Utilization of water hyacinth relevant in water treatment and resource recovery with special reference to India

N. W. Ingole and A. G. Bhole

ABSTRACT

The magnitude of the spread of the water hyacinth (Eichhornia crassipes) makes its extermination, either by physical or chemical methods, a costly and painstaking process. The exercise has to be repeated annually for an indefinite period, a burden that poorer nations are hardly equipped to support. The alternative is to find a use for this plant so that its eradication would entail some financial returns. A variety of studies have been carried out in this direction.

The manifold uses to which the plant has been put include principally: (i) a fertilizer, compost and mulch; (ii) fodder; (iii) a raw material for industry; (iv) a protein source and source for carotene and other chemicals; (v) a pollution control agent; and (vi) biomass for biogas production.

This paper represents a review of the past work on eradication and utilization of water hyacinth relevant in water treatment and resource recovery in the field of environmental engineering with special reference to India.

Key words | BOD, COD, eradication, pollution, utilization, water hyacinth

INTRODUCTION

Water hyacinth (Eichhornia crassipes) is a perennial fresh water aquatic macrophyte (water tolerant vascular plant), with rounded, upright, shiny green leaves and spikes of lavender flowers. Water hyacinth is the most successful colonizer in the plant world, floating in water or partly rooting in mud in shallow waters. It was first described by Karl Van Martin, after he discovered it growing in the Amazon river basin in 1824 (Hasan Zahirul et al. 1989).

The genus Eichhornia was named by Kunth in 1843 in honour of J. A. F. Eichorn, the Prussian Minister of Education at that time, and the nomenclature was later corrected in 1883 by Solmn Laubach to Eichhornia crassipes. There are at least five other distinct species of genus Eichhornia.

At that time, it was believed that hydras were confined to South America and perhaps to Central America and to the larger islands of the Caribbean. Water hyacinth was introduced in India, as an ‘ornamental plant’ at the beginning of the 20th century. It spread rapidly and is now found all over the country. The water hyacinth has been regarded as an expensive nuisance in other countries; Egypt, China, Bangladesh, Australia, Brazil, Pakistan, Philippines, Indonesia and Thailand, to name a few.

NATURE AND MAGNITUDE OF WATER HYACINTH INFESTATION IN INDIA

The nature and magnitude of hyacinth infestation is quite alarming. The trend of aquatic weed infestation from 1965 to 1975 has been highlighted by Biswas (1978). The increased use of manure and fertilizers in agriculture leaves the surface water more enriched with nutrients, helping in the growth of aquatic vegetation. Further, sewage and other wastewater through increased human activities also discharge nutrients useful for aquatic vegetation.
An aquatic weed survey was conducted by the National Committee on Environmental Planning and Coordination, Department of Science and Technology, Government of India, in order to assess the nature and magnitude of aquatic weed infestation. Among the identified weeds, the infestation due to water hyacinth has been reported to be the most troublesome in India (Gopal and Sharma 1981).

The major problems caused by aquatic weed infestation have been identified as:

1. hindrance to fishes
2. choking of flowing water
3. interference with growth of cultivated plants
4. impediment to water transport
5. pollution of water
6. increased loss of water through evapotranspiration
7. interference in hydroelectric power generation and
8. other problems like breeding of insects, etc.

The extent of infestation of water hyacinth or other aquatic weeds is not adequately known. However, from reports it is estimated that about 500,000 ha of water are infested with water hyacinth alone. It is estimated that 40% of the total cultivable water is infested in West Bengal, Orissa, Bihar and Assam. According to Neogi and Raigopal (1949), the water hyacinth infested areas are estimated in Bengal to be about 1.1 million ha.

State-wise infestation

Figures obtained through questionnaires and contacts regarding the widespread infestation show that in the state of Assam, out of 123,000 ha of water consisting of canals, tanks, swamps and fisheries, about 111,000 ha are infested with water hyacinth. Of these, about 34,000 ha are infested to the extent of 25%, and 75,000 ha are heavily infested.

In Manipur, the Loktak lake has been found to be highly infested with water hyacinth. It is estimated that about 10,360 ha are covered with water hyacinth. About 38,850 ha in Andhra Pradesh seem to be under the grip of water hyacinth infestation (Status Report on Water Hyacinth in India, 1979). According to Ramachandran et al. (1973) on the aquatic weed infestation in Andhra Pradesh, out of 19 districts surveyed, 5 districts had more than 60% of water bodies infested. These districts are East and West Godavaris, Nellore, Visakhapatnam and Khammam; while in Krishna, Srikakulam, Anantapur, Nalgonda and Kurnool districts the infestation was between 2 and 11%.

