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Duckweed: The hidden treasure

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Abstract

In recent years, the tiny aquatic angiospermic plants ‘duckweeds’ have become prominent because they provide high protein animal feed, organic fertilizer, bio-fuel; control mosquitoes; and, have great applicability in wastewater purification, toxicity testing, and in basic research and evolutionary model system. In the aforesaid context, this presentation deals in brief with general characteristics, distribution, environmental requirements, aquaculture, and some uses of duckweeds.

Key words**:** Productivity, nutritive value, wastewater treatment.

Introduction

Duckweeds are the smallest, fastest growing, and the simplest flowering aquatic plants which float on or just below the surface of nutrient-rich still or slow moving bodies of fresh and slightly brackish waters. They are monocotyledons belonging to the family Lemnaceae, although they are also classified as the subfamily Lemnoideae within the family Araceae (Sheh-May *et al.* 2004). Duckweed consists of five genera: *Landoltia*, *Lemna*, *Spirodela*, *Wolffia* and *Wolffiella*. However, the most commonly available species belong to the three genera *Lemna*, *Spirodela* and *Wolffia* (Table 1, Figs. 1 and 2). The species of Lemnaceae are found in all possible combinations with each other and other floating plants.

Figure 1. *Lemna aequinoctialis*

Figure 2. *Spirodela polyrhiza*

These plants are very simple, lacking an obvious stem or leaves. The plant body is a few cells thick thalloid frond without any root (*Wolffia*, *Wolffiella*) or may have one (*Lemna*) or more adventitious roots (*Landoltia*, *Spirodela*) devoid of root hairs. The bulk of the frond is composed of chlorenchymatous cells separated by large intercellular spaces that are filled with air and provide buoyancy. Some cells of *Lemna* and *Spirodela* have needle-like raphides composed of calcium oxalate.

Table 1. Duckweeds of the South Asia [modified from Cook (1996)]

Species	Frond	Root	Seed	Habitat and distribution
Lemna aequinoctialis Welwitsch	Flattened (leaf-like), 1-6.5 mm long, 0.8-4.5 mm wide, floating	Solitary, up to 3.5 cm long, root cap sharply pointed	1/fruit, 0.45-0.8 mm long	Eutrophic water bodies like roadside pools, ditches, village ponds, paddy fields, sluggish canals, etc.; often grow together with *Spirodela* and/or *Wolffia*; Pak, Nep, Ban, Mya, SL, Ind (AN, AP, AS, BH, DL, GJ, HP, JH, JK, KL, KT, MH,PJ,RJ,UK,UP, WB)
Lemna gibba L.	Flattened, 4 mm thick, 1-8 mm long, 0.8-6 mm wide, floating	Solitary, >3 mm long, root cap rounded	1-5/ fruit, 0.7-0.9 mm long	Mesotrophic to eutrophic water; Pak, Ind (GJ, JK, PJ)
Lemna minor L.	Flattended, 1-8 mm long, 0.6-5 mm wide, floating	Solitary, >3 mm long, root cap rounded	1/fruit, 0.7-1 mm long	Mesotrphic to eutrophic water; cooler regions of Pak, Nep, Ind (HP, JK, SK, UK)
Lemna tenera S. Kurz	Flattened, 3.5-9 mm long, 1.2-3 mm wide, submerged	Solitary, 2.5 mm long, root cap rounded	-	Humid warm region of Mya
**Lemna trisulca* L.	Flattened, 3-15 mm long, 1-5 mm wide, submerged except when flowering-fruiting	Solitary, 2.5 mm long, root cap pointed	1/ fruit, 0.6-1 mm long	Mesotrophic cooler water (sheltered between emergent reeds); Pak, Ban, Ind (JK, MN, RJ, UK, WB)
**Lemna turionifera* E. Landolt	Flattened, 2 mm thick, 0.8-3.5 mm long, 0.8-3.5 mm wide, floating	Solitary, > 3 cm long, root cap rounded	1/ fruit,, 0.5-0.8 mm long	Temperate regions; Ind (HP, JK)
Spirodela intermedia W. Koch	-	2-5	-	Native of tropical and subtropical South America; introduced in Ind (DL)
Spirodela polyrhiza (L.) Schleiden	Flattened, 1.5-10 mm long, 1.5-8 mm wide, floating	7-21	0.7-1 mm long	Similar to *Lemna acquinoctialis*
Spirodela punctata (G.F.W. Meyer) Thompson	Flattened, 1.5-8 mm long, 1-5 mm wide, floating	2 - 7	0.8-1 mm long	A native from the Southern Hemisphere and East Asia; naturalized in warm regions of Ind (DL, MH, MN, WB)
Wolffia angustata E. Landolt	Boat-shaped, 0.5-0.8 mm long, 0.2-0.4 mm wide, submerged except when flowering - fruiting	-	0.3-0.4 mm long	Eutrophic village ponds; Ind (WB)
Wolffia arrhiza (L.) Horkel	Spherical to ellipsoid, 0.5-1.5 mm long, 0.4-1.2 mm wide, submerged except when flowering,fruiting	-	0.4-0.5 mm long	Cooler water; Ind (JK)
Wolffia globosa (Roxb) den Harto et van der Plas	Ellipsoidal, 0.4-0.8 mm long, 0.3-0.5 mm wide, submerged	-	-	Warm regions; Pak, Nep, Ban, Mya, SL, Ind (AP, AS, BH, CG, DL, GJ, KL, MP, PJ, RJ, TN, UK, UP, WB)
Wolffia	Upper surface suborbicular	-	0.3 mm	Endemic to warmer regions; Pak, Ban,

microscopica (Grif.) S. Kurz	& lower surface tapering downwards, L. 0.4-1 mm, W. 0.3-0.8 mm, submerge except when flowering-fruiting		long	Ind (AP, DL, GJ, HR, TN, UP)
Wolffia neglecta E. Landolt	Boat-shaped, 0.6-0.9 mm long, 0.4-0.6 mm wide, submerged	-	-	Eutrophic water; endemic to Pak, SL, Ind (RJ, WB)
Wolffiella hyalina (Raff.-Del.) Monod	Boat- shaped, 1-3 mm long, 0.8-2 mm wide, submerged except when flowering- fruiting	-	0.3-0.4 mm long	Native of drier regions of Africa; introduced in Ind (Hyd)

