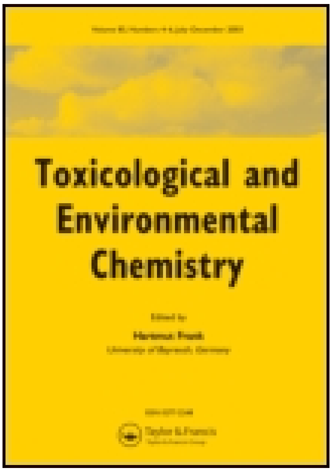

Toxicological & Environmental Chemistry
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gtec20

Duckweed: an effective tool for phyto-remediation

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Accepted author version posted online: 02 Jan 2014.Published online: 31 Jan 2014.

Toxicological & Environmental Chemistry, 2014
Vol. 95, No. 8, 1256–1266, http://dx.doi.org/10.1080/02772248.2013.879309

Duckweed: an effective tool for phyto-remediation

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(*Received 7 October 2013; accepted 20 December 2013*)

Effective wastewater treatment through conventional methods that rely on heavy aeration are expensive to install and operate. Duckweed is capable of recovering or extracting nutrients or pollutants and is an excellent candidate for bio-remediation of wastewaters. Such plants grow very fast, utilizing wastewater nutrients and also yield cost effective protein-rich biomass as a by-product. Duckweeds being tiny surface-floating plants are easy to harvest and have an appreciable amount of protein (15%–45% dry mass basis) and a lower fiber (7%–14% dry mass basis) content. Besides nutrient extraction, duckweeds has been found to reduce total suspended solids, biochemical oxygen demand (BOD), and chemical oxygen demand in wastewater significantly. Depending on the initial concentrations of nutrients, duckweed-covered systems can remove nitrate (NO_3^-) at daily rates of 120–590 mg NO_3^- m^{-2} (73%–97% of initial concentration) and phosphate (PO_4^-) at 14–74 mg PO_4^- m^{-2} (63%–99% of initial concentration). Removal efficiencies within 3 days of 96% and 99% have been reported for BOD and ammonia (NH_3). Besides several genera of duckweeds (*Spirodela*, *Lemna*, *Wolffia*), other surface-floating aquatic plants like water hyacinth (*Eichhornia*) are well known for their phyto-remediation qualities.

Keywords: non-conventional; duckweed; nutrient recycling; nutrition; phyto-remediation; wastewater management

1. Introduction

The treatment of sewage and wastewater from agricultural operations requires the removal of large amounts of nitrogen and phosphate. These wastes are a growing problem around the world because of population growth and the trend of modern farming operations to concentrate livestock in small areas (Iqbal 1999).

Effective wastewater treatment through "conventional methods" which rely on heavy aeration are expensive to install and operate. Hence, there is a need to explore some "non-conventional" methods which are not only economically viable and easy to operate but are also eco-friendly. For remediation of village ponds, the first step is to remove the excess nutrients dumped into it. For this purpose, plant-based bio-remediation (phyto-remediation) technology is the most promising option. Any aquatic plant that is capable of recovering or extracting nutrients or pollutants and which has a fast growth rate coupled with high nutritive value is an excellent candidate for bio-remediation of wastewaters. Duckweeds grow faster when the nutrients are abundant in the medium. Such plants utilize wastewater nutrients and also cost effectively yield protein-rich plant biomass as by-product (Leng 1999).

Duckweeds hold immense potential for both nutrient recovery and utilization as fodder or feed for livestock including fish.

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Sudden appearance of duckweeds is an indicator of water pollution and changing environmental conditions. In recent years, duckweed has become prominent because of its ability to concentrate minerals from heavily polluted water that arises from sewage treatment facilities. However, it has also attracted the attention of scientists because of its apparent high potential as a feed resource for livestock (Skillicorn, Spira, and Journey 1993; Leng, Stambolie, and Bell 1995). Duckweed grows on water with relatively high levels of nitrogen, phosphorus, and potassium concentrates the minerals and synthesizes protein. These are the nutrients which are often critically deficient in traditional fodders and feed given to ruminants, pigs, and poultry, particularly when they depend on agro-industrial by-products and crop residues.

