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Beyond Biocontrol: Water Hyacinth-Opportunities and Challenges

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ABSTRACT

Eichhornia crassipes has become the world's worst invasive aquatic weed due to its rapid proliferation rate, ecological adaptability and detrimental effects caused on environment, human health and economic development. A large number of weed management strategies such as physical removal, chemical methods and biological control agents are being used to control it. But various environmental and financial challenges are associated with these methods. On the other hand, water hyacinth has demonstrated abilities to be used as a raw material in various useful applications. In this review, different applications of water hyacinth have been discussed. The weed biomass can be used for bioremediation and bioadsorption of metals and pollutants; biogas and biofuel production, composting and vermicomposting, as feed for animals and fish; as carbon source for microbial growth; for various medicinal and other uses. Thus for the management of this noxious weed by large scale utilization can be an attractive and efficient method, which can replace the relatively ineffective conventional methods of weed management.

Key words: *Eichhornia*, management, water hyacinth, biocontrol, applications

INTRODUCTION

Water hyacinth, a native of South America is one of the world's worst aquatic weeds (Hill *et al*., 2011). Due to its high noxious nature it has been enlisted in 100 of the world's worst invasive alien species, a selection from the global invasive species database (Lowe *et al*., 2000). This spectacular weed is an aquatic macrophyte, a monocotyledon and belongs to the family Pontederiaceae. This aquatic plant is free floating with beautiful clusters of violet and yellow flowers and bulbous green leaves. It was originally introduced to Australia as an ornamental plant for botanical gardens and decoration of ornamental ponds. Since then it has spread to more than 50 countries on 5 continents. Water hyacinth is prevalent in Southeast Asia, the Southeastern United States, Central and Western Africa and Central America (Bartodziej and Weymouth, 1995; Brendonck *et al*., 2003; Lu *et al*., 2007; Jimenez and Balandra, 2007). Its rapid growth rate (Holm *et al*., 1969; Hill *et al*., 2011) and high adaptability to extreme conditions contributes to its high degree of invasion. It is particularly dominant in the tropics and subtropics due to improper waste water management in these areas (Villamagna and Murphy, 2010). It spreads in the form of dense mats due to its complex root system and thus interfere with boat navigation, fishing and also leads to blockage of canals (Malik, 2007). Water hyacinth further reduces the penetration of light, dissolved oxygen and other nutrients and adversely affects the ecology of water bodies (Malik, 2007). It is even stated that it proliferates so rapidly that it can double its area in five days

(Ojeifo *et al*., 2000; Ntiba *et al*., 2001). Water hyacinth has become one of the most successful invaders due to its highly efficient survival strategies (Guitierrez *et al*., 2000). Once introduced in an area it can easily out compete native vegetation and thus is very difficult to eradicate or control (Villamagna and Murphy, 2010; Hill *et al*., 2011). Various programmes on management of water hyacinth are being run throughout the globe (Guitierrez *et al*., 2000) but no effective control strategy has been developed till date. Thus the management of *Eichhornia* still depends on efforts that focus on reducing the ecological and socio economic damage caused by it.

ORIGIN AND DISTRIBUTION

Water hyacinth originated in the rain forests of Amazon River and thus has its origin from Brazil and other parts of South America. Records of its invasion to river Nile during the late 18th century are also present (Hill *et al*., 1997). During late 19th century it was introduced in various countries as a specimen for ornamental ponds and botanical gardens (Ojeifo *et al*., 2000). From this controlled culture it somehow found its way into the fresh water rivers and lakes. Its infestation throughout the tropics and subtropics is reported from early 20th century. Presently, *Eichhornia* is the most problematic aquatic weed of Central America, North America, Africa, India, Asia, Australia and New Zealand.

ECOLOGY

Water hyacinth is the fastest growing free floating hydrophyte (Gopal, 1987). It is known to grow over a wide range of growth conditions which account for its high degree of invasion. Both tropical and temperate climatic conditions are suitable for its growth. Optimum growth temperature for water hyacinth is 28-30°C (Burton *et al*., 2010). Water hyacinth is not able to grow if the water temperature is more than 30°C or less than 10°C. A very low temperature is lethal for the growth as plant may die if the tip of rhizome becomes frozen. It is euryhaline in nature and thus can grow both in fresh and marine water (Ojeifo *et al*., 2000). However, stagnant or slow flowing fresh water is most suitable for its infestation (Burton *et al*., 2010). Water hyacinth can grow over a pH range of 4.0-8.0. It is also known for its tolerance to extreme climatic conditions including mild frost, the degree of survival depends upon other conditions as well (Burton *et al*., 2010). Growth and spread of water hyacinth is directly dependent on the amount of nutrients present in water (Gopal, 1987; Heard and Winterton, 2000). Growth and clonal propagation is greatly stimulated in an environment with abundant nutrient availability (Xie *et al*., 2004). It requires a large amount of nitrogen, phosphorus and potassium for its growth and development (Burton *et al*., 2010). From various studies conducted worldwide, it has been proved that biomass accumulation, ramet production, shoot: root ratio and plant height increase in accordance with increase in concentrations of nitrogen and phosphorus (Sastroutomo *et al*., 1978; Singh *et al*., 1984; Reddy *et al*., 1989). Thus the rate of infestation of water hyacinth is in direct relation with the concentration of various nutrients especially nitrogen and phosphorus. Water hyacinth is also known to store nutrients which can be used during later stages of life cycle (Heard and Winterton, 2000). Another important factor responsible for its high rate of invasion is that it can even survive on damp soil for months (Burton *et al*., 2010).

