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Transforming aquatic weeds into resources: *Pontederia crassipes*, water hyacinth mining for circular bioeconomy

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Abstract
Globally, a positive shift to renewable and sustainable bioenergy usage has been witnessed over the years. An ideal resource should contribute equally to bioeconomy, circular economy and sustainable development. One such less explored resource is an aquatic weed, *Pontederia crassipes*, commonly known as water hyacinth, which is documented as one of the major invasive aquatic weeds due to its rapid reproduction, capacity to deplete nutrients from water bodies, and adaptation to new habitats. In particular, water hyacinths, which are abundant in India, are a rich source of nutrients and lignocellulosic biomass that may be utilized as a precursor for producing bioenergy and biofuel. At present all management and control strategies lack sustainable use of water hyacinth and in turn harm the surrounding ecosystem. This abundant source of biomass is underutilized, undermanaged, and difficult to collect. Tapping into management and harvesting strategies with efficient biomass conversion from water hyacinth, could lead to solutions for multi-level problems of current circular bioeconomic challenges in India. In this review, we critically discuss water hyacinth issues and management strategies and their potential use as a circular bioeconomic resource using relevant business models and case studies. To efficiently harvest, we present unique weed mining methodologies for the successful collection, treatment, and long-term utilization of the aforementioned bioresource. As a direct result, there may be a feasible answer to the growing need for biomass and bioenergy. Using water hyacinth, an invasive weed by nature, in a circular bioeconomic manner would also significantly advance numerous UN sustainable development objectives.

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Graphical Abstract

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Introduction

Developing economies comprises the global south, like India, South Africa, Brazil, other Asian and South American countries rely heavily on their agriculture sector for their economic growth (Diaz-Bonilla & Robinson, 2010; Dwivedy, 2011). India is a large producer and consumer of agricultural products, making it a key role in the global supply chain. The green revolution has ushered in post-independence India with food self-sufficiency despite its burgeoning population. The agricultural sector, therefore, has been the backbone of economic development in the Indian subcontinent. Hence, it's not surprising that India's economic policies have always been farmer-centric. Agriculture today contributes more than 17% to the Indian GDP while employing about 50% of its working age population (Singariya & Sinha, 2015). India has made significant contributions in the global bio-economy with its focus mainly being on the agriculture and biotechnology sector. According to the Biotechnology Industry Research Assistance Council (BIRAC) report 2022, the Indian economy grew upwards of USD 80 billion in 2022, unprecedented growth of more than 14% in spite of the global COVID-19 lockdown. To augment use of biofuel, India is aiming to achieve 20% ethanol blending in vehicle fuel from the first quarter of 2023. One of the major components of this bio-economic growth has been biomass, bioenergy and biofuel, predicted to contribute upwards of 25% or USD 20 billion in 2025 in the Indian bio-economy sector (S. et al., 2018; Narayanan, Srinivas Rao 2022).

Global circular bioeconomy, integration of bioeconomy and circular economy in the Indian subcontinent

A closely related concept to bioeconomy is the circular economy which purposes to attain maximum utilization of resources through waste utilization. Core concepts of circular economy are "Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover", which are commonly referred to as the 10R's. These principles must be critically contextualized within the lifecycle of specific bioresource, *Pontederia crassipes*, water hyacinth, an invasive aquatic weed with high biomass productivity. When managed sustainably, water hyacinth can be rethought as a renewable resources-harvested to reduce environmental spread, reused, repurposed and recovered from bioenergy. Applying the 10R's to water hyacinth demonstrates the practical relevance of circular economy strategies in transforming biological waste into valuable bioproducts. At the intersection between bioeconomy and circular economy is circular bioeconomy, adding another R for the use of