Duckweed aquaculture is an activity that fits readily into many crop/animal systems managed by small farmers and which can be a major mechanism for scavenging nutrients. It appears to have great potential in securing continuous food production particularly by small farmers as it can provide fertilizer, food for humans, and feed for livestock; in addition, water pollution is decreased and the potential for water re-use is increased (El-Kheir et al. 2007).

2. Duckweed

Duckweed is a free-floating aquatic plant that grows in both still and running freshwater, such as lakes, rivers, and streams. Depending on the circumstances, duckweed can be an extremely invasive species or a welcome aquatic plant. Any plant of the genus *Lemna* can be considered duckweed. The plants usually have small vestigial roots and grow in the form of thick green carpets of rounded free-floating thalloids, flattened structures which resemble leaves. Duckweed can rapidly spread to cover a waterway resisting all attempts to eliminate it. These plants typically reproduce by budding, although they can produce small flowers on occasion, and prefer water which is rich in nitrogen and other nutrients. They readily filter substances including toxins out of the water. They can also provide shelter for aquatic animals, in addition to nutrition for larger creatures like ducks and geese. Some species are even considered attractive making them potentially appealing as ornamentals in the garden. Some have even been genetically engineered to perform specific functions (Gijzen and Khondker 1997).

As municipal and agricultural wastewater is rich in nutrients and organic matter, it favors the abundant growth of duckweeds. Duckweeds also possess a unique ability to accumulate starch that can amount to about 40%–70% of their dry biomass. This starch can then be used and converted into ethanol as a source of biofuel. The other advantages of using duckweed in phyto-remediation are that they can be easily digested by livestock due to their low lignin content. Moreover, they can grow on less fertile land and hence they do not compete for fertile land that can be used for growing other agricultural commodities (Cheng and Stomp 2009; Crop Biotech Update 2009).

Duckweeds belong to family Lemnaceae and taxonomically belong to monocotyledons and have four genera: *Lemna*, *Spirodela*, *Wollfia*, and *Wolffiella*. Some species develop root-like structures in open water which either stabilize the plant or assist it to obtain nutrients where these are in low concentrations. About 40 species are reported worldwide (Les et al. 2002).

Vegetative growth in *Lemna minor* exhibits cycles of senescence and rejuvenation under constant nutrient availability and consistent climatic conditions (Ashby and Wangermann 1949). Fronds of *Lemna* have a definite life span during which a set number of daughter fronds are produced; each of these daughter fronds is of smaller in mass than the one preceding it and its life span is reduced. The size reduction is due to a change in cell numbers. Late daughter fronds also produce fewer daughters than early daughters.

Biomass of duckweeds gets doubled in 2–3 days (Iqbal 1999; Skillicorn, Spira, and Journey 1993) under ideal conditions of nutrient availability, sunlight, pH (6.5–7.5), and temperature (20–30 °C) and can be cultured, harvested, and sun dried without much cost, labor, and expertise.

3. Duckweeds as nutrient pump

Due to their ability to propagate rapidly by consuming dissolved nutrients from water, duckweeds act as an excellent "Nutrient Sink" for harvesting nutrients over a short period of time and thus serve as a "nutrient pump" in wastewater treatment absorbing nutrients like nitrate, phosphate, calcium, sodium, potassium, magnesium, carbon, and chloride from the wastewater. These nutrients are permanently removed from the system when the plants are harvested.

Besides nutrient extraction, duckweeds reduce total suspended solids (TSS), biochemical oxygen demand (BOD), and chemical oxygen demand (COD) in wastewater significantly. Korner and Vermaat (1998) reported that depending on the initial concentration of nutrients, duckweed-covered systems can remove nitrate and phosphate at rates of 120–590 mg NO_3^- m^{-2} day^{-1} (73%–97% of initial concentration) and 14–74 mg $PO_4^{3-}m^{-2}$ day^{-1} (63%–99% of the initial concentration). Removal efficiencies of 96% and 99% by duckweeds have been reported for BOD and ammonia (NH_3), respectively (Alaerts, Rehman, and Kelderman 1996). Reddy and DeBusk (1985) recorded N and P uptake rate of 0.15 and 0.03 gm^{-2} per day by *Spirodela polyrrhiza* in Florida, whereas Alaerts, Rehman, and Kelderman (1996) found it to be 0.26 and 0.05 gm^{-2} per day in Bangladesh. Cheng et al. (2002) reported maximum N uptake of 0.955 mg L^{-1} h^{-1} and P uptake of 0.129 mg L^{-1} h^{-1} by *Spirodela punctata*. Fat duckweed – *Lemna gibba* – has also been found to reduce TSS, BOD, COD, N, NH_3, P, phytoplankton crop, and fecal coliform counts in wastewater by 96.3%, 90.6%, 89.0%, 100%, 82.0%, 64.4%, 94.8%, and 99.8%, respectively, in 8 days (El-Kheir et al. 2007).