BIOLOGY

Eichhornia crassipes has broad, thick, glossy, ovate leaves and may rise above the surface of the water as much as 1 m in height (Adegunloye *et al*., 2013). The leaves are 10-20 cm across and

float above the water surface. They have long, spongy and bulbous stalks. Each plant consists of a rosette of six to ten leaves attached to a rhizome with a well-developed fibrous root system (Hill *et al*., 2011). The roots are unbranched and have a conspicuous root cap. The colour of roots varies. Free hanging roots are purple black while roots embedded in soil are white (Penfound and Earle, 1948). A stalk bears a single spike of 8-15 attractive flowers, mostly lavender to pink in colour with six petals. Branching pattern is different in different environment (Holm *et al*., 1969). Another important feature of water hyacinth is presence of foliar plasticity.

Water hyacinth reproduces sexually by seeds and vegetatively by budding and stolen production. Both vegetative and sexual reproduction has the potential of producing large number of individuals in a small period of time (Barrett, 1980). During vegetative reproduction daughter plant sprouts from the stolen and doubling time is reported from 6 to 18 days. When conditions like temperature and nutrient availability are favourable, the vegetative propagation is very fast and the edge of mat can even increase by 60 cm/month. Germination of seeds into mature plants is found to be rather sensitive and was limited by unfavourable growth conditions such as oxygen stress, light and temperature, dormancy periods, etc (Obeid and Tag el Seed, 1976; Barrett, 1980). The seeds can germinate in a few days or remain dormant for 15-20 years (Center *et al*., 1999). They usually sink and remain dormant until periods of stress (droughts). Upon reflooding, the seeds often germinate and renew the growth cycle. Flowering occurs 10-15 weeks after germination (Barrett, 1980).

IMPACTS OF WATER HYACINTH

Water hyacinth has detrimental effects on environment, human health and economic development. Major problems caused are due to its fast growth in the form of dense mats which completely clog water bodies. Dense mats formed by water hyacinth cause blockage of rivers and canals and thus interfere with irrigation, power generation and navigation and may also lead to flooding (Epstein, 1998). Water hyacinth has serious effects on water quality like higher sedimentation rates within the plant's complex root structure and increased evapotranspiration rates from water hyacinth leaves when compared to open water even by a factor of 10 thus causing scarcity of water in some areas (Gopal, 1987). Dense mats also decrease the dissolved oxygen concentrations thus creating good breeding conditions for mosquito vectors of malaria, encephalitis and filariasis beneath these mats (Hunt and Christensen, 2000; Perna and Burrows, 2005). It also prevents stratification by stabilizing pH levels and temperature within the lotic system (Giraldo and Garzon, 2002).

Water hyacinth decreases the productivity of phytoplankton and submersed vegetation under dense mats but there may be an initial increase in certain colonial types that may get captured within water hyacinth roots. It is known to exclude the native vegetation and associated fauna thus, causing an imbalance in aquatic system (McVea and Boyd, 1975; Brendonck *et al*., 2003; Mangas-Ramirez and Elias-Gutierrez, 2004). Effects of eichhornia on fish community are mainly dependent on fish community composition of the water body during infestation, epiphytic vertebrate community, phytoplankton and dissolved oxygen concentration (Toft *et al*., 2003; Kateregga and Sterner, 2009). However, decrease in overall population and diversity, difficulty in accessing fishing sites is generally observed (Malik, 2007).

Reports of heavy infestation and its effects have been made from different parts of the world like Lake Victoria, Uganda, East Africa; Lake Chapala, Mexico; Lake Navishka; Kafue river, Zambia and Florida. Major problems associated with water hyacinth in these water bodies are

interference with navigation and irrigation, reduction in fish catch, interference with water supply, breeding of mosquitoes, snails and snakes and exclusion of native flora and fauna (Mailu, 2001; Masifwa *et al*., 2001; Mironga, 2004; Plummer, 2005).

CONTROL

Water hyacinth has become a major problem all over the world due to is uncontrolled and fast growth. A large number of methods are being used and millions of dollars are being spent to control it. These methods include weed management methods such as physical removal, chemical methods and release of biological control agents (Harley *et al*., 1996) (Table 1). Each of these methods has certain advantages and disadvantages and thus any of the methods alone is ineffective (Guitierrez *et al*., 2000). A study also suggests use of glyphosate at low concentration along with *A. alternata* in the integrated management of water hyacinth (Ray and Hill, 2012). An integrated weed management system using a microbial herbicide, natural populations of arthropods and chemical herbicides has also been used and suggested (Charudattan, 1986). Initial control of water hyacinth focused on its eradication but due to the limitations of this approach, efforts to reduce its density to levels that minimise economic and ecological impact are made.

APPLICATIONS

Water hyacinth has become the world's worst invasive aquatic plant due to its rapid proliferation rate and ecological adaptability. Its management by various control methods presents serious challenges and is not promising enough to eradicate it completely. However, water hyacinth has demonstrated abilities to be used in various useful applications and thus its management by utilization has attracted significant attention. Various utilities of water hyacinth used for its management are discussed here.