(***** = Turion forming species; Pak=Pakistan, Nep=Nepal, Ban=Bangladesh, Mya=Myanmar, SL=Sri Lanka, Ind = India: AN=Andaman and Nicobar, AP=Andhra Pradesh, AS=Assam, BH=Bihar, CJ=Chhattisgarh, DL=Delhi, GJ=Gujarat, HP=Himachal Pradesh, HR=Haryana, Hya=Hyderabad, JH=Jharkhand, JK=Jammu and Kashmir, KL = Kerala, KT = Karanataka, MH = Maharashtra, MN = Manipur, MP = Madhya Pradesh, PJ = Punjab, RJ = Rajasthan, SK = Sikkim, TN = Tamil Nadu, UK = Uttarakhand, UP = Uttar Pradesh, WB = West Bengal)

The vascular bundles in all duckweeds are greatly reduced. The upper epidermis in free-floating duckweeds is highly cutinized and is unwettable. Stomata are on the upper side in all five genera. Anthocyanin pigments similar to that in *Azolla* also form in a number of species of Lemnaceae. Roots of duckweeds are usually short but this depends on species and environmental conditions and varies from a few millimetres up to 14 cm (Leng 1999). Roots either stabilize the plant on the water surface or assist the plant to obtain nutrients where these are in dilute concentrations. They tend to lengthen as mineral nutrients in water are exhausted.

Duckweeds multiply principally through vegetative propagation by the formation of daughter fronds. New or daughter fronds are produced alternatively from two budding pouches on each side of the mother frond in *Spirodela* and *Lemna*. In *Wolffia* and *Wolffiella* only one budding pouch exists. These budding pouches are situated in *Spirodela* or *Lemna* close to where the root arises, whereas in *Wolffia* and *Wolffiella* the solitary budding pouch is located on the narrow end of the mother frond. Newly formed fronds remain attached to the mother frond during the initial growth phase and the plants therefore appear to consist of several fronds. An individual frond may produce as many as 20 daughter fronds during its lifetime, which lasts for a period of 10 days to several weeks. Generally, however, after 6 deliveries of daughter fronds, the mother frond tends to die. Duckweed colonies produced in laboratory or naturally are always spotted with brown dead mother fronds. The daughter frond repeats the history of its mother frond.

Vegetative growth in *Lemna minor* exhibits cycles of senescence and rejuvenation, mediated by chemicals released by the mother frond, under constant nutrient availability and consistent climatic conditions (Ashbey & 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 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. At the same time as a senescence cycle is occurring an apparent rejuvenation cycle, in which the short lived daughter fronds (with half the life span of the early daughters) produce first daughter fronds that are larger than themselves and their daughter fronds are also larger, and this continues until the largest size is produced and senescence starts again. The cyclic nature of a synchronized duckweed mat (all fronds of the same age) could be over at least one month as the life span of fronds from early to late daughters can be 33 or 19 days, respectively with a three-fold difference in frond rate production (Wangermann & Ashbey 1950).

When the aquatic ecosystem dries out or declining temperatures occur, duckweeds have mechanisms to persist until conditions return that can support growth. This occurs through late summer flowering, or the production of turions.

Although sexual reproduction is rare in duckweeds, some species, however, reproduce by producing very small unisexual and monoecious flowers and seeds in an inflorescence. In fact, the flower of the duckweed genus *Wolffia* is the smallest known, measuring merely 0.3 mm long (Landolt 1986). The inflorescence generally consists of one female (pistil) and two male flowers (stamens), but in *Wolffia*, there is one male and one female. The flowers are naked or surrounded by spathe. The fruit is a utricle and the seeds are smooth or ribbed. The seeds are resistant to prolonged desiccation and quickly germinate in favourable conditions.

During the season of short photoperiods or cold nights, newly developing fronds of several species of duckweed get transformed into small brown to olive green orbicular to reniform dormant bodies, called turions. In comparison to normal fronds, turions have shrunken vacuoles, smaller intercellular space, and abundant starch granules. Because the volume of intercellular space shrinks and starch increases the density of tissue, the turion can sink to the bottom of the water body where it can survive even if top of water freezes. Turions sprout under favourable conditions using the stored starch as an energy source to give rise to normal fronds capable of further multiplication. Several species survive at low temperatures without forming turions. During the winter season, their fronds are greatly reduced but remain at the water surface.

Distribution

In Lemnaceace, disseminules are complete fronds or seeds, and their dispersal occurs by water movement or through surface adhesion to waterfowls. Duckweeds are adapted to a wide variety of geographic and climatic zones and are distributed throughout the world except in waterless deserts, permanently frozen polar regions, and extremely wet areas with very high precipitation (Landolt 2006). Most species are found in moderate climates of tropical and subtropical zones. The appearances of duckweed species not previously seen in areas of Europe have been attributed to rising water temperature throughout the world from global warming (Wolff and Landolt 1994). Some duckweed appears to tolerate saline waters but they do not concentrate sodium ions in their growth. The apparent limit for growth appears to be between 0.5 and 2.5% sodium chloride for *Lemna minor* (Leng 1999).

Environmental Requirements

A variety of environmental factors, such as water temperature, pH, nutrient concentration, crowding by overgrowth of the colony, competition from other plants for light and nutrients, etc., control the growth and survivability of duckweeds. Maximum, minimum and optimum requirements of some of the most important environmental parameters (temperature, pH, conductivity, nitrogen and phosphorus) are given in Table 2, whereas a range of other important mineral levels found in water supporting Lemnaceae is presented in Table 3.