Accumulation of arsenic in *Lemna gibba* L. was investigated in tailing waters of abandoned uranium mine sites in Saxony, Germany where arsenic poses contamination risks (Mkandawire and Dudel 2005). Macrophytes grown on mine tailing waters accumulate high amounts of arsenic which might be advantageous for its transfer to higher trophic levels and for phyto-remediation. Water and *L. gibba* samples collected from ponds of tailing dumps of abandoned mine sites at Lengenfeld and Neuensalz-Mechelgrün were analyzed for arsenic. Laboratory cultures in nutrient solutions modified with As(III) and As(V) and three PO_4^{3-} concentrations were conducted to gain insight into the arsenic–*L. gibba* interaction. Arsenic accumulation coefficients in *L. gibba* were 10 times as much as the background concentrations in both tailing waters and nutrient solutions. Arsenic accumulations in *L. gibba* increased with arsenic concentration in the milieu but decreased with phosphorus concentration. Significant reductions in arsenic accumulation in *L. gibba* were observed with the addition of PO_4^{3-} at all six arsenic test concentrations in laboratory experiments. Plant samples from laboratory trials had on average twofold higher bioaccumulation coefficients than from tailing water at similar arsenic concentrations. This would be attributed to strong interaction among chemical components and competition among ions in the natural aquatic environment. The results of the study indicates that *L. gibba* can be a preliminary bio-indicator for arsenic transfer from substrate to plants and might be used to monitor the transfer of arsenic from lower to higher trophic levels at the abandoned mine sites. There is also the potential of using *L. gibba* for arsenic phyto-remediation of mine tailing waters because of its high accumulation capacity as demonstrated in this study.

4. Duckweed-based wastewater treatment: processes

Duckweed-based wastewater treatment (DWT) systems operate similarly to conventional lagoon systems that can incorporate deep facultative ponds for solids removal and stabilization and polishing ponds for further purification. However, DWT differs from conventional lagoon systems in that they work to prevent rather than encourage planktonic algal growth. Duckweeds prevent growth of planktonic alga by forming a thick duckweed mat floating on the surface that overshadows or out-shades the planktonic algae (including toxic blue-green algae/cyanobacteria). The result is greater discharged effluent standards in terms of reduced TSS and nutrients. Nutrients contained in phytoplankton are difficult to harvest and are generally released back into the environment, whereas duckweed is easily harvested which results in direct removal of nutrients from the waste stream. Inhibiting phytoplankton also regulates pH which shows great diurnal fluctuations in traditional lagoons. In addition, evaporation from the water surface is reduced in DWT systems (Bonomo, Pastorelli, and Zambon 1997). The increased efficiency of DWT over conventional lagoon systems is that they occupy less land area (Skillicorn, Spira, and Journey 1993). Duckweed works to purify wastewater in collaboration with both aerobic and anaerobic bacteria. Therefore, the duckweed plants themselves should be considered as only one component of a complete DWT system.

Heterotrophic bacteria decompose organic waste matter into mineral components specifically in the form of ammonia, nitrate, and orthophosphates that are readily taken by the duckweed plants. Bacterial decomposition consumes oxygen and can cause the mid-water zone to become increasingly anoxic and the bottom of the lagoon to become anaerobic, providing further zones for specialized bacterial processing of organic matter and de-nitrification (Iqbal 1999; Smith and Moelyowati 2001). The duckweed mat maintains these conditions by inhibiting atmospheric oxygen diffusion at the water surface. However, a 10-cm surface layer remains aerobic due to atmospheric oxygen transferred by duckweed roots (Hancock and Buddhavarapu 1993). Bacterial oxidation of organic matter and nitrification are facilitated that are aided by the additional surface area for bio-films provided by the duckweed roots and fronds.