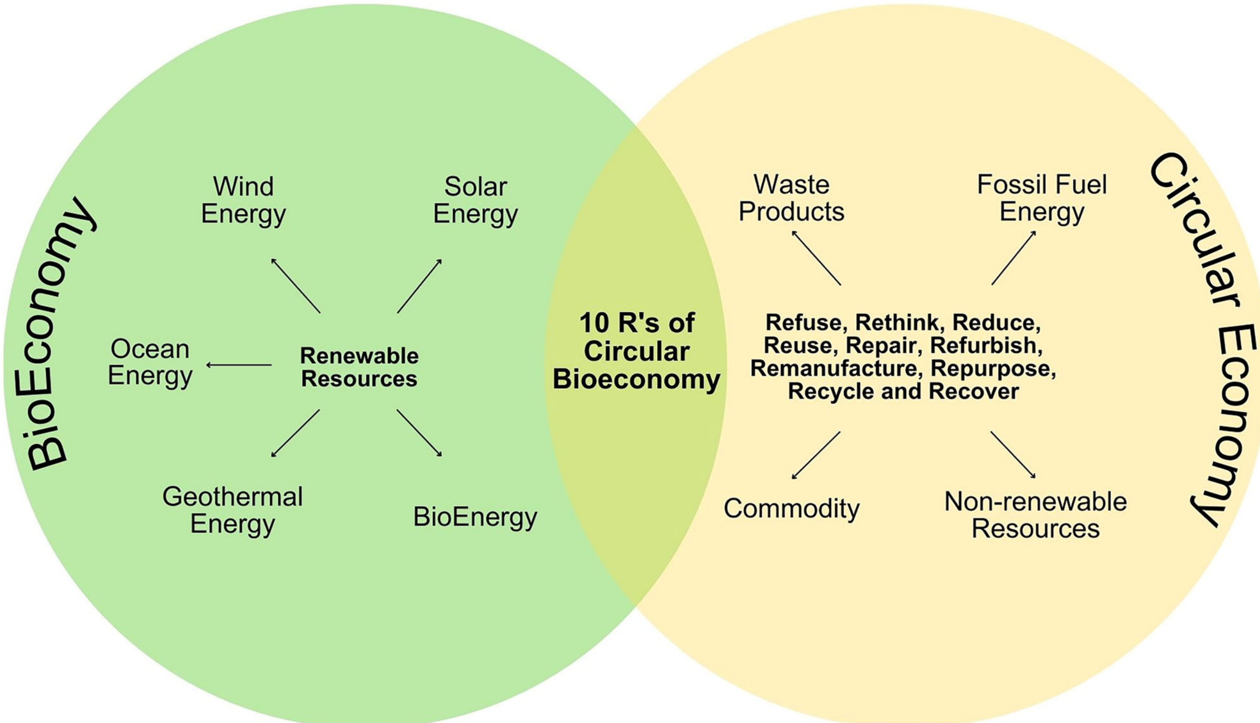


Fig. 1 Figurative description of bioeconomy, circular economy and circular bioeconomy with the 10R's concept

Renewable Resources like water hyacinth. As a whole, this would signify the use of natural, non-replenishable, and renewable resources to produce products and processes using sustainable strategies. This resources can be utilized in other processes, decreasing waste output and minimizing the carbon footprint (Fig. 1) (Bastos Lima, 2022; Kumar Sarangi et al., 2023; Ramachandra & Saranya, 2022; Srivastava & Bandhu, 2022). A circular bioeconomic model calls for the wise and sustainable use of bioresources as a substitute for fossil fuels, promoting waste utilization that is both maximal and minimizes waste (Das et al., 2023; Negi et al., 2021). At its core, global policies aimed at minimizing the impacts of bio-waste while simultaneously generating carbon-negative or neutral bioproducts and bioenergy. Currently, most developing countries lack sufficient policy framework and technical expertise for the valorization of bioresources. Hence, there is a need for formulating newer strategies for achieving circular bio-economy models based on the present biocapacity of select products. The valorization of biomass lies at the intersection of the economy and the circular economy. India's rich natural resources, traditional knowledge and emerging biotech sector, establish India's position as a global contributor to the circular economy industry (Awasthi et al., 2022; Gebreeyessus, 2022; Tarazona et al., 2022).

Circular bioeconomy models like, waste-to-energy initiatives led to the employment of waste management techniques through anaerobic digesters, composting, pyrolysis, etc. used for better regulating and circulating unused waste matter, as per the June 2021 report form Ministry of New and Renewable Energy (MNRE), India has a significant sector for utilizing agricultural and household waste for bioenergy generation, with a 10.61 GW installed capacity from over 5000 small and middle-scale industries (Nagarajan et al., 2021). As a result, the estimated total biomass power potential is 42.31 GW. Revised regulations have enabled the use of various waste materials—such as municipal solid waste, farmers' market refuse, meat packing facility waste, agricultural residues, and industrial waste and effluents—for the production of biogas, bio-CNG, and electricity. In addition to energy generation, biogas plants produce organic fertilizer as a byproduct, which benefits agricultural fields (Mak et al., 2020; Neogi et al., 2022). India holds the fourth position globally in installed renewable energy capacity, which includes large hydro, wind, and solar power. The country aims to expand its renewable energy capacity to 500 GW by 2030 (Ministry of New and Renewable Energy Annual Report 2021-22, 2022). Most of the materials used for bioenergy and biofuel generation are agriculture waste, forest residues, animal waste and municipal waste. Main components of biofuels involve biodiesel contributing USD 650 million plus, bioplastics contributing USD 500 million plus and ethanol blended petrol contributing USD 4500 million plus towards bioeconomy from biofuels in 2021 (Narayanan, Srinivas Rao 2022). An ideal bioenergy source i.e. biomass should have high energy content and high carbon/nitrogen ratio, low moisture and

Fig. 2 Schematic diagram of Sustainable Development Goals covered by water hyacinth monitoring, mining and valorization

ash content, and it should be easily absorbable and abundant in presence (Deep Singh et al., 2022; Sahay, 2020; Wang et al., 2020). Present sources and strategies have few limitations like affecting status quo, such that biofuels are produced from crops with pre-existing economic contribution to the economy. But the question arises whether the current policies and the resources these policies focus on, are sustainable and economic enough to meet the evident dominance of the status quo. Majorly, the current bioeconomy is focused on agricultural/forestry residue, bioconversion and production. The question being is the prevalent strategy enough to encompass the core idea of circular bioeconomy (Sheldon, 2020).