Table 2. The most important environmental requirements of duckweed (Hasan & Chakrabarti 2009)

Parameters	Minimum	Maximum	Optimum
Temperature (^{0}C)	> 0	35	15 – 30
pH	3.0	10.0	6.5 – 8.0
Conductivity (µS/cm)	200	1090	-
Nitrogen (mg/l NH_4-N)	Trace	375	7 – 12
Phosphorus (mg/l PO_4-P)	0.017	154	4 – 8

Table 3. Range of other important mineral contents (mg/l) of water supporting Lemnaceae [modified from Landolt (1986)]

Parameters	Absolute range	Range of 95% of the samples
K	0.5 – 100	1.0 – 30
Ca	0.1 – 365	1.0 – 80
Mg	0.1 – 230	0.5 – 50
Na	1.3 - > 1000	2.5 – 300
HCO_3	8 – 500	10.0 – 200
Cl	0.1 – 4650	1.0 – 2000
S	0.03 – 350	1.0 – 200

The effect of temperature on duckweed growth is affected by light intensity, i.e., as light increases, growth rates increase from 10 to 30^0C. Optimum temperature for maximum growth of most duckweed species lies between 17.5 and 30^0C (Culley *et al*. 1981, Gaigher and Short 1986). Although some species can tolerate near freezing temperatures, growth rate declines at low temperature. Below 17^0C some duckweeds show a decreasing rate of growth (Culley *et al.* 1981). Most species seem to die if the water temperature rises above 35^0C.

In general, water pH for aquatic plants is considered excellent between the range 6.5 – 7.5; good between 6 – 6.4 and 7.6 – 8; fair between 5.5 – 5.9 and 8.1 – 8.5; and poor when it is less than 5.5 or more that 8.6 (Stapp and Mitchell 1995). Koirala *et al.* (2011) observed that *S. Polyrhiza* colony survived in pH range of 4 – 7 only when grown alone, but had 2 – 10 range of pH tolerance when grown with *L. aequinoctialis*. Although duckweed survives at pHs between 2 and 10, it grows best only over the range of 6.5 – 8. In this pH range ammonia in water is present largely as the ammonium ion which is the most readily absorbed N form. An alkaline pH (i.e., pH above 8) shifts the ammonium-ammonia balance toward the unionized state and results in the liberation of free ammonia, which is toxic to duckweed at high concentrations (100 mg NH_3/l).

Electrolyte conductivity gives an account of accumulation of salts (primarily chlorides and sulphates of calcium, magnesium, sodium and potassium) in water. Upadhyay *et al.* (2011) reported electrolyte range 24.8 – 184 µS/cm for the occurrence of *L. aequinoctialis* and *S. polyrhiza* in roadside pools at Biratnagar, Nepal. Zutshi and Vass (1973) found *L. gibba* and *L. minor* growing in stagnant waters rich in electrolyte ranging from 400-500 µS/cm. Gopal and Chamanlal (1991) reported the maximum biomass of *L. perpusilla* and *S. polyrhiza* from roadside pools and ditches within a electrolyte conductivity range of 650 – 1000 µS/cm. Khondker *et al.* (1993) recorded the complete disappearance of *S. polyrhiza* by the end of May when a sharp fall in conductivity and alkalinity was observed. The electrolyte conductivity of water supporting the growth of *L. perpusilla* in Bangladesh reported by Islam and Khondker (1991) and Khondker *et al.* (1994) were 625 µS/cm and 200 – 890 µS/cm, respectively. High electrolyte conductivity (1090 µS/cm) of water supporting the growth of *L. perpusilla* was also reported by Van der Does and Klink (1991) in a lemnid habitat in the Netherlands.

One of the most important factors influencing the distribution of aquatic plants is nutrient availability (Hutchinson 1975). Edwards *et al.* (1992) observed that pond water with less than 3 mg/l total kjeldahl nitrogen (TKN) and 0.3 mg/l total phosphorus did not support normal growth of *L. perpusilla* and *S. polyrhiza*. The reason for the comparatively high nutrient demand of free-floating duckweeds 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).

The value of duckweed as a feed resource for domestic animals depends on its crude protein content which seems to increase to a maximum of nearly 40 % dry matter over the range from trace ammonia concentrations to 7-12 mg N/l (Leng *et al.* 1994). Culley *et al.* (1981) reported that the TKN of water should not drop below 20 -30 mg/l if the optimum production and a high crude protein content of duckweed are to be maintained. A useful indicator of whether conditions in the pond are appropriate for growth of duckweed (*Lemna spp.*) of high protein content is the length of the roots as there is a close negative relationship between root length and protein content of the duckweed and with the N content of the water. By monitoring this characteristic, the user can have an indication of the nutritive corrective measures when the length of the roots exceeds about 10 mm (Leng 1999).

Duckweeds prefer ammonium nitrogen (NH_4-N) as a source of nitrogen and will remove it preferentially, even in the presence of relatively high nitrate concentrations. Luond (1980) demonstrated that higher growth rates were attained when nitrogen was in the NH_4-N rather than the NO_3-N form. In organically enriched waters, nitrogen tends to be concentrated in the NH_4-N rather than the NO_3-N form at pH levels below 9 and plant growth is equally efficient in anaerobic and aerobic waters (Said *et al.* 1979). In lagoons receiving organic animal wastes, the pH seldom exceeds 8, particularly with a full duckweed cover that suppresses phytoplankton growth (Culley *et al.* 1978). Urea is a suitable fertilizer and is rapidly converted to NH_4-N under normal conditions.

Phosphorus is essential for rapid growth and is a major limiting nutrient after nitrogen, although its quantitative requirement for maximum growth is generally low. Fast growing duckweed in nutrient rich water is a highly efficient sink for both phosphorus and potassium; little of each, however, is required for rapid growth. Duckweeds appear to concentrate P up to about 1.5 % of their dry weight and as such are able to grow on high P waters provided the N concentrations are maintained. The plant also appears to be able to draw on the pool of P in its biomass for its biochemical activities and once P had been accumulated it will continue to grow on waters devoid of P. Saturation of phosphate uptake by duckweed occurs at available PO_4-P concentrations of 4 to 8 mg/l. Rejmankova (1975) reported good growth of duckweed within the P concentrations of 6 to 154 mg/l. Culley *et al.* (1978), working in dairy waste lagoons, achieved doubled production from 2 to 4 days at P concentrations in excess of 35 mg/l. Reduced growth in some species occurs only when P values drop below 0.017 mg/l (Luond 1980). Although vigorously growing duckweed is a highly efficient K sink, only low concentrations of K in water are needed to support good growth when other mineral requirements are satisfied. Most decaying plant materials would easily produce the K requirements of duckweed.