Other processes that aid nitrogen removal in DWT systems are sedimentation of organic matter and volatilization of ammonia. Phosphorus is normally reduced in DWT ponds by plant uptake, absorption into clay particles and organic matter, chemical precipitation, and sludge removal (Iqbal 1999; Smith and Moelyowati 2001). A dense duckweed mat has also been reported to decrease and control mosquito larvae and odor in a wastewater body by providing an interface between the water and air (Culley and Epps 1973; Iqbal 1999).

Smith and Moelyowati (2001) suggested that pathogen removal is likely to be less effective in DWT ponds than algae-based lagoons due to the absence of very alkaline conditions and less light radiation. However, this can be countered by a sufficient detention time since parasites and suspended pathogens simply die as a function of time (Skillicorn, Spira, and Journey 1993; Iqbal 1999). A study (Bell 2003) comparing fecal coliform counts at the Harrington, NSW sewage treatment plant showed levels exiting the duckweed pond were significantly lower than levels exiting the control pond (46 CFU/100 ml compared with 7900 CFU/100 ml in the duckweed and control pond, respectively).

5. Effectiveness of DWT

DWT has great potential for renovating effluent from a wide variety of sources including municipal sewage treatment plants, intensive livestock industries (including aquaculture), abattoirs, and food processing plants. The effectiveness of DWT depends on a system design that facilitates the correct combination of organic loading rate, water depth, and hydraulic retention time. These will vary depending on the effluent source and the level of pre-treatment. In the case where raw sewage (human or livestock waste) is to be processed, the primary objective of treatment is to remove solids. This can be achieved in conventional deep anaerobic ponds that encourage the fermentation and breakdown settled solids by bacterial processes into simple organic and inorganic molecules. Duckweed enhances primary treatment in these ponds by maintaining anaerobic conditions and reduces odor nuisance (Skillicorn, Spira, and Journey 1993). While conventional anaerobic ponds, effective at reducing BOD, have a negligible effect on total nutrient concentrations (Caicedo et al. 2000), duckweed assimilation enhances the nutrient removal capacity of these anaerobic systems.

High levels of ammonification occur in primary treatment systems. Cheng et al. (2002) found that a range of duckweed species tested could tolerate and grow at high ammonium levels of 240 mg L^{-1} in swine wastewater – the best performer being a Queensland native, *Spirodela punctata* (recently renamed *Landoltia punctata* – Cross 2004). Phan (2002), however, found that duckweed may need an acclimatization period to adapt to the very high N levels in raw agricultural wastewaters.

Most researchers, however, suggest that efficiency gains using DWT are greater in secondary and tertiary treatments of effluent where organic sludge has already been removed or converted into simple organic and inorganic molecules that can be used directly by duckweed (Alaerts, Rehman, and Kelderman 1996; Caicedo et al. 2000; Smith and Moelyowati 2001; Dalu and Ndamba 2003). In the Burdekin, as with most communities in Australia, primary sewage treatment infrastructure is used to remove solids. The problems currently encountered with municipal wastewater treatment include difficulties in meeting TSS and nutrient (total nitrogen, phosphorus, and ammonia) discharge regulations. Intensive livestock and other industries that release effluent into natural waterways must comply with similar regulations.