In Kerala the problem is different. The wetland surrounding the Vembanad Lake is the rice bowl of Kerala, spreading over approximately 40,000 ha. This area is heavily infested with Salvinia (Unni 1978). This weed has succeeded in eliminating Pistia stratiotes and even water hyacinth to some extent. While Salvinia, known locally as ‘African Payal’, is a major infestation, water hyacinth is quite abundant in the wetland and neglected ponds (Unni 1978). From a study carried out by Maley and Thakur (1973) to assess the extent and type of aquatic weed infestation near Jabalpur in Madhya Pradesh, it was found that most of the ponds and rice fields were infested with aquatic weeds. In 50% of the tanks, the entire water surface was covered with weeds, while the remaining tanks had a minimum of 25% infestation. Water hyacinth was the most dominating type, causing over 80% infestation.

An anonymous report (1950) stated that in the state of Rajasthan, long stretches of Chambal irrigation canals were infested with submerged waterweeds, causing diminished thoroughfare of water. Water hyacinth infestation has been reported from 14 out of the 26 districts surveyed in Rajasthan. In certain parts of country, the menace due to water hyacinth is considered negligible. Except for some southern districts, where the infestation is negligible, the state of Gujrat is free from water hyacinth infestation. Similarly, no record of water hyacinth infestation has been observed in Jammu and Kashmir. The presence of water hyacinth in Punjab is seasonal, with more infestation in summer. During the winter it remains dormant and reappears in spring. However, water hyacinth infestation is not serious in this area.

UTILIZATION OF WATER HYACINTH

The biggest handicap in the eradication of aquatic weed is the cost factor. A rational eradication programme should
consider the utilization of weed to recover the expenditure involved. Based on the chemical composition of water hyacinth, several utilization schemes have been suggested for it. The chemical composition of water hyacinth (Status report on water hyacinth in India, 1979) is given in Table 1. According to Shrivastava et al. (1985) the dry weight composition of water hyacinth plants removed from the wastewater system is as given in Table 2.

Water hyacinth can be utilized for various purposes:

1. as manure
2. as animal feed
3. for paper board and cellulose
4. for protein and other useful substances
5. in pollution control
6. for biogas production.

### MANURE

The high ash content of water hyacinth has led many workers to use the ash for manure. As early as 1917, Finlow and McLean (1917) suggested its use for manure. About 17,000 t of water hyacinth were collected and from this, 170 t of ash were extracted and sold. The ash from a dried biomass of water hyacinth contains approximately 30% potash, 7% phosphoric acid and 13% lime. This can be used as a muriate of potash. The ash obtained from larger plants is reported to contain 34–35% potash.

Another profitable and practicable way of utilizing water hyacinth is by converting it into compost (Biswas 1978). A comparative chemical composition of compost manure obtained from town compost, farmyard compost and water hyacinth compost is given in Table 3 (Status report on water hyacinth in India, 1979).

The compost obtained from water hyacinth is gaining popularity, as it is superior to the two mentioned above. Watson (1947) suggested the use of wilted water hyacinth, rather than fresh, for compost making. According to the field trials carried out with rotted water hyacinth and ash on crops like jute and paddy, they were found to have excellent manurai value. The authors also suggest the Indore method of hyacinth composting, in which well-wilted hyacinth plants and vegetable refuse along with

| Table 1 | Chemical composition of water hyacinth
<table>
<thead>
<tr>
<th>S. No</th>
<th>Parameters</th>
<th>Fresh plants (g %)</th>
<th>Dry plants (g %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Moisture</td>
<td>92–95</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>Organic matter</td>
<td>1.0–3.5</td>
<td>24–30</td>
</tr>
<tr>
<td>3</td>
<td>Nitrogen</td>
<td>0.04–0.1</td>
<td>1.5–2.0</td>
</tr>
<tr>
<td>4</td>
<td>Ash</td>
<td>1.0–1.25</td>
<td>17–20</td>
</tr>
<tr>
<td>5</td>
<td>Phosphorus</td>
<td>—</td>
<td>0.4–0.5</td>
</tr>
<tr>
<td>6</td>
<td>Calcium</td>
<td>—</td>
<td>1.0</td>
</tr>
<tr>
<td>7</td>
<td>Magnesium</td>
<td>—</td>
<td>1.0</td>
</tr>
<tr>
<td>8</td>
<td>Potassium</td>
<td>—</td>
<td>4.0–5.0</td>
</tr>
</tbody>
</table>

| Table 2 | Composition of water hyacinth (dry basis)
<table>
<thead>
<tr>
<th>Constituents</th>
<th>Weight in percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash</td>
<td>15.00</td>
</tr>
<tr>
<td>Protein</td>
<td>22.00</td>
</tr>
<tr>
<td>Cellulose</td>
<td>21.20</td>
</tr>
<tr>
<td>Hemi-cellulose</td>
<td>35.80</td>
</tr>
<tr>
<td>Lignin</td>
<td>6.00</td>
</tr>
<tr>
<td>Lipids</td>
<td>2.00</td>
</tr>
</tbody>
</table>