Most research on nutrient requirements have centred on the need for N, P and K. However, like all plants, duckweeds need an array of trace elements and have well developed mechanisms for concentrating these from dilute sources. From the experience of the Non-Government Organization PRISM (Project in Agriculture, Rural Industry, Science and Medicine) in Bangladesh, it appears that providing trace minerals through the application of crude sea salt (9 kg/ ha/day) is sufficient to ensure good growth rates of duckweeds in ponded systems (Leng 1999).

Aquaculture

Unproductive marginal land along roads and paths or derelict ponds may be suitable choice to cultivate duckweed, as rental or purchase prices for such lands 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 (Iqbal 1999). Long narrow ponds with water depth between 20 and 50 cm are generally recommended to buffer heat, nutrient and pH extremes by dilution, and to facilitate harvesting (Gaigher and Short 1986). Duckweeds are prone to be blown into heaps by heavy winds or wave action. This allows light to penetrate the water column and would stimulate phytoplankton and algal growth. If the plants become piled up in deep layers, however, the lowest layer will be cut off from light and will eventually die (Skillicorn *et al.* 1993). Plants pushed from the water onto a bank will also dry out and die. To counteract this problem, ponds should be sited perpendicular to the common wind. In large ponds and wide canals a floating bamboo or plastic containment grid system is required to prevent the plants from drifting to the shore by the action of wind or water current. The sides of the ponds must preferably be vertical to prevent the plants from becoming stranded and at least 10 cm higher than the water level to accommodate heavy rains. Banana, papaya, lemon, bamboo, etc., planted on the pond embankments can serve as a protection for duckweed from wind and direct sunlight. Besides, the co-crops may generate additional income.

Rainwater collected in ponds may need a balanced NPK application which can be given as inorganic fertilizer or as rotting biomass, manure or polluted water from agriculture, sewage or industry. The ponds must be fed with effluent through furrows rather than pipes because the latter tend to become clogged. Several inlets must be provided to spread the inflowing nutrients over the pond. Urea is a suitable fertilizer, containing approximately 45 % nitrogen, and is rapidly converted to ammonia under normal conditions. Muriate of potash (MP) and triple superphosphate (TSP) each in a ratio to urea of 1 : 5 work satisfactorily as sources of potassium and phosphorus, whereas crude sea salt is used as the source of trace minerals (Skillicorn *et al.* 1993). Application methods of the inorganic fertilizer include broadcasting, dissolving in the water column of the plot, and spraying a fertilizer solution on the duckweed mat.

A fertilizer application matrix aimed to achieve variable daily production ranging from 500 – 1000 kg of fresh duckweed per hectare was developed by Project in Agriculture, Rural Industry, Science and Medicine (PRISM, an NGO) in their experimental programme at Mirzapur, Bangladesh (Table 4). Furthermore, PRISM recommended daily fertilization rates for different types of duckweed (Table 5). The application rate varies from 21 – 28 kg/ha/day (amounting to >7 tonnes/ ha/ year) with an anticipated fresh biomass yield of 900 – 1000 kg/ ha/ day. The daily fertilization rate for duckweed cultivation developed by the Bangladesh Fisheries Research Institute (B F R I) is presented in Table 6. The fertilizer schedules developed by PRISM and BFRI are very similar (Tables 5 and 6), except that BFRI recommended half the dosage of inorganic fertilizer when cow dung was used at the rate of 750 kg/ ha/ day.

Table 4. Daily fertilizer application matrix for duckweed cultivation (Skillicorn *et al.* 1993)

Fertilizer Application (kg/ ha)	Daily production of fresh plants (kg/ ha)					
	500	**600**	**700**	**800**	**900**	**1000**
Urea	10.0	12.0	14.0	16.0	18.0	20.0
TSP	2.0	2.4	2.8	3.2	3.6	4.0
MP	2.0	2.4	2.8	3.2	3.6	4.0
Sea salt	4.5	5.4	6.3	7.2	8.1	9.0

Table 5. Rates of fertilizer application for duckweed cultivation (D W R P 1998)

Duckweed	Rate of application (kg/ ha/ day)		
	Urea	**TSP**	**MP**
Spirodela	20	4	4
Wolffia	15	3	4
Lemna	15	3	3

Table 6. Rates of fertilizer application for duckweed cultivation (B F R I 1997)

Fertilizer combination	Rate of application (kg/ha/day)			
	Urea	**TSP**	**MP**	**Cow dung**
Inorganic fertilizer only	15-20	3-4	3-4	-
Combination of organic- inorganic fertilizer	7.5	1.5	1.5	750

Any waste organic material that is readily biodegradable and has a sufficiently high nutrient content (Table 7) could be used for duckweed cultivation. The most economical sources of such waste materials are all kinds of animal manure, kitchen wastes, wastes from a wide range of food processing plants, biogas effluents, and slaughter house wastes. Solid materials, such as manure from livestock, night soil from villages, or food processing wastes, can also be mixed with water and added to ponds at suitable levels. All wastewater containing manure or night soil must undergo an initial treatment by holding it for a few days in an anaerobic pond, before using it to cultivate duckweed.