How and why aquatic weed, water hyacinth is a critical element in circular bioeconomy

New strategy to employ circular bioeconomy policies would include under-utilized resources which are self-propagating and demand little to no economic input for development, administration, and harvest; hence, their use would minimize their unfavorable effects on socio-economic and environmental features (Kaur, 2020; Prasad et al., 2019; Saravanan et al., 2020). As a whole this would signify the use of natural replenishable and renewable resources to produce products and processes using sustainable strategies, valorization of the biowaste in other processes, decreasing the biowaste output and minimizing the carbon footprint. Moving towards a circular bioeconomy not only means the use of biological resources as an alternative but also the use of end waste produced from biological resources or to minimize the waste production itself. Thus, creating a global network of sustainable development. Many United Nations goals for sustainable development focus on the responsible assumption and consumption, affordable clean energy, economic growth, sustainable cities and communities, life on land and below water (Fig. 2). Here circular bioeconomy converges with sustainable development and our key bioresource, aquatic weed - Water hyacinth, which has the potential for encompassing the idea of circular bioeconomy with extending its contribution towards many United Nations sustainable development goals (Kaur, 2020; Prasad et al., 2019; Saravanan et al., 2020). Aquatic bioresources, such as aquatic weed and water hyacinth, are underexplored under present laws and regulations. Aquatic resources are increasingly attractive for bioenergy, bioremediation, biotextiles, and other biotechnological uses due to their availability and potential bioeconomic benefits. Aquatic weed digestion produces biogas, which can be used for energy, heat, or transportation fuel. Bio-oil and syngas can be produced through pyrolysis and gasification (Sarkar et al., 2021). Aquatic weed burning can provide heat and energy for industrial and home usage. Aquatic weeds can be used for bioremediation of contaminated water bodies in addition to bioenergy generation (Arora et al., 2023). The possible utilization is limited by its extraction methods where decentralized strategies like manual or mechanical extraction are prevalent, a need for better 'weed mining' methods and transport channels is necessary for effective utilization of this valuable resource (Yehualaw et al., 2022).

Policies and regulatory framework

India has made great progress in fostering the growth of a bioeconomy, owed to new strong policies and regulatory framework (Karim et al., 2020). Acknowledging the potential of biological resources to achieve sustainable development goals, lessen reliance on fossil fuels, and enhance the standard of living for farmers in rural regions has been the central idea for bioeconomy in India (Perea-Moreno et al., 2019; Singh & Singh, 2019). The National Biofuel Policy, introduced in 2018 has encouraged new changes to economic policies and strategies, with main objectives pertaining to increasing the quantity of biofuels in fossil fuels and to develop an ecosystem for the production and distribution of biofuel blends (Das, 2020). Another initiative, The National Biodiesel Mission, 2003 encouraged higher production of oilseeds and the manufacture of biodiesel throughout the nation. The objective strives to increase job options for farmers in the nation and their standard of living. Under this program, the government offers farmers financial and technical assistance so they may grow oilseeds and build up facilities to make biodiesel (JAIN, 2021). Another significant project with the goal of promoting bamboo use and cultivation across the nation is the National Bamboo Mission. By using bamboo in a variety of industries, including bioenergy, the mission is to foster sustainable development and the creation of job possibilities (Arjumand, 2023; Bhargava, 2022). National Agricultural Policy is another policy focusing on sustainable agriculture, seeking to boost agricultural production, improve food security, and promote long-term growth; which supports organic farming, use of natural fertilizers and pesticides. India has also implemented regulatory frameworks for GM crops and biodiversity protection inaddition to existing restrictions. To monitor the use of genetically modified crops and verify their safety for human health and the environment, the country formed the Genetic Engineering Assessment Committee (GEAC). The Indian government has recognized potential for fostering bioeconomy and sustainable development, generating job opportunities, and reducing reliance on fossil fuels, enabling a new sector for bioeconomy reforms.