6. Other applications of duckweeds

6.1. High nutritive value

Duckweeds are the rich source of proteins (up to 45%, on DM basis) in the plant kingdom (Fasakin 1999) and have a better array of essential amino acids than most plant proteins and they more closely resemble to animal protein (Hillman and Culley 1978). Furthermore, its amino acid spectrum, especially lysine (7.5% of total protein) and methionine (2.6% of total protein), is much higher as compared to other plant feed stuffs (Rusoff, Blakeney, and Culley 1980; Mishra 2007). The nutritive value of duckweeds is comparable to that of soybean. With an annual duckweed yield of 20 t dry weight ha^{-1} yr^{-1} and protein content of 35% (DM basis), protein productivity of 7 t ha^{-1} yr^{-1} can be achieved which indicates that relative annual protein production per unit area through duckweeds is about 10 times higher than that of soybean (Skillicorn, Spira, and Journey 1993; Khateeb 2004). Nutritionally also duckweeds have been found to substitute soya and fish meal in feeds of farmed animals like chickens, goats, pigs, ducks, and fish (Hillman and Culley 1978; Culley et al. 1981; Edwards 1990; Leng, Stambolie, and Bell 1995; Men, Ogle, and Preston 1995; Anh and Preston 1997; Leng 1999; Iqbal 1999; Landesman et al. 2002).

Table 1. Nutritive value of duckweeds on DM basis.

Type	Crude protein (%)	Crude fat (%)	Crude fiber (%)	Ash (%)
Duckweed (mixed/species)	6.8–45.0	1.8–9.2	5.7–16.3	12.0–27.6
Spirodela polyrrhiza	30.52	1.97	17.0	9.45
Lemna minor	28.48	4.75	10.35	10.1
Lemna spp.	36.0–38.6	4.5–9.8	10.7–18.7	8.46–19.0

The nutritive value of the duckweeds (Table 1) depends on the nutrient status of the water on which they grow. They grow slowly on nutrient poor waters and under such growth conditions have low protein content associated with high fiber, ash, and carbohydrate content. In contrast, they grow rapidly on nutrient-rich waters and have a high protein content associated with high ash and low fiber content.

Protein content of duckweeds growing on nutrient-poor and nutrient-rich waters varies between 15%–25% and 35%–45% (DM basis), respectively (Mbagwu and Adeniji 1988). Root length is a useful indicator of whether pond conditions are appropriate (with respect to nutrients) for production of high protein duckweeds or not (Rodriguez and Preston 1996; Chau 1998). Roots less than 10 mm in length indicate higher protein content in duckweeds than roots more than 10 mm in length and the reverse is true for the fiber content which can be observed very easily under field conditions. Duckweeds are also a rich source of carbohydrates (30%–35%), vitamin A and pigments, particularly beta-carotene and xanthophylls. They contain 92%–94% of moisture and harvested biomass can be easily sundried within a period of 24–48 h during the dry summer months and 4–6 days during winter.

6.1.1. Storage of duckweeds

Sundried as well as pelleted forms of duckweed can be stored for 13 years without any sign of fungal growth and nutrient loss (Mbagwu 2001). It is due to the presence of a wax coat on the upper surface of plants which acts as a barrier for fungal growth. A recent finding by Effiong and Sanni (2009) of decreased mold infestation in duckweed (*Lemna pauciscostata*) incorporated pelleted fish feeds also highlights its value addition potential with great application in feed storage.

6.2. Duckweeds as vermi-compost

Duckweeds are rich source of macronutrients and characterized by high amounts of nitrogen and phosphorus. Compost made from duckweeds is, therefore, rich in these macronutrients. Kostecka and Kaniuczak (2008) developed a high quality macronutrient-rich (N, P, and K) vermi-compost from duckweed (*Lemna spp.*) biomass by using *Eisenia fetida* (SAV.) earthworms. Hence, vermi-composting of harvested duckweed biomass further corroborates its potential for utilization in environmental reclamation including aquaculture as well as agriculture.

6.3. Duckweeds as source of other value added products

Besides quality protein resource, duckweeds are also a good resource of starch. Hence, there is great scope of production of value added products like protein concentrate and ethanol from duckweeds. About 64.4% crude protein content has been reported in leaf protein concentrates prepared from *Spirodela polyrrhiza* (Fasakin 1999), which can be used as feed supplement not only in animal feeds but also for human consumption. *Spirodela polyrrhiza* grown on anaerobically treated swine wastewater has been found to have a starch content of 45.8% on DM basis and its enzymatic hydrolysis yielded a hydrolysate with a reducing sugar content corresponding to 50.9% of the original duckweed biomass. Further, fermentation of the sugar hydrosylate by yeast gave an ethanol yield of 25.8% of the original dry duckweed biomass which reflects an additional scope of harvested duckweed biomass in ethanol production (Cheng and Stomp 2009).