Table 7. Moisture, organic and mineral content of some organic wastes expressed in percent dry matter (Gijzen & Khondker 1997)

Nutrient source	Moisture	Dry organic matter	C	N	P_2O_5	K_2O	CaO
Human faecal matter	65-80	88-97	40.55	5-7	3-5.5	1-2.5	4-5
Human urine	93-96	65-85	11-17	15-19	2.5-5	3-4.5	4.5-6
Urban refuse	10-60	25-35	12-17	0.4-0.8	0.2-0.5	0.8-1.5	4-7.5
Water hyacinth compost	85-95	-	-	1.9	1	2.9	4.6
Cow dung (fresh)	85	-	-	0.4	0.02	0.1	-
Cow dung (compost)	-	-	-	0.5	0.3	0.2	0.3
Pig manure (fresh)	80	-	-	0.5	0.5	0.45	-
Poultry (fresh)	-	-	-	1.6	1.5	0.85	-
Digester effluent charged with pig manure	-	6.5	-	3.4	-	-	-

Sutton and Ornes (1975) and Said *et al.* (1979) demonstrated the necessity of periodic additions of nutrients to small duckweed culture systems receiving municipal or dairy cattle wastes. Within 1-3 weeks, there was a noticeable drop in N, P and K within the plants. There was a corresponding drop in crude protein as the plant nitrogen declined. In fact, due to the high nitrogen requirement of duckweed and the relative rapid loss of nitrogen from aquatic system, this nutrient tend to be limiting in ponds fed with wastewater (Gaigher and Short 1986). Large scale duckweed production therefore requires the availability of relatively large quantities of organic waste.

Algal blooms: Light penetration in the water column and subsequent competition for nutrients and space by algae can become a nuisance when the duckweed mat is incomplete due to disturbances or poor growth. Edwards *et al.* (1987) reported that the filamentous green alga *Spirogyra* bloomed in duckweed ponds fed with latrine effluent. The farmers removed the 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.

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.

A study in Thailand revealed that occasional insect infestation by larvae of *Nymphula* (Order Lepidoptera, Family Pyralidae) and/ or by the waterlily aphid *Rhopalosiphum nymphaeae* (Order Homoptera, Family Aphididae) caused heavy damage to duckweed (Edwards *et al.* 1987). Infestation by *Nymphula* was more frequent than by aphids. In one case, *Nymphula* infestation caused the death of plants within two weeks. 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*. However, 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. In this context, Zirschky and Reed (1998) opined that a mixture of several duckweed species would be less susceptible to infestations and diseases than a monoculture.

Relief of heat stress: As aforementioned, duckweed growth rapidly declines at temperatures above 31 to 35^0C, as the plants experience severe heat stress. Relief of heat stress during extremely hot days can be achieved by manual dunking (dipping the duckweed below the water surface) once a day, which is an efficient and immediate way of lowering temperatures by 5 to 10^0C. Dunking consists of agitating the whole-cultivated area by hand until all plants have been physically immersed and wetted.

Productivity: Duckweed growth is largely a function of available nutrients, temperature, light, and degree of crowding. The highest growth rate reported for Lemnaceae under optimal laboratory conditions is about 0.66 generations per day, which corresponds to a doubling time of 16 hours (D W R P 1997). Duckweed generally doubles their mass in 16 hours to 2 days under optimal nutrient availability, sunlight, and water temperature. This result in an exponential growth, at least until the plants become crowded or run out of nutrients. The rate of harvesting duckweed is important since there is a minimum biomass at which yields will decrease and an upper biomass where yield will be limited by crowding, all other variables being equal. In a study where most of the conditions for growth were unlimited, the effect of harvesting indicated that above about 1.2 kg/m^2 duckweed (fresh) growth decreased and below 0.6 kg/m^2 duckweed (fresh) biomass limited growth potential. It appeared that if 1 kg (fresh) duckweed/ m^2 could be maintained by frequent harvesting then an extrapolated yield of 32 tonnes dry matter/ ha/ year could be produced under other non-limiting conditions (Leng *et al.* 1994). In an experimental programme in Bangladesh, a base *Spirodela* density of 600 g/m^2 was shown to yield incremental growth of 50 to 150 g/m^2/day (Skillicorn *et al.* 1993). Culley and Myers (1980) obtained an annual dry weight production of 23.31 tonnes/ha with daily harvesting ranging from 10 to 35% of the standing crop each day, depending on the season. Edwards (1990) recommended 25% harvesting of the duckweed biomass at 1-3 days intervals when duckweed growth completely covers the pond, with the remaining 75% left in the pond for further growth.

Table 8 represents the yields of various duckweed species under different environmental conditions. The value varied widely, ranging from 9 to 38 tonnes dry matter/ha /year. This wide range of productivity may be attributed to differences in species, climatic conditions, nutrient supply and environmental conditions. Many of the reported high yields are based on extrapolated data obtained from short-term growth from small-scale experimental systems rather than potential long-term yields from commercial-sized systems. Edwards (1990) reported extrapolated yields of about 20 tonnes dry matter/ha/year of *Spirodela* from experiments that were carried out for periods of 1-3 months in septage-fed 200 m^2 ponds in Thailand; however, the yield declined to the equivalent of about 9 tonnes dry matter/ha/year over a 6 months period. On the basis of available data (Table 8), Hasan and Chakrabarti (2009) opined that an average annual yield of around 10-20 tonnes dry matter/ha/year can be obtained from an aquatic environment where nutrients are generally not limiting and frequent harvesting is practised to avoid plant overcrowding.

Table 8. Yields of various duckweed species under different environmental conditions

Species	Environmental condition	Yield (dry matter tonnes/ha/year)	Reference
L. minor	Upflow Anaerobic Sludge Blanket Reactor (UASB) effluent	10.7	Vroon & Weller (1995)
L. minor	Nutrient non-limiting water	16.1	Reddy & De Busk (1984)
L. perpusilla	Septage-fed pond	11.2	Edwards *et al.* (1990)
L. perpusilla, S. polyrhiza, & *W. arrhiza*	Septage from septic tank	9.2-21.4	Edwards *et al.* (1992)
Lemna	Domestic wastewater	26.9	Zirschky & Reed (1998)
Lemna	Sugar-mill effluent	32.1	Ogburn & Ogburn (1994)
Lemna, Spirodela & *Wolffia*	Domestic wastewater	13-38	Skillicorn *et al.* (1993)
Lemna & *Wolffia*	Faecally polluted surface water	14-16	Edwards (1987)
S. polyrhiza	Domestic waste water	17-32	Alaerts *et al.* (1996)
S. polyrhiza	Sewage effluent	14.6	Sutton & Ornes (1975)
S. polyrhiza	Nutrient non-limiting water	11.3	Reddy & De Busk (1985)

Harvesting and storage: For shallow ponds, the most simple harvesting techniques include manual skimming of the plants from the pond surface with a net, or moving the floating plants to one corner of the pond with a bamboo pole and removing them with baskets. Two people were reported to require 3.5 hours for manual harvesting of duckweed from a 0.3 ha pond in Taiwan (Iqbal 1999). Large – scale harvesting in industrialized countries is carried out with mechanical harvesting machines requiring, however, deep ponds.