Comprehensive and progressive bioeconomy policy and regulatory framework is required to allow the use of water hyacinth as a bioresource in India, with a policy paradigm shift, water hyacinth may be seen as a valuable bioresource with the potential to considerably contribute to the bioeconomy. Fostering cooperation among academic institutions, industry players, and government agencies to create novel technologies and techniques for converting water hyacinth biomass into high-value goods is one example. Furthermore, financial incentives and grants to assist the construction of pilot projects and commercial-scale companies might encourage investment in this industry. Here, a well-designed regulatory framework can assure sustainable harvesting and use practices while minimizing environmental damage. This can contain guidance for effective water hyacinth management and control, as well as techniques for biomass collection, transportation, and processing. Implementing steps to monitor and manage any possible environmental problems linked with the use of water hyacinth can also help to ensure the bioeconomy's long-term viability. Scientific and technological advancements have the potential to significantly alter the usage of water hyacinth as a bioresource. Bioconversion technologies such as anaerobic digestion and thermochemical processes, for example, can transform water hyacinth biomass into biogas, biofuels, and valuable chemicals (Carlini et al., 2018). Enzymatic hydrolysis and microbial fermentation are biotechnological methods that can harness the potential of water hyacinth cellulose and hemicellulose for the production of bio-based goods and biochemicals, offering both economic and environmental benefits. The burden on natural resources, such as forests and fossil fuels, can be alleviated by converting this invasive weed into a useful feedstock, resulting in a more sustainable and circular economy. Furthermore, the use of water hyacinth can help waste management efforts by transforming a troublesome waste stream into useful goods, reducing the environmental effect of typical disposal methods. Maximizing the potential of water hyacinth in the bioeconomy requires developing partnerships between government agencies, academic institutions, industrial players, and local people. Public-private partnerships may promote information exchange, technology transfer, and capacity building, therefore fostering the development of water hyacinth-based bioindustries. Involving local people in sustainable harvesting and processing can also improve their livelihoods and promote inclusive development. Finally, an appropriate legislative and regulatory framework, together with scientific and technical advances, can open the road for water hyacinth to be used as a significant bioresource in India. The bioeconomy may profit from the commercial worth of water hyacinth while also contributing to environmental sustainability and resource efficiency by recognizing the potential of this invasive weed and supporting sustainable and creative practices.

Biology, global spread and management of water hyacinth

Aquatic weeds like water hyacinths grow with little to no monetary or human resources. They are already present in record numbers around the planet, are quite prolific, and require little in the way of nutritional care. A body of water can have 15 to 85% of its surface covered by aquatic weeds, based on surveys and studies. The water hyacinth, or *P.crassipes*, is the most widespread and intrusive aquatic weed that poses a terrible global issue to aquatic environments or water bodies (Serafini et al., 2024). In a few weeks, the whole surface of a eutrophic water body is covered with water hyacinths due to their rapid invasion. The plant covers the water body with a thick mat, preventing natural gas exchange and sunlight access, limiting diatom development in the limnetic zone. this aquatic weed invasion upsets the water body's natural richness of vegetation and wildlife due to reduced light access, subsurface photosynthetic activity, low dissolved oxygen levels, and nutrient depletion due to lack of natural aeration and a free water surface (Mailu, n.d.). Water hyacinth mat decays in ponds, raising BOD and reducing pisciculture activity (Honlah et al., 2019; Odame Appiah et al., 2019). Old mats emit nutrients, which are then absorbed by fresh plants, reinforcing the infestation cycle. The seeds of the water hyacinth may survive for up to 20 years in benthic muck and reproduce both sexually and asexually. It is among the fastest-growing plants, doubling in number in only two weeks (Chen et al., 2010). Moreover, disease-carrying insects, particularly mosquitoes, thrive in areas where water flow is slowed by water hyacinth growth (Tewabe, 2015). Mats of water hyacinth enhance snail populations, which play a role as vectors for the Schistosomiasis parasite (Borokini & Babalola, 2012).

Origin, global spread and localization in Indian subcontinent

Water hyacinth is supposed to be native to South America's Amazon River region, but it is now widespread on every continent except Antarctica, making it a readily available natural resource. Water hyacinth, introduced in the 1800s, has spread to over two-thirds of the United States, affecting economic regions near Victoria Lake. It is also prevalent in southern and northern Africa, and has developed in stagnant water bodies in Bangladesh, carrying mats weighing 300 tonnes per acre. During the monsoon, it multiplies and spreads rapidly on newly inundated flood plains (Fig. 3) (Dechassa, 2020; Dersseh et al., 2019).

The water hyacinth was brought to the Indian subcontinent during British colonial rule in the late 1700 s as a visually pleasing flowering plant. It is not native to the Indian subcontinent. Water hyacinth, known for its beautiful purple or violet blossoms encircled by a rosette of green leaves, was a popular take-home present at exhibits. It was dubbed "Bengal terror" & "blue devil," not long after it was brought as an ornamental plant to the Indian state of Bengal and is now found in practically all water bodies in Bengal, Assam, Odisha, and other places. It has become a significant concern for ecologists, scientists, and local residents across the country, from Kerala to Srinagar, Nagaland to Rajasthan (Fig. 4) (Harun et al., 2021).