6.4. Duckweeds as fish feed

Initially, duckweeds had been used only in commercial applications to treat wastewater in North America in 1989 staff of a non-governmental organization based in Columbia, MD. The PRISM Group initiated a pilot project in Bangladesh to develop farming systems for duckweed and to test its value as a feed for herbivorous/omnivorous fishes like carps and tilapia. The results of the pilot operations were extremely promising and dried duckweed meal provided an excellent substitute for expensive conventional feed ingredients like soybean and fish meal (Iqbal 1999). Fresh duckweed is converted efficiently to live weight by fish. Feed conversion ratio of 1.2 to 3.3 for *Spirodela* in carps and 1.6 to 3.3 for *Lemna* in tilapia has been recorded by Gijzen and Khondker (1997). Duckweed incorporated dry diets have also been found to support growth in not only herbivorous or omnivorous fishes like carps and tilapia but in high protein demanding carnivorous fishes like catfishes and snakeheads as well.

Duckweed plants, as a function of their surface area, accommodate attached pathogens from the wastewater. As such, pathogens will inevitably be harvested along with the crop. When fresh plants are fed to fish, dilution of pathogens will occur in the fish pond. Surviving pathogens consumed by fish will be digested in their guts (Skillicorn, Spira, and Journey 1993). In instances where plants are processed and dried, desiccation will further destroy pathogens. Haustein, Gilman, and Skillicorn (1987) found that no viable human pathogens could be cultured from dried sewage-grown duckweed in 4 years of testing.

7. Use of duckweed for bio-remediation

The focus on duckweed as a key step in waste recycling is due to the fact that it forms the central unit of the recycling engine which is driven by photosynthesis making it energy efficient, cost effective, and eco-friendly. Hence, duckweed based bio-remediation model is an effective, cheap, and simple way of reclaiming polluted ponds. For this, the major pond is divided into two parts, i.e., duckweed culture pond and fish culture pond, by erecting earthen partition. Only the duckweed pond receives the waste and duckweed is cultured in surface-floating frames (made up of either PVC pipes or split bamboo sticks) to mitigate wind action which can disturb the growing duckweed mat and carry it in the direction of wind. Remediated water from duckweed pond is released periodically into the fish culture pond. In case if it is not possible to divide the ponds into two parts as desired, it is suggested to culture duckweed in enclosed pens (constructed by erecting partitions made up of bamboo poles and fine mesh net) near the periphery of the ponds.

In Punjab, a pilot duckweed project for bio-remediation of village pond was initiated in 2001 by the State Government in collaboration with Punjab State Council for Science and Technology (PSCST) in villages Sanghol and Chanarthal kalan in District Fatehgarh

Sahib (Singh, Singh, and Walia 2003). Under this project, village ponds were divided into a duckweed pond and a fish culture pond. Bio-remediated water from the duckweed pond was used for poly-culture of carps (Indian major carps and exotic carps) in the fish culture pond and harvested duckweed biomass was utilized to feed the fish. Encouraging results in terms of enhanced fish production from the bio-remediated village pond has lead to continuation of the project till date. After the success story of first duckweed pilot project in Punjab, another project was taken up by PSCST in village Sandhua in district Ropar in 2003 and many other are in pipeline (PSCST 2005).

8. Duckweed harvesting schedule

Regular harvesting of duckweed is necessary as it helps in regular extraction or recovery of nutrients from the village ponds. A well-planned harvesting schedule is required to maintain vigorous growth of duckweed and nutrient removal. It should be designed according to the growth rate of duckweeds, usually having biomass doubling times ranging from 2 to 3 days. Hence, removal of half of the duckweed biomass or cover on every third day is a practical option which not only ensures development of full duckweed cover over the pond surface within a short period but also helps in blocking the sunlight from entering into the waste water. This is required for preventing growth of unicellular and filamentous algae in the wastewater, which otherwise grow very fast and compete for nutrients affecting growth and quality of duckweed. Duckweed productivity from 10 to 50t (dry biomass) ha^{-1} yr^{-1} has been reported (Gijzen and Khondker 1997) from different parts of the world. Fresh duckweed yields in the range of 0.5 to 1.5 t ha^{-1} day^{-1} have been reported in Bangladesh which corresponds to the production of 185 to 550t of fresh or 13 to 38t of dry duckweed biomass ha^{-1} yr^{-1} (Skillicorn, Spira, and Journey 1993).