High moisture content of the fresh duckweed increases its handling, transport and drying costs. This fact is less important in integrated systems where fresh duckweed is fed to animals as the only feed or, in combination with other feed components. 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).

The economic potential of duckweeds may not be fully realized until it can be economically reduced to a dried, compact commodity. This requires solar drying and either pelleting, powdering or other potential preservation methods like ensilaging. 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: The entire body of duckweeds is composed of non-structural, metabolically active tissue; most photosynthesis is devoted to the production of protein and nucleic acids, making the plants very high in nutritive value. The nutritional content of duckweed is probably more dependent on the mineral concentrations of the growth medium than on the species or their geographic location (Hasan and Chakrabarti 2009). Water low in nutrients generally results in reduced nutritional content and slow growth in duckweeds.

Compared with most plants, duckweed fronds have little fibre as they do not need to support upright structures. Crude fibre content is generally lower (varying between 7-10%) for duckweeds grown in nutrient-rich water than that grown in nutrient-poor water (11-17%) (Leng *et al.* 1994). Similarly, ash content (that ranges between 12-18% in duckweeds) is also higher in duckweed colonies with slow growth.

Duckweeds are rich source of nitrogen, phosphorus, potassium and calcium (Guha 1997). The concentration of N and P in duckweed tissues depend on the amount of N and P in the water, up to a threshold concentration that has not been clearly defined. Above this threshold, there is little increase in the tissue.

When conditions are good, duckweed contains considerable protein, fat, starch and minerals, which appear to be mobilized for biomass growth when nutrient concentrations in the growth medium fall below the critical levels for growth. The crude protein content of duckweed seems to increase from trace ammonia concentrations to 7-12 mg N/l when crude protein reaches a maximum of about 40 % (Leng *et al.* 1994). Assuming a mean annual yield of 17.6 tonne dry matter/ ha / year, with a protein content of 37% dry weight, a protein production of about 6.5 tonne/ ha / year can be obtained. This per hectare protein yield is far higher than for most other crop plants, and about 10 times that of soyabean (Table 9). 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). Besides, duckweed protein has a better amino acid profile than most plant proteins and more closely resembles animal protein than any other plant proteins. The levels of amino acids are very similar in the various species and all the essential amino acids are generally present.

Table 9. Comparison of protein yields of duckweed and selected crops (Gijzen and Khondker 1997)

Plant / Crop	Yield (tonne dry matter/ha/year)	Crude protein (% dry weight)	Relative protein production*
Duckweed	17.6	37	100
Soyabean	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 tonne dry matter/ ha/ year

The lipid content is lower (1.8-2.5%) in duckweed species grown in nutrient-poor water, while it generally varies between 3-7% for duckweed grown in nutrient-rich water (Hasan & Chakrabarti 2009). Cultured duckweed has high concentrations of trace minerals and pigments, especially β-carotene and xanthophylls (Haustein *et al.* 1988). Duckweeds, however, store varying amounts of calcium as calcium oxalate crystals in the vacuoles. A summary of the nutritional composition of different species grown under different environmental conditions is presented in Table 10.

Use of Biomass

Human consumption: *Wolffia arrhiza* has traditionally been eaten in Myanmar, Laos, and northern Thailand (Bhanthumnavin & McCarry 1971). However, 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 crystallized 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 & Khondker 1997).

Animal feed: Use of duckweed as fish feed is by far the most widespread application. Duckweeds can be fed to fish in fresh form as a sole feed or in combination with other feed ingredients. Duckweeds are also fed as a dried meal ingredient in pelleted diets. Fresh and dried duckweed are fed to grass carp, Nile tilapia, common carp, Indian major carps (rohu and mrigal), silver carp, Java barb, hybrid grass carp and hybrid tilapia.

Fresh duckweeds are fed as a sole feed (*ad libitum* or at restricted level) whereas dried duckweed meal is incorporated by partially replacing other conventional feed ingredients (oil cake, wheat bran, rice bran, etc.) in pelleted diets. *Ad libitum* feeding of fresh duckweed is mostly used for herbivorous fish. Nikolskij and Verigin (1996) reported that grass carp consumed fresh duckweed equal to their body weight over a 24 hour period. Baur and Buck (1980) reported that grass carp consumed from 85% to 238% of their body weight/ day (BW/ day) on a mixed diet of *Lemna*, *Spirodela* and *Wolffia* spp. Shireman *et al.* (1977) recorded consumption rates varying from 7.2-7.4% BW/day on a dry weight basis (DW) while fresh duckweed (*L. minima*) was fed *ad libitum*. Since duckweed contains about 92% moisture, the dry weight feeding rates given above are equivalent to 90-92% BW/day on a fresh weight basis. Hassan and Edwards (1992) studied the effect of feeding rate of *L. perpusilla* on the survival, growth and food conversion rate of Nile tilapia and recorded that the optimal daily feeding rates of *Lemna* were 5, 4 and 3% BW/ day DW for fish of 25-44 g, 45-74 g and 75-100 g, respectively. Though carp polyculture using duckweed as the only feed input is reported to be feasible, there is some evidence that duckweed as a sole feed for fish is a diet too low in fats and carbohydrates. Therefore, for a balanced diet a mixture of 50-60 % (DW) duckweed and 40-45% (DW) fat and carbohydrate-rich feed has been suggested (Iqbal 1999).