Management strategies

The spread of invasive weed species is a major danger to biodiversity, economic growth, and human health. Management techniques have been established across the world to restrict and slow its growth, but recent decades have demonstrated that social abatement, in addition to physical, chemical, and biological measures, is required to effectively remove this invasive weed from polluted water bodies. Involving local stakeholders in decision making through adequate awareness raising and using their traditional know-how would result in long-term sustainable abatement measures. Researchers studying the aquatic weed invasion in Victoria Lake emphasized the contributions of the different organizations involved in the management process (Brooks & Patel, 2022; Honlah et al., 2022; Sharma et al., 2015).

Physical management

In order to keep the surface of inland surface water bodies and navigation channels clean for fishing and boat traffic, regular physical removal of mats requires cutting, harvesting, or mining using manual or automated instruments (Moyo et al., 2013). Physical eradication of water hyacinth mats may include draining the contaminated body of water or lifting the mat using nets (Patel, 2012a). Recently, the use of mechanized harvester or crusher boats for vast swathes of contaminated sections has become common. Harvested mats often accumulate near water bodies, causing odor nuisance and causing water quality issues. A large percentage of the mat frequently falls to the bottom, which is compounded by its in-situ disintegration (Anteneh Wassie, 2014). Physical removal procedures, while only providing brief respite and being expensive, are frequently selected when quick cleansing of the water surface is sought. It is

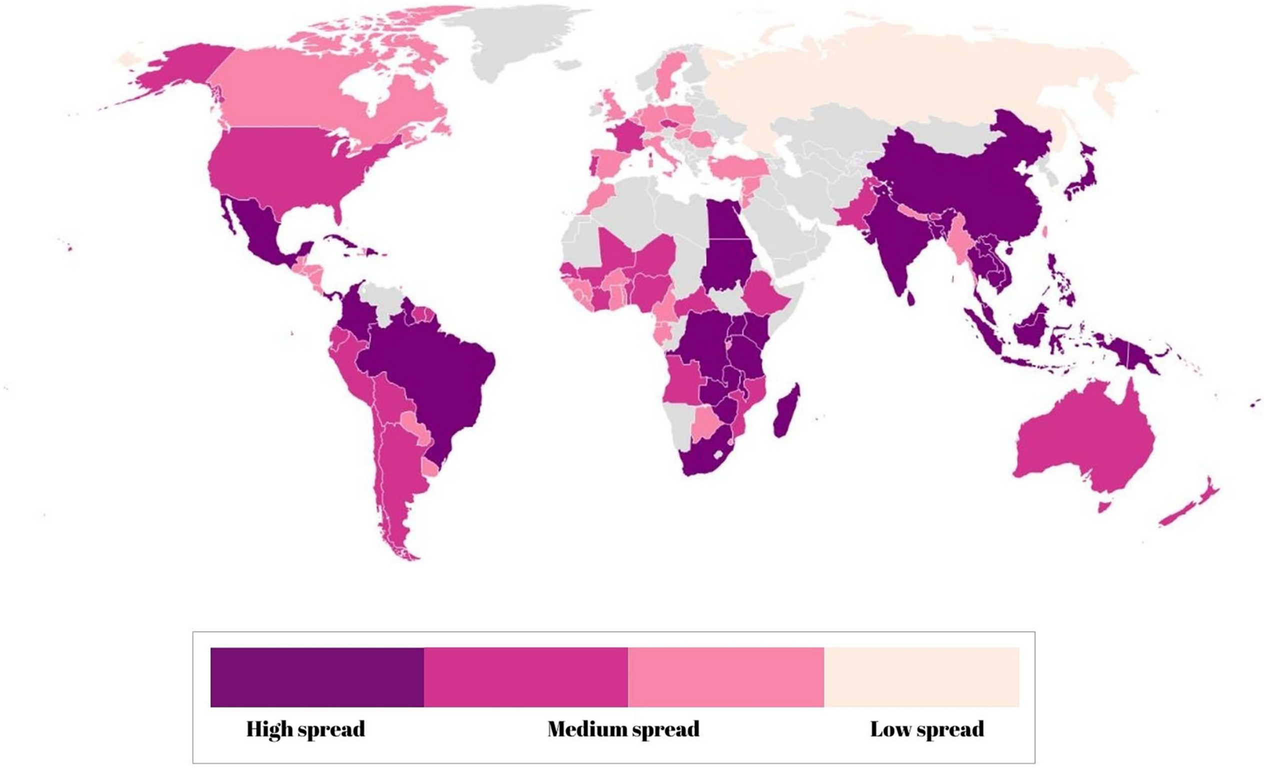
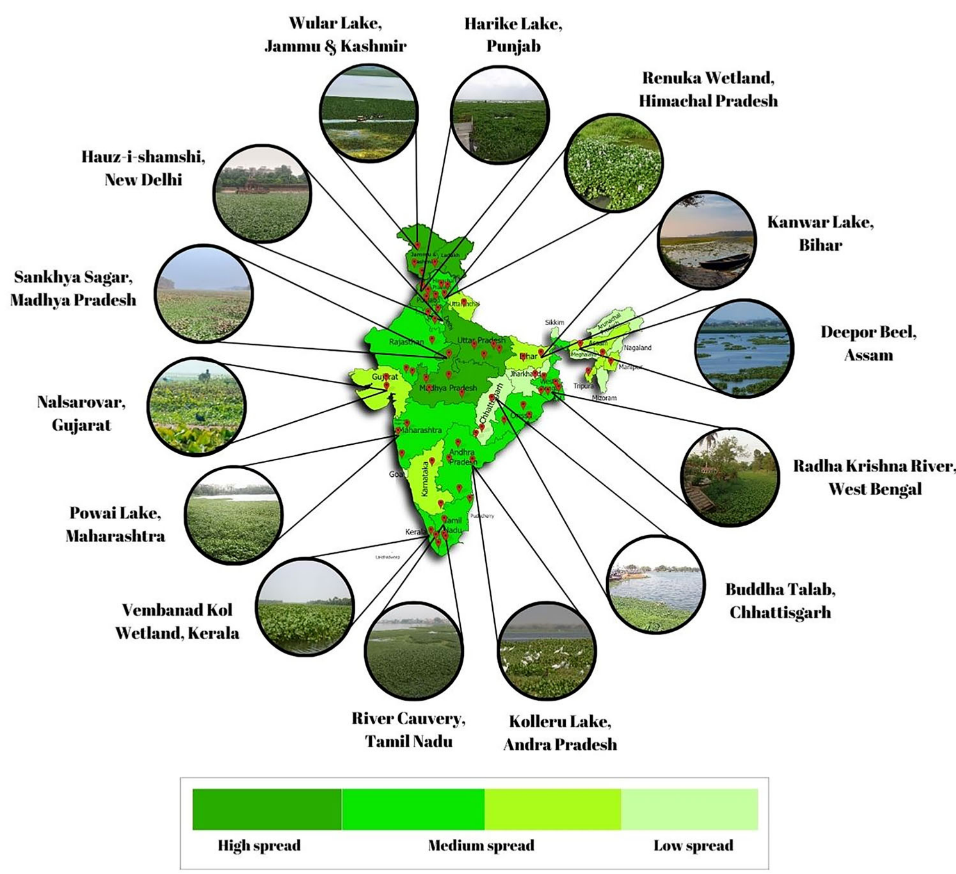