| Table 3 | Chemical composition of compost manure (all values in percentages)
<table>
<thead>
<tr>
<th>Chemicals</th>
<th>Water hyacinth compost</th>
<th>Town compost</th>
<th>Farmyard compost</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>2.05</td>
<td>1.00</td>
<td>0.5</td>
</tr>
<tr>
<td>P&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;5&lt;/sub&gt;</td>
<td>1.10</td>
<td>1.00</td>
<td>0.25</td>
</tr>
<tr>
<td>K&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>2.50</td>
<td>0.80</td>
<td>0.30</td>
</tr>
<tr>
<td>CaO</td>
<td>3.91</td>
<td>5.00–5.00</td>
<td>0.20</td>
</tr>
<tr>
<td>C/N</td>
<td>13.00</td>
<td>10.00</td>
<td>12.00–13.00</td>
</tr>
</tbody>
</table>
fresh manure, wood ash or finely powdered earth are put into a heap. The temperature generated within the heap due to fermentation of the material kills all parasites and seeds, and the compost is matured within three months.

**ANIMAL FEED**

Investigation of the utilization of water hyacinth as cattle feed was taken up in India during 1923–24. Later on the Animal Nutrition Section, West Bengal, started investigations on the digestion and metabolic aspects of water hyacinth in certain districts of Bengal where cattle are known to feed on the plants. From the data available in the ‘Status Report on Water Hyacinth in India, 1979’, water hyacinth contains 6.54% crude protein, 27.76% crude fibre, 50.59% nitrogen free extract, 1.7% ether extract and 16.43% total ash. The corresponding figures for Napier grass are 5.35%, 31.9%, 44.1%, 1.98% and 16.70%, respectively. This shows that water hyacinth is richer than Napier grass in crude protein. Nevertheless, an exceptionally high content of potash and chlorine in water hyacinth probably makes it less palatable, and affects the general mineral metabolism. Some workers suggested a moderate use of hyacinth as fodder, and recommend the use of the plant in combination with other feed to get better results. Feeding water hyacinth to cattle and farm animals has been proposed. No doubt this is a very promising use of aquatic weeds like water hyacinth. While considering the use of water hyacinth as feed, the following considerations have to be taken into account:

1. the digestibility of proteins and carbohydrates
2. acceptability and palatability
3. toxic constituents present in the weed
4. effect on the growth rate and the long-term effect on the animals.

**PAPER, BOARD AND CELLULOSE**

The possibility of using water hyacinth for the manufacture of paper, board and other cellulose-based products was tested earlier. Srivastava et al. (1985) discovered that the lignocellulosic group is present in water hyacinth. The yield of lignin and cellulose in water hyacinth on a dry basis has been found to be 6% and 21.2%, respectively. According to Deshpande et al. (1999), one of the major factors contributing to high enzyme cost is the cost of substrate. The pure substrate such as cotton, solka floc and sulphite pulp used at present for cellulose production, contributes around 48–52% of the overall cost of cellulose production. Cellulose from aquatic weed works out cheaper compared with this substrate. In addition, they suggested that the water hyacinth residue left after cellulose production could serve as a fertilizer and soil conditioner because of its nitrogen and nutrient content. The integrated approach of utilizing the weed for cellulose production and using the residue generated in the process as biofertilizer and biocontrol agent will change the status of this weed from a persistent pest to a real potential provider. Saikia et al. (1986) report the possibility of making paper and boards. According to them green leaves along with a stack constituent of 40% are suitable in papermaking. The shrinkage property of unbleached paper is rather high. However, this can be minimized by careful bleaching and by an addition of about 10% of waste paper or any other fibre such as bamboo, jute or rags. The fibre length and strength characteristic indicates that good quality paper can be made from water hyacinth. The tensile and brushing strengths are comparable to those prepared from some conventional raw materials.

**PROTEIN AND OTHER USEFUL SUBSTANCES**

The use of water hyacinth as a source of protein, carotene and vitamin A has been reported by Sharma Archana (1971). The medicinal value of the plant has also been investigated by researchers. Pirie found that protein from water hyacinth could be extracted easily. On a dry basis, the whole plant contains about 15% protein and the roots and leaves contain 12% and 50%, respectively. Datta et al. (1966) reported a method of extraction of protein from the leaves of water hyacinth. In that process, the leaves of
water hyacinth are crushed and the mass is mixed with three times its weight of 2% Na₂CO₃ for 30 min to extract the protein. The filtrate is separated from the fibrous material by centrifugation. The filtrate, when treated with HCl (pH 3.5–3.8), followed by heating, results in 96% precipitation of protein. Drying the protein becomes easier if moist materials are washed with alcohol. Water-extracted protein contains 30–40% alcohol ether extractable material (lipids). Acetone has proved to be the best solvent for removing colour and odour.