PHYTOREMEDIATION

Phytoremediation is a promising and cost effective technology for the removal of metals, hydrocarbon, pesticides and chlorinated solvent from contaminated waste sites (Macek *et al*., 2004; Xia *et al*., 2003). Attention towards phytoremediation by water hyacinth is due to its rapid growth, large biogas production, ability to grow in heavily polluted water and metal ion accumulation (Xia and Ma, 2006; Malik, 2007). Water hyacinth is a potential scavenger of heavy metals (Table 2) and toxic elements from industrial and domestic effluents (Ogunlade, 1992). Water hyacinth is known to accumulate heavy metals like cadmium, mercury and nickel from agriculture and industrial effluents (Muramoto and Oki, 1983; Zhu *et al*., 1999; Soltan and Rashed, 2003; Tiwari *et al*., 2007).

Water hyacinth has been used as one of the main component of advanced wetlands and aquatic systems for municipal waste water treatment (EPA.,1988). The capacity of water hyacinth to absorb nutrients and other pollutants has been exploited to improve effluent quality from oxidation ponds (Wilson *et al*., 2001; Sim, 2003). Also, its capability to absorb nutrients makes it a potential biological alternative to secondary and tertiary treatment for wastewater (Ho and Wong, 1994; Cossu *et al*., 2001).

During a study, Greenfield *et al*. (2007) found that water hyacinth leaf tissue had the same mercury concentration as the sediment beneath, suggesting the role of water hyacinth in mercury removal. De Souza *et al*. (1999) studied the phytoaccumulation of trace elements cadmium, chromium, nickel, copper by *E. crassipes* hydroponic condition. A study by Alvarado *et al*. (2008)

Table 1: Different methods to control *Eichhornia crassipes*

Types of control	Methods	Advantages	Disadvantages
Physical	Manual removal by harvesting *In situ* cutting (Greenfield *et al*., 2007) Mechanized removal using cranes, draglines, mowers, dredges and barges (Harley *et al*., 1997) Installation of floating barriers to forestall the movement to other areas (Uka *et al*., 2007)	No water use restriction No technical expertise	Labour intensive Decreases dissolved oxygen concentration Eutrophication Costly due to expensive cutting and dredging equipment (Gopal, 1987)
Chemical	Glyphosate, diquat, 2,4 D amine (Gutierrez *et al*., 2000; Lugo *et al*., 1998; Ram and Moolani, 2000) 2,4-dichlorophenoxyacetic acid (2,4-D) + complexed copper (Westerdahl and Getsinger,1988) Endothall dipotassium salt Slow process endothalldimethylalkylamine salts, (Olaleye and Akinyemiju,1996)	Less labour intensive Cost effective as compared to physical methods	Less selective Deleterious effects on non-target algae and macrophytes (Arora and Mehra, 2003; Rocha-Ramirez *et al*., 2007) Deoxygenation (Lugo *et al*., 1998) (Wilson *et al*., 2007; Coetzee *et al.,* 2007) Insufficient reduction and resurgence in growth
Biological	**Insects** *Neochetinaeichhorniae, N. bruchi* and *Sameodes albiguttalis* (Julien and Griffiths, 1998; Julien and Orapa,1999; Ogwang and Molo, 2004; Mbati and Neuenschwander, 2005) **Fungal pathogens** *Alternaria eichhorniae* (Babu *et al*., 2004; Shabana and Mohamed, 2005) *Alternariaalternata, Drechslerahawaiiensis* and *Ulocladiumatrum* (El-Morsy, 2004) Allelopathic plants (Pandey *et al*., 1993; Kauraw and Bhan, 1994; Kathiresan, 2000; Saxena, 2000; Zhang *et al*., 2005)	Not labour and equipment intensive Has potential to be self-sustaining (Seagrave, 1988)	

Table 2: Metal extraction by Eichhornia crassipes

Metals	References
As	Al Rmalli *et al*. (2005)
Ag	Pinto *et al*. (1987) and Yao and Ramelow (1997)
Zn	Delgado *et al*. (1993), Zaranyika *et al*. (1994), Sridevi *et al*. (2003) and Rupainwar *et al*. (2004)
Cr	Delgado *et al*. (1993), Zaranyika *et al*. (1994), Zhu *et al*. (1999), Ingole and Bhole (2003), Elangovan *et al*. (2008) and Hasan *et al*. (2010)
Cd	Delgado *et al*. (1993) and Zhu *et al*. (1999)
Co	Zaranyika *et al*. (1994)
Fe	Zaranyika *et al*. (1994)
Ni	Zaranyika*et al*. (1994), Sridevi *et al*. (2003), Zhu *et al*. (1999) and Ingole and Bhole (2003)
Cu	Zaranyika *et al*. (1994), Zhu *et al*. (1999) and Zheng *et al*. (2009)
Pb	Zaranyika*et al*. (1994), Mukherjee and Mondal (1995) and Shekinah *et al*. (2002)
Hg	Ingole and Bhole (2003) and Kadirvelu *et al*. (2004)

proved that removal rate of arsenic by water hyacinth was higher than that of duckweed when monitored under concentration of 0.15 mg L^{-1}. Water hyacinth was found to grow in a mixture of heavy metal concentration up to 3 mg L^{-1} during a study on survival and behaviour under varying condition of heavy metal concentration (Soltan and Rashed, 2003). Non-living roots of water hyacinth are also known to remove arsenic from contaminated water (Shabana and Mohamed, 2005). Water hyacinth is also used as biological monitor during field studies to monitor metal pollution (Zaranyika *et al*., 1994). Raw dried water hyacinth roots and activated carbon and ash derived from it have been explored and can be used as a potential decontaminator

