evaluation of the acceptance of duckweed-based systems and products by rural and urban communities of a specific sociocultural background.
- Optimisation and testing of different target group organisation structures.
- Assessment of the impact of project implementations on the beneficiaries.

Duckweed Production and Feeding Applications

The key questions in this research field are:

- What kind of duckweed-based production systems can be developed and introduced in rural and (peri-)urban areas?
- How can available and under-utilised nutrient and land resources be optimally used in duckweed-based systems?
- Which farming system is most appropriate for incorporation of duckweed-based production?

The research objectives should include:

- Identification and testing of alternative nutrient sources, such as cattle dung, poultry droppings, biogas effluents, or food processing and industrial wastewaters for duckweed cultivation at rural and (peri-)urban level.
- Optimisation and stabilisation of duckweed production with respect to its yield and nutritional quality.
- Development and testing of preservation methods like solar drying, pelleting or ensilaging.
- Study of prevalent duckweed pests, such as insect larvae and fungi, and development of environmentally sound countermeasures to protect duckweed crops from infestation.
- Optimisation of the use of duckweed as fish feed with regard to feeding ratio (mixed feed), selection of fish species, cultivation method (mono or polyculture, continuous vs. batchwise fish production), FCRs, and use of duckweed as nursery fish feed (*Lemna* and *Wolffia*).
- Determination of the most appropriate duckweed form (dry or fresh) and feeding ratio (mixed feed or pure) for chickens, ducks, goats, and ruminants as regards digestibility, voluntary intake, FCRs, yield and quality of products (meat, eggs, milk).

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