Fig. 3 Diagrammatic heat map depicting the global distribution of water hyacinth's prominent presence

Fig. 4 An illustration of the spread and locations of notable water hyacinth presence in India using a schematic heat map



also suggested for hand plucking water hyacinth from shallow areas of a contaminated water body where people can readily stroll in. Locations with low-cost manual labor (Coetzee et al., 2017).

Chemical management

Chemical eradication with herbicides such as glyphosate is prevalent in Kerala rice fields to control water hyacinth infestation. Chemical management methods have the potential to effectively and swiftly restrict the growth of water hyacinth over a large area, in contrast to physical eradication techniques. Chemical control measures, on the other hand, are only effective for a short time and frequently have a negative influence on the aquatic ecosystem (Oyedeji & Abowei, 2012). Herbicides and other hazardous synthetic chemicals are often banned in coastal water bodies or estuaries due to their potential negative impact on marine life. Biological management techniques for water hyacinth have been documented in recent decades (Coetzee et al., 2017). These strategies investigate the possible use of water hyacinth natural enemies to restrict the fast growth of water hyacinth mat (Bownes et al., 2013).

Biological management

Biological management strategies include releasing water hyacinth-feeding moths, fungus, and weevils into the environment (Jernelöv, 2017). The fundamental challenge is that such efforts might take several years to attain sufficient numbers to cope with pests (Julien, 2001). To avoid negative impacts on the ecosystem and the formation of new environmental issues, the introduction of a foreign moth or bug must be handled with extreme caution. In order to control water hyacinth infestation organically, *Neochetina eichhorniae* Warner was introduced to South Africa.So far, periodic yearly evaluation has proven reasonable success (Hill & Coetzee, 2017). However, the success of biological management is frequently tied to the lake's nutritional level and other environmental conditions such as water temperature. According to some research, combining low nutrient waters with greater temperatures might reduce the efficiency of these treatments. The study indicates that herbivorous insects significantly impact water hyacinth mats, which rapidly grow and are linked to mesotrophic and eutrophic nutrient levels in water (Firehun et al., 2014; He et al., 2022).

Water hyacinth monitoring on a regional and national scale

In order to make use of water hyacinth, it is necessary to determine the types and distribution of the plant in certain farms, agricultural zones, freshwater bodies, and locations with stagnant water. Weed monitoring is critical for this process. The most efficient methods for monitoring weeds involve the use of Artificial Intelligence (AI) and Machine Learning (ML) models, as well as remote sensing and GIS technologies. Remote sensing, in particular, provides precise real-time data for live monitoring. Various sensors are available for this purpose, such as RGB or visible sensors, multispectral, and hyperspectral sensors. Unmanned aerial vehicles (UAVs) have also emerged as highly effective tools in precision agriculture. Combining UAV technology with ML algorithms allows for accurate identification of weed patches in fields, contributing to sustainable weed management. Different ML algorithms can be used to support weed monitoring effectively, shown in Table 1.