Table 3: Bioadsorption of pollutants by various parts of water hyacinth plant

Parts of water hyacinth	Absorbed pollutants	References
Dried root	Methylene blue, Victoria blue	Low *et al*. (1995)
	Various metals	Schneider *et al*. (1995)
	Uranium	Shawky *et al*. (2005)
	Arsenic	Al Rmalli *et al*. (2005)
	Fluoride	Simha *et al*. (2002)
Treated roots	Various metals	Elangovan *et al*. (2008), Ibrahim *et al*. (2009) and Mahmood *et al*. (2010a,b)
Biomass	Various metals	Schneider *et al*. (1995)
Activated carbon prepared from water hyacinth	Lead	Shekinah *et al*. (2002)
	Mercury	Kadirvelu *et al*. (2004)
	Methylene blue	Rashwan and Girgis (2004)
	Congo red	Rashwan and Girgis (2004)
	p-nitro phenol	Rashwan and Girgis (2004)
	phenol	Rashwan and Girgis (2004)
Water hyacinth ash	Various metals	Mahmood *et al*. (2010b)
	Ni^{2+}	Hussain *et al*. (2010)

(Schneider *et al*., 2001; Mahmood *et al*., 2010a; Mahamadi, 2011). Water hyacinth was used to remediate aquatic environments contaminated with the lanthanide metal, europium (Eu(III)) and determination of europium adsorbed onto the surface of the roots from water was done using Scanning Electron Microscopy (SEM). Highest concentration of europium was found on the root hairs (Kelley *et al*., 1999).

The extraction rates of inorganic contaminants such as nitrates, phosphates, ammonia, silicates, chlorine and sulphur by water hyacinth are remarkable (Reddy, 1983; Ogunlade, 1992). Studies prove that water hyacinth is capable of absorbing organic pollutants as phenol but the mechanism of absorption is not well studied (Nora and Jesus, 1997; Zimmels *et al*., 2007). Kiran *et al*. (1991) investigated the utility of four aquatic plants in the removal of nitrogen and phosphorus and observed that *E. crassipes* has the highest capacity for nitrogen and phosphorus extraction. An investigation on the potential of water hyacinth to remove a phosphorus pesticide ethion was carried out and results suggested plant uptake as the dominant mechanism of removal (Xia and Ma, 2006). Water hyacinth has been used to treat waste water from pulp and paper mill, tannery and textile industry (Jayaweera and Kasturiarachchi, 2004). Different parts of water hyacinth have been exploited for bioadsorption of various metals and pollutants (Table 3). The sorption of uranium, copper as well as basic dyes by dead water hyacinth roots has also been investigated (Low *et al*., 1994; Shawky *et al*., 2005). Water hyacinth is also known to accumulate recalcitrant organic chemicals such as herbicides. Roy and Hanninen (1994) demonstrated the uptake/elimination kinetics and metabolism of pentachlorophenol (PCP) by water hyacinth.

These studies suggest that water hyacinth might be utilized as an efficient and economical alternative to accelerate the removal of agro industrial waste water polluted with heavy metals, organic and inorganic pollutants.

BIOFUEL

Rapid industrialization and urbanization with corresponding depletion of renewable energy sources on the earth has led to the problem of energy crisis all over the world. This has necessitated the development of technology for production of fuels from readily available and renewable sources of energy. Water hyacinth due to its low lignin content is an attractive source of biomass, as cellulose and hemicellulose are more easily converted to fermentable sugar thus resulting in large amount of utilizable biomass for the biofuel industry. Also, water hyacinth being an aquatic plant

does not compete with land resources used in food crop cultivation (Bhattacharya and Kumar, 2010). A study was conducted to produce ethanol from water hyacinth leaves using Separated Hydrolysis and Fermentation (SHF). The efficiency of the process was increased by acidic pretreatment and enzymatic hydrolysis to produce more sugars to be fermented to ethanol. The efficiency of three different yeast strains, *Saccharomyces cerevisiae* TISTR 5048, *Saccharomyces cerevisiae* KM 1195 and *Saccharomyces cerevisiae* KM 7253 to produce ethanol was compared. It was found that SHF by monoculture of *Saccharomyces cerevisiae* KM 1195 produced the highest yields of ethanol. Further investigations proved that a co-culture of *S. cerevisiae* TISTR5048 and *Candidat ropicalis* TISTR 5045 in the ratio of 1:1 contributed to the highest increase in ethanol production (Sornvoraweat and Kongkiattikajorn, 2010).

Mahmood *et al*. (2010a) studied ethanol production from metal contaminated water hyacinth by two methods. In the first method, saccharification of water hyacinth with diluted sulphuric acid (1% v/v at 110°C for 1 h) and then fermentation by yeast (*Saccharomyces cerevisiae*) resulted in the formation of 55.20% ethanol and 41.66% acetic acid. In another experiment, gasification by using Ni and Co nano catalysts at 50-400°C and atmospheric pressure resulted in the production of CH_4 (2.41-6.67%), C_2H_4 (19.74-45.52%), C_3H_4 (21.04- 45.52%), CH_3OH (1.43 - 24.67%) and C_3H_8/CH_3CHO (0.33-26.09%). Simultaneous saccharification and fermentation of H_2SO_4 pretreated water hyacinth detoxified with CaOH and NaOH was done using *Z. mobilis* CP49MTCC 2427 and *A. niger*. Various parameters were optimized and the final concentration of bioethanol produced by this method was 68.3 g L^{-1} (Kasthuri *et al*., 2012).