Table 10. Chemical analyses of various duckweed species grown under different environment conditions

Duckweed species	Aquatic environment	Mois -ture (%)	Proximite composition[1] (% dry matter)					Minerals (% dry matter)		Reference
			CP	EE	Ash	CF	NFE	Ca	P	
L. aequinoctialis, Nepal	Low-nutrient[2] roadside pool	-	7.1	-	-	-	-	-	0.35	Koirala (2015)
L. gibba, USA	Low-nutrient[2] lagoon	-	9.4	1.8	16.8	17.0	55.5	1.38	0.72	Culley *et al.* (1981)
L. minor, Bangladesh	Pond, nutrient status not specified	92.0	14.0	1.9	12.1	11.1	60.9	-	-	Zaher *et al.* (1995)
L. minor, Bangladesh	Ditch, nutrient status not specified	93.8	20.3-23.5	-	-	-	-	-	-	Majid *et al.* (1992)
S. polyrhiza, USA	Low-nutrient[2] lagoon	-	13.1	2.5	13.3	16.1	55.0	1.21	0.56	Culley *et al.* (1981)
S. polyrhiza, Bangladesh	Ditch, nutrient status not specified	95.0	17.3-28.4	-	-	-	-	-	-	Majid *et al.* (1992)
S. polyrhiza, Nepal	Low-nutrient[2] roadside pool	-	13.3	-	-	-	-	-	0.32	Koirala (2015)
S. punctata, USA	Low-nutrient[2] lagoon	-	10.6	2.3	14.1	11.3	61.7	0.98	0.61	Culley *et al.* (1981)
W. arrhiza, Bangladesh	Ditch, nutrient status not specified	91.2	14.9	-	-	-	-	-	-	Majid *et al.* (1992)
L. gibba, USA	High-nutrient[3] lagoon	-	36.3	6.3	15.5	10.1	31.8	1.81	2.60	Culley *et al.* (1981)
L. gibba, USA	Dairy cattle waste lagoon	-	38.5	3.0	16.4	9.4	32.7	1.00	1.60	Hillman & Culley (1978)
L. minima, USA	Source not specified	-	31.0	2.0	14.0	10.0	42.2	-	-	Shireman *et al.* (1977)
L. perpusilla, Thailand	Septage-fed earthen pond	94 - 94.3	25.3-29.3	3.8-4.5	15.4-17.6	6.9-7.6	-	-	-	Hassan & Edwards(1992)
S. oligorrhiza, USA	Dairy cattle waste lagoon	-	37.8	3.8	12.0	7.3	39.1	1.30	1.50	Hillman & Culley (1978)
S. oligorrhiza, USA	Treated waste water effluent	-	32.7	6.3	20.3	13.5	27.2	1.49	1.15	Culley & Epps (1973)
S. oligorrhiza, USA	Anaerobic swine waste lagoon	-	41.4	5.1	12.9	8.3	32.3	0.91	2.07	Culley & Epps (1973)
S. polyrhiza, Thailand	Septage-fed earthen pond	91.0	23.8	3.8	18.3	11.7	42.4	-	-	Hassan & Edwards (1992)
S. polyrhiza, USA	High-nutrient[3] lagoon	-	39.7	5.3	12.8	9.3	32.9	1.28	2.10	Culley *et al.* (1981)
S. polyrhiza, USA	Dairy cattle waste lagoon	-	40.9	6.7	12.9	8.7	30.8	2.10	1.40	Hillman & Culley (1978)
S. punctata, USA	High-nutrient[3] lagoon	-	36.8	4.8	15.2	9.7	33.5	1.75	1.50	Culley *et al.* (1981)

([1] CP = Crude protein, EE = ether extract, CF = crude fibre, NFE = nitrogen free extract, Ca = Calcium, P = Phosphorus; [2] Low-nutrient water body contained less than 5 mg/l TKN; [3] High-nutrient water body contained more than 30 mg/l TKN)

Haustein *et al.* (1992) reported a reduced meat production and a lower *feed conversion ratios* (g dry duckweed per g animal fresh weight) for pigs fed on duckweed whose protein content amounted to 23% and fibre content to 7.5% dry matter. 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. Further research is needed to show how duckweed can be used as the protein source in diets for pigs. Studies using fresh and dry duckweed and conventional (grain-based) and non-conventional feeds (for example, sugarcane juice or molasses) are urgently needed.

Observations in Bangladesh and Taiwan (Edwards *et al.* 1987) clearly revealed that ducks readily feed on fresh duckweed, often directly from the pond surface. However, chickens are preferably fed on dried duckweed. In general, small ammounts (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). There are reports of an increase in weight by 10-32% for chicken fed with small amounts of duckweed (2-5%) in addition to their regular diet (Iqbal 1999). Shahjahan *et al.* (1981) obtained very good results with a 10% addition of *Spirodela* to a mixed chicken diet.

Duckweeds grown on nutrient-rich waters have the potential to be of high nutritional value particularly for the young or lactating ruminant and preliminary observations suggest that they might form the basis of a supplement to diets based on mature biomass such as crop residues, mature grass or pasture. Rusoff *et al.* (1980) 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. However, Leng *et al.* (1994) 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 is, thereby, minimized. It is likely that duckweed is initially used as a source of essential microbial nutrients to enhance the efficient fermentative digestion of straw in the rumen. Neverthless, feed technology research is needed to enhance the use of duckweed as direct protein source for ruminants.

Organic fertilizer: Duckweed can be used as an organic fertilizer in agriculture by direct land application or via composting. 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 harvest of 4 crops of vegetables or corn, annually.