Neogi and Rajgopal (1949) reported a method for production of carotene concentrate from water hyacinth. The yield ranged from 134.6 to 146.7 mg/3 kg of water hyacinth and the recovery achieved varied from 84 to 87.9%. Ingole and Bhole (2001) concluded in their laboratory study that carotene is efficiently isolated using a chromatographic column of calcium hydroxide, waste lime and alumina, and the recovery of carotene was found to be 95–96% when the extraction was carried out in benzene for 2 h.

Ganguly and Sirkar (1964) extracted and partially purified an auxin from *Eichhornia crassipes* roots with chilled alcohol. The effects of the auxin on cell elongation, division and changes in the sugar and nitrogen content of pea seedlings have been also reported. The medicinal value of water hyacinth to prevent and cure goitre has been investigated (Anon 1974).

**POLLUTION CONTROL**

One of the serious problems in the wake of industrialization is pollution. Large quantities of materials present in industrial waste and municipal effluent pollute lakes and rivers enhancing algal, bacterial and plant growth and interfering with the uses of natural water. To overcome this problem, attention is being given in advanced countries to culturing certain aquatic vegetation in polluted waters, which can absorb various pollutants from the water and thereby reduce pollution. The aquatic weed can be occasionally harvested and can be put to some uses. Extensive research is being carried out in countries like the USA for stripping out nutrients from sewage, effluent and natural water by cultivating aquatic vascular plants.

Water hyacinth systems are capable of removing high levels of biochemical oxygen demand (BOD), suspended solids (SS), metals, nitrogen and significant levels of trace organics. The treatment concept has been developed through extensive laboratory and pilot research as well as evaluation of full-scale facilities. Hyacinths can be used to upgrade existing systems, or to produce secondary, advanced secondary or tertiary effluents, depending on design loading rates and management practices used (Status Report on Water Hyacinth in India, 1979).

Hyacinths on the water surface of a pond create a totally different environmental condition in the water, compared with an exposed water surface. The dense canopy of leaves covers the surface and prevents algal growth. This in turn maintains the liquid pH at a neutral level. The mass of plants on the surface also minimizes wind-induced turbulence and mixing, as well as surface re-aeration, and moderates water temperature fluctuations. Consequently, the near surface water has low dissolved oxygen and the benthic zone is usually anaerobic even in shallow ponds.

The plants can survive and grow in anaerobic waters, since oxygen is transmitted from the leaves to the root mass. The attached biological growth of the root mass is similar to that of a trickling filter but, in this case, the oxygen source (from the roots) is near the centre of mass, rather than outside. Bacteria, fungi, predators, filter feeders and detritivores have been reported in large numbers on the plant roots. The following criteria have been identified over the years for selecting a plant species or combination of species as the main bioagent(s) in water treatment systems (Abbasi et al. 2000):

1. adaptability to local climate
2. high photosynthetic rates; in other words high growth rate
3. high oxygen transport capability
4. tolerance to adverse concentration of pollutants
5. high pollutant uptake efficiency
6. tolerance to adverse climatic conditions
7. resistance to pests and diseases
8. ease of management
The various types of pollution removal qualities of the water hyacinth system can be studied under the following headings:

**BOD removal**

The removal of BOD in the hyacinth pond is caused by the same factor as in the conventional stabilization ponds. Further, very significant treatment contribution can be ascribed to the attached growth on the plant roots. The efficiency of BOD removal will be directly related to the density of plant cover and the depth of water in the system. At a water depth of 1–2 m, a BOD loading of about $6.7 \times 10^{-4}$ kg kg$^{-1}$ plant mass per day has been recommended by Wolverton and McDonald (1979), when facultative pond effluent is applied to a hyacinth cell. Aowal and Singh (1981) reported the growing of water hyacinth in Vanaspati Ghee Manufacturing Plant effluent under laboratory conditions for a period of 7 days. They found that by mixing sewage at a ratio of 1:100 with the effluent and growing hyacinth thereon, the removal efficiency could be further improved (without mixing the removal efficiency was 97%). Gudekar and Trivedi (1987) used water hyacinth treatment on waste collected from Kirloskar Brothers Ltd factory in Karad in various dilution ratios and reported that at 50% dilution, the maximum reduction in BOD was 90.42%. Debusk et al. (1983) and Pradeepkumar et al. (1981) reported 87% and 100% BOD removal in domestic waste by water hyacinth in a 5 day period.

A pilot study by Saxena (1991) to study the feasibility of upgrading the Wimco Match Factory waste with the concept of treatment by aquatic macrophytes found that the performance with respect to BOD was reasonably good, i.e. 79.62%. A batch study performed by Ingole and Bhole (1999) for different industrial and domestic wastes observed that water hyacinth was very effective in removing the BOD in domestic waste by up to 95.66% followed by industrial waste.