A study even suggested that bioethanol generating capacity of water hyacinth is comparable to that obtained from agricultural waste, thus making it a potential new crop for biofuel production (Mishima *et al*., 2008). Reports have also suggested that genetic engineering of microorganisms can increase ethanol production from hemicellulose by fermenting it into oligosaccharides (Dien *et al*., 2003; Mishima *et al*., 2008). Biological delignification of water hyacinth by *Phanerohaete chrysosporium* using solid state fermentation was explored and various factors studied to obtain lignin free biomass for bioethanol production (Sari *et al*., 2011). Other studies on biological treatment of water hyacinth prove that it is a promising cost effective and environment friendly approach to obtain biomass for biofuel production. Reports of attempt to produce biodiesel from water hyacinth are also available (Sagar and Kumari, 2013).

BIOGAS

Biogas is produced by anaerobic digestion or fermentation of biodegradable materials such as lignocellulosic biomass, manures, sewage, municipal waste, green waste, plant material and energy crops. It is composed primarily of methane and carbon dioxide. Use of animal, agricultural and industrial wastes to produce biogas has been widely studied. However, not much work has been done using aquatic plants like water hyacinth. Water hyacinth is an attractive source of biomass for biogas production due its fast growth and enormousness. It can thus provide the continuous supply of biomass required for the production of methane. It is rich in nitrogen, essential nutrients, has a high C/N ratio and high content of fermentable cellulose and hemicellulose (Chanakya *et al*., 1993). Water hyacinth biomass is lighter than water, it thus floats and clogs the digester during fermentation which makes it difficult to feed it even after chopping to the conventional digesters (Abbasi *et al*., 1992). Thus, conventional single stage reactors are being replaced by multiphasic reactors to overcome the problems of feeding, frothing, clogging and lack of efficiency. Abbasi and Ramasamy (1999) produced 38 m^3 kg^{-1} of volatile solids/day of biogas

containing 60% methane using biphasic reactors. As much as 4000 L of gas per tonne of semi dried water hyacinth was produced during studies carried out in India with a methane content of up to 64% (Gopal, 1987).

Most of the experiments on biogas production have used a mixture of animal waste and water hyacinth (Jafari, 2010). The mixture of cowdung and water hyacinth slurry has produced more biogas than water hyacinth used alone (El-Shinnawi *et al*., 1989). The slurry or sludge left after biogas production is usually transported and used as liquid fertilizer. Water hyacinth has been used to extract volatile fatty acids to be fed as a supplement in a slurry biogas digester to generate biogas (Abbasi and Ramasamy, 1996; Ramasamy and Abbasi, 1999).

Sharma *et al*. (1999) demonstrated biogas production using fed batch fermentation. Solid phase fermentation using aqueous suspension of biodegradative bacteria on water hyacinth bed for efficient biogas production has been reported (Chanakya *et al*., 1993). Ingole and Bhole (2000) explored the use of a triphasic digestion system containing alkali pretreatment reactor, acid reactor and methane reactor for biogas production.

Patil *et al*. (2011) studied the biomethanation of fresh water hyacinth with different amount of water. The study was carried out in mesophilic temperature range of 30-37°C for a period of 60 days. The results indicated that fermentation slurry of water hyacinth to water in the ratio 1:4 (FWH-1:4) produced maximum biogas yield of 0.245 L/g VS, followed by FWH-1:5 and FWH-1:3. Effect of water hyacinth (*Eichhornia crassipes*) on the production of biogas from pig dung was evaluated. There was increase in the percentage composition of the methane gas in biogas when water hyacinth and pig dung were blended and mixed in ratio 1:3. It was found that lower the water hyacinth in the mixture more was the concentration of methane produced (Adegunloye *et al*., 2013). A study on biogas production discussed the potential of the mixture of water chestnut, water hyacinth and cow dung in the ratio of 1:1:2. The three variants were subjected to anaerobic digestion in a 20 L portable bio-digester in the ratio of 1:1 with water. The average production of biogas estimated during this study was 0.326 L per day (Kumar *et al*., 2013). Use of water hyacinth to produce biogas by low cost and labour intensive techniques on small scale is being encouraged. This process helps weed harvesting thus keeping its growth and spread under check. Thus, the utility of water hyacinth as a biomass for biogas production may not only help to sustain the energy availability but may also improve environmental sustainability.

ANIMAL FEED

Water hyacinth is a good source of animal feed due to its protein and mineral content. Studies have proved that the nutrients in water hyacinth are available to ruminants. Water content in water hyacinth must be reduced from 95% to about 15% or less than that to prevent spoilage (Wolverton and McDonald, 1979). The use of water hyacinth for animal feed is encouraged in developing countries to help solve some of the nutritional problems (Jafari, 2010). Practice of feeding non ruminant animals on rations containing water hyacinth is prevalent. Boiled chopped water hyacinth mixed with vegetable waste, rice bran, copra cake and salt is used to make a suitable feed for pigs in china (Malik, 2007). Fresh water hyacinth cooked with rice bran and fish meal and mixed with copra meal is used as feed for pigs, ducks and pond fish in countries like Thailand, Malaysia and Philippines (Van der Meer and Verdegem, 1996). Kivaisi and Mtila (1997) demonstrated the use of water hyacinth as cattle feed. Fresh water hyacinth alone or as a silage with paddy straw (Mitra *et al*., 1997) and addition of 10-20% molasses to water hyacinth silage to improve in vitro organic matter digestibility (Aboud *et al*., 2005) has also been investigated. Water

hyacinth is a good quality protein source with enhanced nutritive value and digestibility when combined with concentrate of other high energy feed (Aderibigebe and Brown, 1993; Ojeifo *et al*., 2000).