Discussed are some general types of machine learning approaches that may be utilized for weed detection and monitoring, which include supervised and unsupervised learning. Supervised Learning refers to a method where the training and validation datasets are labeled, meaning the input-output pairs are known beforehand. The model is trained to map inputs to specific outputs based on this labeled data. It is commonly employed in solving classification and regression tasks. Semi-Supervised Learning, on the other hand, lies between supervised and unsupervised methods. It makes use of both labeled and unlabeled data. An example of a semi-supervised learning model is the Graph Convolutional Network (GCN) (Berg et al., 2017). Unsupervised Learning, on the other hand, is used when the training dataset is unlabeled, meaning the model does not have predefined outputs. The model's task is to discover underlying structures or patterns in the data. Analyzing the input clusters, similar data points are grouped into groups based on shared characteristics without prior knowledge of the categories. This process allows the unsupervised model to categorize the entire dataset into distinct clusters, with items in the same cluster being more similar to each other than to those in other clusters. One common application of unsupervised learning is clustering, which is used in areas such as market segmentation, anomaly detection, and natural language processing.

In deep learning, various algorithms can be applied to tasks like weed detection. Convolutional Neural Networks (CNNs) are frequently used for image-based tasks due to their ability to learn spatial hierarchies in visual data. Region Proposal Networks (RPN) are specialized networks that identify regions of interest in images, commonly used in object detection tasks. CNNs are extended by Fully Convolutional Networks (FCN), which substitute convolution layers with fully connected layers. This allows CNNs to be used for pixel-level tasks, such as image segmentation. Graph Convolutional Networks (GCNs) are applied when the data has a graph structure, and they leverage the

Table 1 Different machine learning techniques for water hyacinth and weed monitoring

Research Objective	Target crop	Experimental Approach	Major findings	Dataset	Reference.
To detect Water Hyacinth using coarse and high-resolution multispectral data	Water hyacinth	This study aims to identify water hyacinth by employing multispectral data with different spatial resolutions. Sentinel-2 MSI gathers coarse-resolution data (10 m), while an unmanned aerial vehicle (UAV) gathers high-resolution data (0.1 m).	In the analysis of UAV-based multispectral data for OA, all classifiers demonstrated high accuracy, with the lowest accuracy being 87% for SVM and the highest achieved by the RF classifier at 94%.	Study area: Mondego River basin, located between Coimbra and Figueira da Foz in Portugal.	(Pádua et al., 2022)
Using sentinel-1 Sar data to track water hyacinth in Kuttanad, India.	Water hyacinth	The study shows the use of Sentinel-1 for aquatic weed monitoring in Kerala's Kuttanad Lake and explores the use of Synthetic Aperture Radar (SAR) Sentinel-1 to identify water hyacinth in its early stages of development. It also explores alternative change detection approaches based on dual po-larimetric data.	Water hyacinth was found in Lake Vembanad, as evidenced by the pixel analysis from several locations of the lake, which showed differing backscattered intensities between infested and clean areas.	Dual-polarimetric Sentinel-1 Sar data, provided by the European Space Agency (ESA)	(Simpson et al., 2020a)
Tracking the Proliferation and spread of Water Hyacinth	Water hyacinth	The most current developments in the application of remote sensing for water hyacinth monitoring are examined and evaluated in this research. Additionally, they provide a possible multi-modal approach based on combinations for better outcomes.	A multi-modal system was developed and tested for continuous monitoring of water hyacinth. Various technologies were integraated, including Synthetic Aperture Radar (SAR), optical imaging, drone-mounted multispectral cameras, an Internet-of-Things-enabled ground sensor network, and contributions from citizen science.	SAR and optical imaging by European Satellites	(Datta et al., 2021a)
To use convolutional neural networks for weed detection.	Not specified	The Research presents a weed identification approach based on convolutional neural networks. CNN approach is divided into two major parts. First and foremost, image collecting and labeling. The second part is creating a 20-layer convolutional neural network model to detect the marijuana.	With an increasing number of epochs, the training set's accuracy improves. This implies that the model learns the complex patterns and features required for accurate weed identification through more training rounds.	Kaggle database, a set of 1000 images depicting weeds and crops was used.	(M. S. et al., 2021)
To distinguish and categorize weed various species.	8 weed plants	For weed species detection in an agricultural field, the study employs a recognition approach based on Grabcut and local discriminant projections (LWMDP). Grabcut is used to eliminate the background. K-means clustering (KMC) is used to segregate weeds from the entire picture. LWMDP is used to extract low-dimensional discriminant features. Finally, the support vector machine (SVM) is used to identify weed species.	The local weighted maximum margin discriminant analysis, along with the GrabCut and local discriminant projections algorithms, provided superior performance compared to other methods. Data augmentation: 20 times: affine transformation, perspective transformations, and basic image rotations, 99% identification rate with convolutional neural network (CNN). Average recognition rates for all algorithms, based on 50 runs, yielded recognition results with a 95% confidence level.	South China crop fields provided 1600 weed images.	(Y. Zhang et al., 2019)