**Nitrogen removal**

Plant uptake, ammonia volatilization and nitrification/denitrification all contribute to nitrogen removal in the hyacinth system (Debusk et al. 1983). Plant uptake with plant harvest can be an important removal pathway, but nitrogen removal far in excess of plant uptake levels has been observed in a number of systems. A typical plant growth rate of about 220 kg ha$^{-1}$ day$^{-1}$ (dry weight) would remove about 10 kg ha$^{-1}$ day$^{-1}$ of nitrogen. Debusk et al. (1983) evaluated nitrogen and phosphorus in the wastewater treatment system by water hyacinth in South Florida. The treatment system considered four ponds (0.1 ha each) from which plants were harvested and one (0.2 ha) from which the plants were not harvested. Nitrogen and phosphorus were removed in the plant standing crops at higher rates in the harvested ponds, i.e. 362 mg m$^{-2}$ day$^{-1}$ and 115 mg m$^{-2}$ day$^{-1}$, respectively. However, immobilization of nitrogen and phosphorus as plant detritus in the sediments was lower in the harvested ponds (3% and 1% of standing crop assimilation, respectively) than in non-harvested plants (33% and 13% of standing crops assimilation). Denitrification accounted for 92% of the nitrogen removed from the non-harvested pond. On an areal basis, approximately 2.5 times more nitrogen was removed by denitrification in the non-harvested ponds than was assimilated by water hyacinth growth in harvested ponds (875 mg N m$^{-2}$ day$^{-1}$ versus 362 mg N m$^{-2}$ day$^{-1}$). Mean total nitrogen removal from the complete system resulted in an 87% reduction from 9.96 mg l$^{-1}$ to 1.25 mg l$^{-1}$.

Wolverton & McDonald (1975) suggested that if treatment was given to the wastewater, mainly domestic sewage, up to 60% of the nitrogen would be removed in 5 weeks. Debusk & Reddy (1985) reported that water hyacinth showed the highest nitrogen removal efficiency in the summer months.

Mosse and Megalhaes (1985) reported that there was a 49.64%, 37.89% and 36.79% reduction in nitrate-nitrogen, TKN and total phosphorus, respectively, in the presence of water hyacinth in the case of domestic waste.

**Phosphorus removal**

The only significant removal pathway for phosphorus is plant uptake, and that will usually not exceed 30–50% of the phosphorus present in typical municipal wastewater.
The removal does not even approach that range, unless there is a careful vegetation management programme, involving frequent harvest. Maximum plant uptake of phosphorus may also require supplemental nitrogen fertilization, since the ratio of nitrogen to phosphorus in typical wastewater is significantly different from the balance required by the hyacinth plants (N:P = 6:1). As a result, there may be a nitrogen deficiency in the final basin of the water hyacinth system and these plants cannot use the available phosphorus without additional nitrogen. According to Stowell Rich et al. (1981), phosphorus removal rate and effluent concentration of aquatic systems have not been consistent. Generally, phosphorus removal rate is less than 2 kg ha\(^{-1}\) day\(^{-1}\) during the summer months and decreases during the winter months when release of phosphorus to the wastewater (instead of removal) is not uncommon. Though the phosphorus removal mechanism and storage compartment in aquatic systems have been identified, the significance of each of these facets in the removal and storage of phosphorus in aquatic systems has not been determined.

A comprehensive observational study of phosphorus removal in an ‘advanced’ hyacinth system consisting of five ponds in series was conducted by Coral Spring Properties. Significant phosphorus reductions occurred only in the first pond; but this phosphorus removal cannot be attributed to simple sedimentation of solids because influent SS concentrations were very low. Once the total nitrogen concentration was below approximately 1 mg l\(^{-1}\) (which also occurred in first pond), further reduction in phosphorus concentration was insignificant. Although both nitrogen and phosphorus removal could be caused by the physical/chemical condition present only in the first aquatic processing unit (APU) but absent in the secondary clarifier, an equally reasonable hypothesis is that some type of biological activities requiring both nutrients has a significant effect on the removal of phosphorus. This biological activity is not water hyacinth growth because this mechanism could not account for the quantities of nutrient removed, and hyacinth grew very well in later APUs of the Coral Spring System without decreasing the phosphorus concentration appreciably. For the phosphorus removal of an aquatic system to be predicted, either empirically or theoretically, predesign pilot-scale studies will be necessary.