In a study, growing goats were fed on sundried water hyacinth, cowpea pod and groundnut stubbles mixed in the respective proportions: 30:40:30 (diet 1), 30:30:40 (diet 2) and 40:30:30 (diet 3) to evaluatethe variations in intake, feed conversion and rate of gain. The results showed that mean final weight of goats fed on diet 3 (6.87 kg) was significantly ($p<0.05$) higher than the similar goats fed on diet 1 (6.80 kg) and 2 (6.76 kg). It was also found that growth rate of animals fed on diet 3 (11.00±2.80) was also significantly ($p<0.05$) higher than of goats fed on the respective diet 1 (8.55+-2.80) and 2 (8.20+-2.80). These results indicated that sundried *E. crassipes* at up to 40% dietary level of inclusion is beneficial for the growth of goats (Sunday, 2002).

Mukherjee *et al*. (2004) studied the role of colonization of three white rot fungus (2 *Plurotus* sp. and 1 *Colocibe indica*) on *in vitro* dry matter digestibility and substrate composition of water hyacinth and its relation to biodegradation of lignin and structural carbohydrates. Percent change of *in vitro* dry matter digestibility of water hyacinth increased after 8 days and reached maximum after 32 days after which there was a decrease in it. The results demonstrated the potential of this white rot fungus in the efficient degradation and conversion of water hyacinth to mycoprotein rich ruminant food.

Aboud *et al*. (2005) conducted two experiments investigating the potential of *Eichhornia crassipes* as ruminant feed in Tanzania. Biomass yield, chemical composition, *in vitro* dry matter (IVDMD) and organic matter digestibility (IVOMD) and in Sacco degradability of water hyacinth was investigated. After this 0, 10 and 20% molasses were added to water hyacinth and this mixture was subsequently analyzed for Dry Matter (DM), water soluble carbohydrates, IVDMD and IVOMD. He concluded that water hyacinth could be exploited to provide large quantities of nutritious feed to ruminants.

A recent study conducted in three water bodies in Nigeria to examine the biomass yield, chemical composition and nutritive potential of water hyacinth proved that it is available in enormous quantity all the year round and contains nutrients and minerals to be utilized as feed for animals specially ruminants (Akinwande *et al*., 2013).

FISH FEED

A number of fishes including Chinese grass carp, tilapia, silver carp and the silver dollar fish are known to eat aquatic plants and thus can be used to control aquatic weeds. Further due to this feature of fishes, water hyacinth can be exploited as a fish feed (Jafari, 2010). It has also been reported that decay of water hyacinth after chemical control releases nutrients which promote the growth of phytoplankton thus increasing fish yield. Igbinosun and Talabi (1982) conducted a study which proved that water hyacinth feed has more fibre, fat content and was found suitable in comparison to NIOMR (Nigerian Institute for Oceanography and Marine Research) fish feed. Addition of dehydrated water hyacinth to the diet of channel cat fish fingerlings led to the increase in their growth (Gopal, 1987).

A laboratory trial carried out in Germany on the feeding of water hyacinths to grass carp reported that roots and leaves were accepted readily by the grass carp and the fish grew well, producing 6.5 g live weight from 10 g DM hyacinth (Feed Conversion Ratio (FCR = 1.54)). It was also noted that grass carp above 80-100 g were better able to utilize hyacinth leaves compared to smaller fishes (Riechert and Trede, 1977). Tuan *et al*. (1994) reported that the specific growth rates

of grass carp, Java barb and common carp increased when fermented water hyacinth were used as supplementary feed in nursery ponds in Vietnam for fingerlings (1-6 g) of Nile tilapia, common carp, grass carp and Java barb. Inclusion rates of 20-25% as a supplementation of basic feed (e.g. rice bran, broken rice, chicken manure) or 5-10% as a replacement protein source in formulated feeds (fish meal, vegetable oil meals/cake) have been suggested in farm-mixed feeds for the farming of herbivorous or omnivorous freshwater fish (Hertrampf and Piedad-Pascual, 2000). Major problem associated with the use of water hyacinth meal in fish diets is its relatively high crude fibre content (Buddington, 1980). Composting of water hyacinth has been reported to increase the nutritive value and acceptability by fish. A comparative study on the proximate composition of composted water hyacinth and dried water hyacinth meals revealed that while the crude protein levels were similar, the crude fibre and crude fats levels were approximately halved and the ash content approximately doubled by the composting process (Edwards *et al*., 1985). Mashing is another method used to prepare water hyacinth as feed for Chinese carps in China.

COMPOST

Composting is one of the most widely used techniques to prepare biofertilizer from water hyacinth biomass. Inorganic nitrogen and phosphorus present in the roots makes it a suitable substrate for compost or inorganic fertilizer. Water hyacinth being hygroscopic in nature has high moisture retention properties and thus makes an excellent organic soil supplement for sandy soil. It generally takes three to six months depending on temperature and aerobic conditions. Drying of compost is an important requirement after completion (Wolverton and McDonald,1979). Water hyacinth can be used both as a green manure on land or in the form of compost (Woomer *et al*., 2000). Addition of urea is often recommended to speed up the decomposing process. Compost is usually prepared by mixing water hyacinth, cow dung, urea and lime; water hyacinth and cow dung being the main constituents (Hasan and Chakrabarti, 2009). Roots of water hyacinth are exploited for the preparation of a powder to be employed in the production of vegetables (Oso, 1988). Water hyacinth has been known to increase the production of vegetable crops like ladyfinger, potato and tomato by 67, 14 and 90%, respectively (Sannigrahi *et al*., 2002). Use of manure treated with herbicides should be avoided as they decrease the yield when compared to untreated water hyacinth manure (Stocker and Haller, 1999).