9. Other issues of duckweed

There is accumulating evidence that duckweeds release compounds that have insecticidal properties particular to the larval stages of mosquitoes. Thus the development of duckweed aquaculture in the wet tropics may have implications for mosquito control in rural areas where malaria is a serious problem.

Eid et al. (1992a) published evidence that an extract of *Lemna minor* had insecticidal action against the mosquito *Culex pipiens*. The same extract contained synomones which also repelled oviposition by the female mosquito. When sub-lethal doses of synomones were added to water, it was found that all larval stages of the mosquitoes were malformed. Duckweed synomones added to water also repelled the ovipositing of *Piophila casei* and affected larval development and reduced survival. Similarly *Spodephera littarolis* larvae were malformed when synomones from *Lemna minor* were added to their culture medium.

Other research workers have also associated duckweed presence with reduced (or elimination) mosquito development. Marten et al. (1996) showed that *Anopheles albimanus* populations were negatively correlated with the amount of cover of the water by *Lemna*. The relative cover of water surface with duckweed was also negatively correlated with populations of fish and other insects indicating how intricate the associations are in natural ecosystems. Eid et al. (1992b) have made the observation that the mosquito *Culex pipiens* never colonized sewage water covered with duckweed. Bellini et al. (1994) reported that *Lemna* covering the surface of rice paddy fields strongly affected mosquito populations. However, again other organisms might also have been involved in the control of mosquitoes.

Thus the insecticidal properties of *Lemna minor* and other duckweeds are sufficient to control mosquito populations. It will have an immense effect on the health of people in areas where mosquito-borne diseases are endemic and resistance of the parasitic stage to drugs has increased. It is also a further inducement to cultivate duckweeds widely for water treatment (purification) and animal feed. A further potential is the commercial cultivation of duckweed as a source of insecticides in water where it is difficult to spray for control of mosquito larvae or where the use of other control measure are impractical.

Lemna trisulca appears to produce allelo chemicals that are active against algae (Crombie and Heavers 1994). Mesmar and Abussaud (1991) suggested that extracts of *Lemna minor* were active in inhibiting the growth of *Staphylococcus aureus*.

The role of duckweeds in preventing algal growth can be by shading, by the production of algacides, and in addition, because they lower the nutrient supply, particularly P concentrations either in effluent waters from sewage plants or in water bodies.

Cholera has long been associated with seasonal coastal algal blooms of Bangladesh. Fluorescent antibody techniques have shown that a viable, non cultivatable form of *Vibro cholerae* is present in a wide range of marine life, including algae. In unfavorable conditions, *V. cholerae* assumes spore-like forms which as conditions improve reverts to a readily transmittable and infectious state. Algal blooms which are associated with eutrophication have been related to the spread and persistence of cholera. Prevention of algal blooms may, therefore, be of considerable benefit (Epstein 1993).

10. Conclusion

Thus duckweed culture is an eco-friendly approach of phyto-remediation which will not only help in free-of-cost extraction of nutrients in the form of protein-rich biomass but also bio-remediate the ponds, lakes, and other water bodies and make them a more suitable water resource for aquaculture. Wastewater-duckweed-carp poly-culture makes the perfect integrated package for pollution control and re-use of recovered nutrients. Moreover, in view of increased pressure on land over the years for production of food and fodder (due to ever increasing population, urbanization, industrialization, etc.), utilization of an alternate resource for the purpose makes sense. In this direction, duckweed culture holds ample scope not only for high quality food production through aquaculture but also releasing pressure on the underground water resources.

Acknowledgments

The authors are highly grateful to Dr Ashok K. Chauhan, Founder President and Mr Atul Chauhan, chancellor, Amity University UP, Noida, India for their continuous motivation, encouragement, guidance, and financial support. The authors are thankful to Dr Girish Sharma, professor and coordinator, Amity Centre for Cancer Epidemiology and Cancer Research for critical reading of the manuscript.

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