Debusk et al. (1983) evaluated the importance of water hyacinth plant material (living or detritus) as a sink for nitrogen and phosphorus in a waste treatment system in Florida. The treatment system consisted of four ponds (0.1 ha each) from which plants were harvested and one pond (0.2 ha) from which plants were not harvested. Nitrogen and phosphorus were removed in the plant standing crops at higher rates in the harvested ponds (362 and 115 mg m\(^{-2}\) day\(^{-1}\), respectively) than in the non-harvested pond (55 and 15 mg m\(^{-2}\) day\(^{-1}\), respectively). However, immobilization of nitrogen and phosphorus as plant detritus in the sediment was lower in the harvested ponds (3 and 1% of standing crop assimilation, respectively) than in the non-harvested pond (33 and 13% of standing crop assimilation).

**Metal removal**

Hyacinth systems are capable of a high level of metal removal. Plant uptake can be significant, the principal mechanisms are believed to be chemical precipitation and adsorption on substrate and on plant surfaces. The mature plants begin to slough root materials; so any adsorbed material will then become part of the detritus or benthic sludge. In a study in Texas (Dinges 1978) it was observed that hyacinths accumulate chlorides, phosphorus, magnesium, chromium, mercury, iron, lead, nickel, copper, magnesium and manganese, among other minerals, from basin water during the active generation period. Plant tissue contained large amount of chloride, potassium, magnesium and phosphorus.

Trivedi and Jog (1993) used a hyacinth treatment for electroplating industry waste and reported a reduction of chromium, nickel and zinc of 79%, 90% and 89%, respectively. In plant analysis, it is observed that roots absorb as much as 1,294 mg nickel and 218 mg chromium per 100 g of plant sample.

The pollutant removal efficiency of water hyacinth plants in batch treatment of Calcutta City sewage was studied by Nath et al. (1983). In their study the observed percentage reduction of different heavy metals for a 3-day detention period were:
• iron 96.33%
• manganese 82.5%
• chromium 32%
• cadmium 78%
• copper 90%

Omprakash et al. (1987) also used a batch type treatment for a synthetic sample and reported that the percentage cadmium removal is a function of time. From their study, it is clear that the percentage removal of cadmium (II) is initially very fast and that finally 82–92% of cadmium (II) was removed in 16 days. The detention period depended on the initial concentration of cadmium in the solution.

Wolverton and MacDonald (1975) conducted a study on the removal of cobalt, silver and strontium by using water hyacinth. He used a batch type treatment for diluted wastewater with different metal concentrations. Based on his experiments, he reported that hyacinths are capable of removing 0.439 mg of silver per g dry plant weight and 0.568 mg of strontium per g dry plant weight.

Chigbo et al. (1982) studied water hyacinth as a pollution monitor for the simultaneous accumulation of arsenic, cadmium, lead and mercury. After cultivation of plants for 2 days in tanks containing 10 ppm of each of the metals in aqueous solution, the plants were harvested and rinsed with tap water. The leaves and stems were separated and analysed for each of the metals. The ratio of concentrations of arsenic and mercury in the leaves to the concentrations in the stem was found to be 2:1. Cadmium and lead showed a concentration ratio in leaves to stem of about 1:1. The leaf concentration of arsenic was the lowest among the metals at 0.3428 mg g⁻¹ dried plant material while the leaf concentration of cadmium was highest at 0.5740 mg g⁻¹ dried plant material. Control plants were grown in unpolluted water. Plants grown in Bay St Louis, Mississippi, sewage lagoons were also analysed. The mercury concentration of leaves of plants grown in the sewage lagoon were significantly different from the control sample, which had a concentration of 0.0700 mg g⁻¹ dried plant material.

Selvapathy and Shubhash Babu (1995) concluded the following from their study. That duckweed (Lemna minor) is a simple, small, floating aquatic plant. It has the ability to absorb heavy metals. Removal of heavy metals such as cadmium, copper, manganese, nickel and zinc from wastewater by duckweed for different initial concentrations of 5, 10, 20, 50 mg l⁻¹ for a detention period of 10 days was observed. Efficiency of removal was determined when each metal was present separately, as well as when all five metals were present together. Results indicated that, at lower concentrations, the plant growth was normal and removal efficiencies were higher. At higher concentrations, leaves started wilting and removal efficiencies were lower. Finally, it was concluded that, using duckweed, the heavy metals can be effectively removed from wastewater when their concentration is lower than 20 mg l⁻¹.

Panda (1996) compared another commonly available weed, water lettuce (Pistia stratiotes), with water hyacinth for removing nickel and zinc from simulated contaminated aquatic systems. It was observed that at up to 25 ppm of nickel treatment, the general health conditions of both plants were normal until the end of the seventh detention day. Beyond this concentration, plants started wilting, leading to death. Similar observations were made in the case of zinc treatment up to 75 ppm. A plant appears healthy until the seventh day in the case of mixed metal treatment up to a concentration of 25 ppm of each metal. The plants showed uptake of nickel of 5.35 and 7.85 mg g⁻¹ dry plant tissue by water hyacinth and water lettuce, respectively. Both plants showed a higher absorption capacity for zinc. An uptake of 14.42 mg zinc g⁻¹ dry plant tissue by water hyacinth and 18.04 mg zinc g⁻¹ dry plant tissue by water lettuce was observed. It was concluded that the effect of both nickel and zinc on water hyacinth and water lettuce was that both plants survived up to 25 ppm of nickel and zinc present together. The result also reveals that zinc is preferentially absorbed by both plants. However, water lettuce is the better option for effluent treatment than water hyacinth. A similar methodology was described by Singaram (1994) for the removal of chromium using water hyacinth, pseudo water hyacinth and Lemna minor.