Biofuel: As mentioned earlier, there are conditions like temperature shifts due to seasons that can cause a morphological change of the normal fronds of several species of duckweed to a different structure, called turions. Turion formation can also be induced by transferring the fresh fronds from a nutrient-rich medium to tap water (Cheng & Stomp 2009), addition of abscisic acid (ABA) in the growth medium (Perry & Byrne 1969), or by " hot day-hot night "treatment of normal fronds of 30^0C photo-temperature and 25^0C dark-temperature and a photoperiod of 16 hours (Perry 1968). Because fronds have little lignin (Blazey & McClure 1968), which would interfere with the digestion of the carbohydrate fraction (which amounts up to 70% in dry weight) of biomass, and turions have high starch content (60.1% in dry mass), duckweed might also be suitable as an alternative source of bioenergy (Wang & Messing 2012). Whereas cellulose is a crystalline, compact and structural compound resistant to biological attack and enzymatic degradation, starch is readily digested. Even though many advances have been made in the commercialization of cellulosic biomass (Gray *et al.* 2006), the cost of producing equal amounts of ethanol from cellulosic biomass is still much higher than production directly from starch (Wyman 2003). Therefore, growing attention is being devoted to use duckweeds as a source of carbon compounds and convert duckweed biomass into bio-ethanol (Cheng & Stomp 2009).

Mosquito control: A positive effect of a duckweed cover on the decrease of mosquito larvae was reported for *S. punctata* (Furlow & Hays 1972), *L. minor* (Angerilli & Beirne 1980), *Wolffia* (Bentley 1910), and *Spirodela* (Culley & Epps 1973). The authors suggested 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 & 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 (Iqbal 1999).

Wastewater Treatment

Solids are relatively easy to remove, what is most difficult to remove from the wastewaters are dissolved salts such as nitrates, phosphates, and other nutrients, and toxic metal ions and organic compounds (xenobiotic pesticides, etc.). In this context, the basic concept of a duckweed wastewater treatment system is to farm local duckweed on the wastewater requiring such treatment. Duckweed systems distinguish themselves from other wastewater treatment mechanisms in that they also produce a valuable, protein-rich biomass as a by-product.

Landolt and Kandeler (1987) reported that of all aquatic plants, duckweeds have the greatest capacity in assimilating the macro-elements N, P, K, Ca, Na and Mg, however, this may not be supported by other literature sources. The data presented in Table 11 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) stated that despite contradictory data, it is an established fact that duckweed has a high nutrient removal efficiency.

Water hyacinth has been widely used for its extremely high nutrient uptake efficiency (Table 11). However, no economically attractive application of the harvested biomass has so far been identified. In addition, water hyacinth only grows efficiently in tropical climates.

Table 11. Daily nitrogen and phosphorus uptake rates by different floating aquatic macrophytes (DeBusk & Reddy 1987, Reddy & DeBusk 1985)

Plant	Uptake (g/ m^2/ day)			
	N		P	
	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. polyrhiza*)	0.15		0.03	

A specific comparison of duckweed with water hyacinth for wastewater treatment and biomass use is presented in Table 12.

Table 12. Comparison between duckweed and water hyacinth for wastewater treatment and biomass use

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 surface area for attached bacteria growth and higher oxygen supply to the root zone. - Treatment of wastewater with very high BOD concentrations(>1000 mg/l)
Removal capacity of organic xenobiotics and heavy metals	High	High
Mosquito control	Positive	Negative
Harvesting	- Easier - Can be done manually 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 (3045%) - Carbohydrate (35%) - Fibre (7-14%) - Fat (3-7%) - High vitamin and mineral content	- Protein (10-25%) - Carbohydrate (35-72%) - Fibre (17-20%) - Fat (1-3%)
Use of biomass	- High quality feed supplement for fish and other animals - Land application - Composting - Methane & ethanol fermentation - Medicinal plant	- Generally not consumed by fish and other animals - Land application - Composting - Biogas digestion - Paper production
Water loss through evapotranspiration (ET)	Lower ET rates compared to open water (20-30% reduction)	Equal or increased ET rates compared to open water

Duckweeds have been generally applied for the treatment of domestic or agricultural wastewaters. However, they may also be applied for the treatment of wastewaters arising from industries like petroleum, paper manufacturing, metal extraction, etc., which often contain toxic substances, notably, heavy metals (defined as elements with density >5 mg/ cm^3 such as cadmium, chromium, copper, lead, mercury, zinc, etc.) and a variety of organic compounds. Lemnaceae can tolerate and accumulate high concentrations of heavy metals and organic compounds at accumulation factors ranging multiples of 10^2 and 10^5 (the accumulation factor for heavy metals being much higher at low metal concentrations). It is therefore, important that the plants are harvested at regular intervals to prevent the metals and organic compounds from settling on the sediments with the decaying duckweed. The duckweed cover or sections of it grown on wastewater contaminated with heavy metals and organic toxins should, under no circumstances be used anymore as animal feed or organic fertilizer, but rather be disposed off as safely as possible in bottom-sealed landfills. Alternatively, heavy metals can be regained from the plant tissues through low temperature caronization.

General Considerations

Duckweeds, the tiny aquatic plants, have a leaf-like body, called frond that performs photosynthesis. Fronds grow vegetatively and can increase biomass rapidly, lowering carbon dioxide in the air and reducing nitrogen and phosphorus in the water. Duckweeds have been fed to animals and fish to complement diets, largely to provide a protein of high biological value. Besides, the dormant phase of some duckweed species, called turions, is rich in starch, a suitable substrate for ethanol production. However, like a hidden treasure, duckweeds are unutilized in Nepal.

The growing awareness of water pollution and its threat to the ecology of a region and agriculture per se has also focussed attention on potential biological mechanisms for cleansing water of these impurities making it potable and available for reuse. There are thousands of derelict ponds polluted to eutrophication levels in Nepal alone that could potentially be cleansed of much of their pollutants and resurrected for duckweed aquaculture and fish farming. To resurrect derelict ponds, the approach might be to first establish duckweed aquaculture as a source of nutrients for terrestrial crop production (for example, mulches and organic fertilizer) and as the ponds' oxygen levels rise with harvesting of the crop, to introduce fish farming either in part of the pond or in adjacent (clean water) ponds.

Duckweeds will remain an unutilized/ underutilized resource unless the farmers are familiar with their economic and environmental values. There is vast need for popularization, market, and research support for the duckweed.

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