Water hyacinth mixed with farm yard manure prepared from various kinds of animal excreta, crop residues, kitchen wastes, vegetable wastes, house sweepings, etc., has been used to enhance organic matter and water holding capacity of soils in drought prone areas of Bangladesh (Stephan and Selvaraju, 2012). Field experiments conducted by Lata and Veenapani (2011) to study the effect of water hyacinth manure on the growth and productivity of *Brassica juncea* (Indian mustard) revealed that the growth of *Brassica Juncea* was enhanced with 50% water hyacinth manure while there was a significant increase in productivity with 100% water hyacinth manure treatment. Another study investigated high rate pile composting of water hyacinth in combination with cattle manure and saw dust/rice straw as a bulking agent. Results suggested that cattle manure with rice straw as a bulking agent led to the better degradation of water hyacinth in comparison with saw dust (Dhal *et al*., 2012).

The sludge from the biogas process contains almost all the nutrients of the substrate and can be used as a fertilizer (Patil *et al*., 2011). It can be used directly or can be mixed with other organic matters. Slurry from biogas plants is collected regularly to be used as a biofertilizers for cultivation of maize, peanuts, soybean and cassava (Ojeifo *et al*., 2000). Composting on large scale can be used

in the management water hyacinth (Stoffella and Kahn, 2001). However, compost preparation being a labour intensive process is often avoided.

VERMICOMPOSTING

Vermicompost of water hyacinth has the advantage of plant losing its ability to reproduce vegetatively after passing through the earthworm gut (Abbasi and Ramasamy, 1996). Enzymes and hormones present in vermicast are also known to stimulate plant growth (Ismail, 1997; Abbasi and Ramasamy, 1996). Gajalakshmi and Abbasi (2002) studied the impact of the application of compost and vermicompost obtained from *Eichhornia crassipes*on plants in terms of growth and flowering of the angiosperm *Crossandra undulaefolia*. Results indicated that application of vermicompost led to significant improvement in the growth and flowering of *Crossandra* compared to the untreated plants. Also the impact of vermicomposting was also more distinct than the impact of compost.

MEDICINAL USES

Water hyacinth has long been used to treat Goitre in India. The formulation contains water hyacinth in equal quantity with table salt and *Piper congum* (Oudhia, 1999). A study by Ogunlesi *et al*. (2010) investigated the vitamin C contents of tropical plants and weeds including water hyacinth by Cyclic Voltammetry (CV) and titration with N-bromosuccinimide (NBS) and their relevance to medicinal uses of plants. Results related the role of ascorbic acid determined as 10.19 mg/100 g by CV and 16.34 mg/100 g by NBS in water hyacinth to its relevant medicinal uses like skin care and goitre.

An investigation by Bodo *et al*. (2004a, b) confirmed the antioxidative properties of water hyacinth. The antioxidative activity was measured in terms of equivalent glutathione (EG, in nmoles equivalent glutathione per gram of dry plant material selected and compared to those of soya beans and garlic bulbs. The highest oxidative potential was observed for freeze-dried leave extract, while the lowest value was obtained upon heating at 60°C. The results indicated the potential of this plant as an alternative and convenient low-cost raw material for antioxidizing agent recovery.

Reducing power of various solvent extracts of *Eichhornia crassipes* was evaluated, compared to standard antioxidant L ascorbic acid and found greater than that of the standard suggesting the potential of development of useful natural antioxidants (Jayanthi and Lalitha, 2011). Lalitha and Jayanthi (2014) demonstrated the potential of extracts of *Eichhornia crassipes* in antiaging. Two skin creams of the ethyl acetate extract were evaluated for its antiaging efficacy by DNA damage inhibition assay and DPPH radical scavenging assay. There was an increase in DNA damage inhibition and DPPH radical scavenging ability with increase in concentration for both the creams promising the future of water hyacinth in cosmeceutical industry. Water hyacinth has also been reported to contain compounds with anticancer properties (Aboul-Enein *et al*., 2014). These studies confirm *Eichhornia* as a valuable resource for natural compounds of desirable medicinal properties like antioxidants, antiaging and anticancer.

AS A CARBON SOURCE

Protein hydrolysate of water hyacinth, singly or in combination with hydrolysate of pea husk has been used in yeast extract mannitol medium for the cultivation of *Rhizobium* sp. (Gulati, 1980). Water hyacinth cellulose was exploited as the sole carbon source in the culture medium for the production of cellobiase-rich preparation by *Aspergillus niger*. Cellobiase, CMCase and FPI

cellulase were obtained by controlling the pH of the culture medium at 5.0 during fermentation (Ismail *et al*., 1995). Mukhopadhyay and Nandi (1999) evaluated the use of a mixture of molasses, hydrolysate of water hyacinth and pea husk in ratio of 1:2:2 as a substitute for mannitol in yeast extract mannitol medium and found that it gave a better yield of both *R. trifolii* and *R. japonicum* in comparison to the standard medium. During a study, lignocellulosic hydrolysate of water hyacinth was used as the carbon source and the fermentation medium containing 50% lignocellulosic hydrolysate of water hyacinth was found to produce highest amount of riboflavin by *Aspergillus terreus* (Foaad and Afifi, 2000). *Pleurotus sajorcaju* has also been successfully cultivated using water hyacinth biomass (Gupta *et al*., 2004).