Ingole and Bhole (2000a, b) performed a batch study on a synthetic sample to study bioaccumulation of heavy metals such as arsenic, mercury, lead, chromium, zinc and nickel. An examination of Table 4 shows that the maximum uptake of arsenic, chromium, mercury, nickel,
lead and zinc was 0.0309 mg g$^{-1}$, 0.087 mg g$^{-1}$, 0.0315 mg g$^{-1}$, 0.753 mg g$^{-1}$, 0.107 mg g$^{-1}$ and 2.270 mg g$^{-1}$ dry plant tissue, respectively, by water hyacinth. The mass of metal per plant mass increased with higher aqueous concentration of nickel, lead and zinc. No trend was seen for chromium and mercury. No apparent significant difference was noted for arsenic.

### Table 4 | Removal of heavy metals by water hyacinth

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Metal</th>
<th>Treated metal concentration (mg l$^{-1}$)</th>
<th>Metal concentration in dry plant tissues (mg g$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Arsenic</td>
<td>5</td>
<td>0.0266</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>0.0267</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>0.0309</td>
</tr>
<tr>
<td>2</td>
<td>Chromium</td>
<td>5</td>
<td>0.1080</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>0.1570</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>0.0610</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>0.0870</td>
</tr>
<tr>
<td>3</td>
<td>Mercury</td>
<td>5</td>
<td>0.0327</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>0.0250</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>0.0315</td>
</tr>
<tr>
<td>4</td>
<td>Nickel</td>
<td>5</td>
<td>0.2230</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>0.3550</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>0.4570</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>0.5960</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25</td>
<td>0.7530</td>
</tr>
<tr>
<td>5</td>
<td>Lead</td>
<td>5</td>
<td>0.0456</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>0.0520</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>0.1070</td>
</tr>
<tr>
<td>6</td>
<td>Zinc</td>
<td>5</td>
<td>0.1830</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>0.4890</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>0.6190</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>0.7460</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25</td>
<td>1.1090</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>2.2700</td>
</tr>
</tbody>
</table>

**BIOGAS PRODUCTION**

Biogas is a mixture of methane and carbon dioxide produced as a result of the anaerobic decomposition of organic matter. Sen & Chatterjee (1931) studied the possibility of using dried water hyacinth for generation of biogas and power alcohol. Sen reports that the green plant contains 0.018% starch, which is lost through photochemical decomposition on drying. This can be utilized by bacterial fermentation, and the gas produced after fermentation can be used for power production.

The high content of water (95% in the green plant) adds considerably to the cost of transport and drying the plant, which impedes its utilization as an industrial raw material. However, in recent years in view of food crises, energy shortages and environmental pollution, biogas technology has attracted worldwide attention. Low cost technology is ideally suited to the developing countries, for providing fuel, electricity and high-grade manure, besides maintaining sanitation in villages. In India, much attention has been paid to the development of a programme. With a view to meeting the increasing demand for organic manure and to provide cheap fuel it is proposed to install five lakhs (500,000) gas plant in the 6th Five-Year Plan in India. This will create an annual production capacity of 1,176 million m$^3$ of gas, equivalent to 750 million l of kerosene, besides producing 12 million t of organic manure (Anon 1978).

The possibilities of utilizing water hyacinth in biogas digesters have been examined in the Central Mechanical Engineering Research Institute, Durgapur (India). It has been found that water hyacinth containing 60–70% moisture is fermented quickly. According to their process, the stem is ruptured to get rid of the extra moisture in a shorter time. Under optimum conditions, the fermentation starts within 2–3 days. A usable quality of gas is obtained after only 15–20 days. The calorific value of the gas...
increases after this period and reaches a peak value of 4,397–4,670 Kcal/m³ BTU/CFT after 20 days at 30–35°C. A retention time of 40–50 days is recommended for economic usage. The calorific value of gas increased to 5,413 Kcal/m³ after the second charging. It is estimated that 100 kg of semi-dried water hyacinth can give 400 l of gas daily. The compost obtained as a by-product has a high manure value. Average compost yield is about 10% of the weight of plant used (Status Report on hyacinth in India, 1979). A review of the work on biogas production has been summarized below.

Ingole and Bhole (2000c, d) attempted methane recovery from powdered water hyacinth by using single phasic, diphasic and triphasic anaerobic digestion processes and observed that the yield of biogas can be increased by adopting a modified triphasic digestion process. Day to day performance of digesters is shown in Figure 1. From the results, it can be inferred that the triphasic digestion process gives a maximum gas yield of 124.2 l kg⁻¹ of dried water hyacinth as against 25 l kg⁻¹ of wet water hyacinth (Gole et al. 1985) and 100 l day⁻¹ kg⁻¹ of dried water hyacinth (Sankis Malvyn 1983) and 20 l kg⁻¹ of dried water hyacinth from conventional biogas technology at Khadi and Village Industries Commission (KVIC). As the gas production from dried water hyacinth plants by the triphasic digestion process is greater than from the single phasic and diphasic processes, the modified process proves also to be more efficient and economical. On the basis of volatile solids destruction the maximum rate of gas production is found to be 0.273 m⁻³ kg⁻¹ of volatile solids destroyed and 0.210 m⁻³ kg⁻¹ of volatile solids added. The percentage of methane in the gas produced varied between 68% and 73% when tested on Orsat apparatus. Thus, biogas produced from dried water hyacinth plants by the triphasic digestion process has better fuel value.

The authors also studied the effect of activators, inhibitors and temperature on biogas production from water hyacinth (Ingle and Bhole 2000d, 2001b). It was concluded that ammonium sulphate was the best activator, giving a maximum gas yield of 107.52 l kg⁻¹ dried water hyacinth powder followed by ammonium chloride and urea, yielding 68.1 l and 49.11 l kg⁻¹. In the control digester without activator, the maximum gas yield was found to be 38.21 kg⁻¹ dried water hyacinth powder, which was comparatively less than the yield of gas using activators as shown in Figure 2. From the results, it was observed that a small quantity of activator increases the gas yield by a great extent, so use of the activator, preferably ammonium sulphate, in a small quantity to increase the quantity of biogas from water hyacinth was recommended.

The effect of temperature on biogas production from water hyacinth has also been studied and the effect on the yield of gas is shown in Figure 3. In this study, the optimum temperature for biogas production was observed to be 35°C.

During the course of study, four inhibitors, namely copper (fed as cupric chloride), nickel (fed as nickel...
chloride), phenol and sodium chloride (NaCl) were used to determine their inhibitory concentrations. Toxicity data is usually presented with reference to a control unit. The performance of a unit containing added quantities of the substance under study is compared with the performance of a control unit. Invariably, the control unit is one that exhibits satisfactory biological activities and to which none of the substance under study has been added.

The inhibition study in each case was started only after stable baseline parameters were established. All the parameters describing baseline performances of the digesters were also monitored after inhibitor dosing. Inhibitor dosing consisted of the addition of particular concentrations of inhibitor to the digester and observation of the digester performance in terms of gas production, volatile acid concentration, COD reduction, pH and alkalinity for the next three days. Subsequent dosing was resumed only when the digester was not affected in performance or when the digester showed signs of recovery after a period of impaired performance. The reduction in the gas performance with the usual variations compared with the gas production of the control units was used as a basic parameter in deciding the inhibitory concentration of the particular inhibitor. The threshold doses for the four inhibitors under study were estimated to be:

- 125 mg l\(^{-1}\) for copper in the form of cupric chloride
- 150 mg l\(^{-1}\) for nickel in the form of nickel chloride
- 600 mg l\(^{-1}\) for phenol
- 30,000 mg l\(^{-1}\) for common salt (NaCl)

CONCLUDING REMARKS

These varied uses of water hyacinth strengthen its claim to be regarded as a crop, and its eradication can be a profitable proposition if plants, on collection, are suitably employed. Financial outlay is moderate and it can be undertaken by either state or private enterprises. Persistent removal of water hyacinth followed by sowing with *Trapa natans* or *Lotus sp.* for a few successive years would soon result in the replacement of the water hyacinth population by the latter plants and lead finally to its extermination or controlled growth.

ACKNOWLEDGEMENTS

The authors thank Professor J. S. Deshpande, Principal, and Professor A. R. Mundhada, Head of Civil Engineering Department, College of Engineering, Badnera, for their fullest cooperation. We also thank Dr P. D. Sawalakhe for his constant encouragement. Help rendered by Professor Jaya Nitin Ingole, Senior Lecturer, Department of Electronics and Telecommunication, in handling the spectrophotometer is sincerely acknowledged. The authors also thank the Director, NEERI, Nagpur, P. K. V. Akola, for permission to collect literature from the library.

REFERENCES


Sankaran, T. 1975 Possibilities of biological control of aquatic weed (Eichhornia crassipes) and Salvinia auriculata in India.

Seminar on Noxious Aquatic Vegetation in Tropics and Subtropics. Abstracts, p. 50.


First received 14 February 2001; accepted in revised form 4 December 2001