Ali *et al*. (2004) evaluated the production of cellulases by *Aspergillus niger* and *A. nidulans*ona medium containing water hyacinth in Czapek-Dox medium (4:1) and also optimized various culture conditions for maximum activity of cellulases for both isolates. Oluwanisola and Adebayo (2009) investigated the pH, nutritional and cost benefit of the use of different growth media (Potato Carrot Agar (PCA), Potato Dextrose Agar (PDA), Sabouraud Agar (SA), Tap Water Agar (TWA), Water Hyacinth Agar (WHA) and Czapek Dox Agar (CDA)) for the production of *Curvularia pallescens*. The effect of pH range between 5.5 and 8.6 and various nitrogen sources was evaluated. Mycelial growth was highest with WHA, spore concentration with TWA and the colony size was highest when sodium glutamate was used as the nitrogen source. The formulated water hyacinth agar medium was found to be the most economical for the mycelial production of *C. pallescens*. These studies suggest the potential of water hyacinth as a cheap source of carbon.

OTHERS

Water hyacinth can be used as a raw material for the production of pulp, paper, rope, basket and various other products which can be used for the development of small scale industries. Water hyacinth is used in the production of fibreboards and bituminized boards for use as a low cost roofing material (Jafari, 2010). The stalks of water hyacinth have the potential to bepulped and converted into medium quality papers or boards such as cardboard and coloured cards or cover papers. The shrinkage of paper during drying can also be minimized by blending them with long fibrous pulps such as cotton rags and waste paper pulps (Thyagarajan, 1983). It is also suggested to establish the manufacturing unit in places where water hyacinth is available in abundance and free of cost to help reduce the nuisance created by water hyacinth and also create job opportunities. Akobundu (1987) demonstrated the role of aquatic weed as a raw material for pulp and paper, fibre for making chairs, mats and baskets.

Goswami and Saikia (1994) investigated the use of water hyacinth as a pulp material for producing greaseproof paper. The proximate chemical analysis of the raw materials, the morphology of the water hyacinth stalk and fibre, pulp characteristics and the physical properties of the paper hand-sheets formed from water hyacinth and bamboo pulps and their blends were evaluated. It was found that blending of water hyacinth and bamboo pulps increased the physical strength and also gave satisfactory greaseproof properties. Various small-scale cottage industry and papermaking projects have been established successfully in a number of countries, including the Philippines, Indonesia, Bangladesh and India. The fibre from the stems of aquatic weed has been used to make rope. These ropes are used in furniture to wind the rope around a cane frame to produce elegant finished products (Jafari, 2010). Another application of water hyacinth is as a raw material to make baskets and matting for domestic use. Technologies for briquetting of charcoal dust from the pyrolysis of water hyacinth have also been proposed (Jafari, 2010). Reports of

production of handsheets and other paper based products with different success rates are available (Knoshaug *et al*., 2013). Extraction of cellulose fibre is a laborious process and is not economically viable for commercial production of fibre for paper making. Thus, Most of the work relies on crudely processed aquatic biomass as a material source and a little work has been done on the use of actual cellulosic fibres derived from the plant.

CONCLUSION

Eichhornia is considered as one of the world's worst invasive weeds due to its rapid growth rate, efficient survival strategies in extreme conditions and its impact on environment, ecological communities, human health and socioeconomic development. Various strategies have been adopted to control it including weed management methods such as physical removal, chemical methods and release of biological control agents and integrated management using two or more different methods. However, complete eradication of water hyacinth is not possible because of the various environmental and financial challenges associated with these methods. On the other hand, water hyacinth has demonstrated abilities to be used as a raw material in various useful applications and thus its management by large scale utilization is an attractive approach. Water hyacinth, due to its low lignin content is a rich source of lignocellulosic biomass for biofuel and biomass production. High protein and mineral content of water hyacinth makes it an attractive substrate for animal and fish feed. Antioxidizing, antiaging and anticancer properties have also been explored but more research is required to establish their commercial viability. Utility of water hyacinth has also been exploited in phytoextraction of heavy metals, bioadsorption of organic and inorganic pollutants and dye degradation thus proving its potential in phytoremediation. Studies prove that water hyacinth can be used as a carbon source for the cultivation of various industrially important microorganisms and for the production of various products like cellobiase, CMCase, FPI cellulose, riboflavin, etc., thus making the process cost effective. Water hyacinth is also used as a compost, vermicompost and green manure and is known to increase the productivity of various agricultural crops and vegetables. Water hyacinth is used as a raw material for the production of pulp, paper, rope, baskets, fibreboards, chairs and mats. Various small-scale industries manufacturing such products have been established successfully in a number of countries, including Philippines, Indonesia, Bangladesh and India. Utilization of water hyacinth in industrial scale application is still far from the level required except for some localized cottage industries and small scale biogas production. More research is needed on individual applications before they can be used for sustainable management or human welfare. Design of effective management strategies requires refined knowledge of density of invasion, degree of impact, uses of infested water body, control methods and the feasibility of the application for which water hyacinth biomass can be exploited in a region.

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