connectivity between data points to improve learning. Lastly, Hybrid Networks (HN) combine different deep learning architectures, enabling models to benefit from multiple approaches, which is particularly useful in complex tasks like weed detection where both image and relational data may be important. These deep learning models are powerful tools in precision agriculture, allowing for improved detection and classification of weeds, which contributes to more sustainable farming practices. Studies have been conducted to detect and track water hyacinth and aquatic weeds, as well as estimate the water loss caused by these plants (Ali & El-Din Khedr, 2018), development of early weed detection with the help of image processing and machine learning (N. Islam et al., 2021), identification and classification using Grabcut and local discriminant projections (LWMDP) algorithms (S. Zhang et al., 2019), and monitoring water hyacinth in Kuttanad, India using sentinel-1 Sar data (Simpson et al., 2020a). Such studies pave way for better analysis of actual regional spread of water hyacinth and projections for potential harvest.

Weed Mining, a new avenue for circular bioeconomy industries

After monitoring and identification of sources, the next aspect for valorization of water hyacinth is its harvest. Aquatic weed mining and collection, at its core aquatic b or more specifically water hyacinth mining gives solution to a two faced problem; firstly, mined weed is used for national/regional socio-economic and bioeconomic development through valorization of the product in the form of handicrafts, textile, fiber additive, bioenergy and feedstock substation/additive; secondly, proper management of a highly invasive aquatic weed is achieved which if left unmanaged would enable irrigational, water harvest and pisciculture challenges, along with adversely affecting on the aquatic ecosystem, flora and fauna of the region. Aquatic weed mining or extraction involves the application of various manual and automated techniques to mitigate the proliferation of invasive aquatic weeds, such as water hyacinth, in water bodies. Aquatic weed mining encompasses a range of approaches aimed at efficiently removing and collecting water hyacinth to be used for further applications (Fig. 5).

Manual techniques involve the physical labor and use of manual tools. Manual techniques can be functional for smaller water bodies or locations with a logistical barrier where access to heavy machinery is limited. Hand pulling a labor-intensive method that entails manually uprooting aquatic weeds by hand. Hand pulling is particularly suitable for smaller infestations or situations requiring precision removal (Patel, 2012b). tools like rakes or skimmers can be employed to collect floating water hyacinth near the edges. This technique could be advantageous for dense weed growth and can be combined with manual or mechanical harvesting methods to enhance the harvest process. Very effective for removing loose or dispersed water hyacinth mats on the surface. Water hyacinth can be severed using tools such as sickles or handheld weed cutters, after which they are gathered and extracted from the water (Pradhan & Kumar, 2019).

Mechanical approaches enable large-scale and effective weed extraction through the use of machines and equipment. These methods work best on larger bodies of water and widespread infestations. Weed harvesters, a specialized machinery made to chop, gather, and remove aquatic weeds, can be employed for raw extraction of water hyacinth. Conveyor systems are frequently used in these devices to move the weeds that have been picked into containers for disposal or additional processing. Dredgers can be used to clear sediment and aquatic weeds from the bottom of a body of water. Together with the underlying ground, they remove the weeds using suction or excavation techniques. Machinery like weed mowers can employ cutting blades or rotating drums to shred water hyacinth underwater. The chopped water hyacinth can then be collected using conveyor belts or other attachments.

Technological progress can enable the creation of automated or semi-automatic methods for harvesting crops, which can be adjusted to fit processes for aquatic extraction. These methods could remove weeds effectively by utilizing robotics and artificial intelligence. Drones and remotely operated boats are examples of unmanned vehicles that can be outfitted with cutting or collection tools to target certain aquatic weed-affected areas. They are especially helpful in remote or environmentally delicate areas. Real-time detection and identification of particular weed species is possible through the use of image recognition and machine learning. The automated weed extraction process is then guided by this information, increasing efficiency and decreasing the need for manual intervention (Kaizu et al., 2021; Tudor et al., 2022).

The best method for mining aquatic weeds depends on a number of variables, including the extent of the infestation, accessibility, environmental concerns, and available resources. A blend of mechanical, automated, and manual methods can be utilized to efficiently gather raw materials for different sectors. A recent study served as a proof of concept for the idea of weed mining, whereby hyacinth was manually gathered from community ponds located throughout the Puri district in the Indian state of Odisha. The captured biomass was left to drain the surplus water overnight. A fresh biomass sample was obtained for examination. Water hyacinth biomass was combined with Madhyam culture, paddy straw and cow dung. At regular intervals, heap turning and watering were performed to

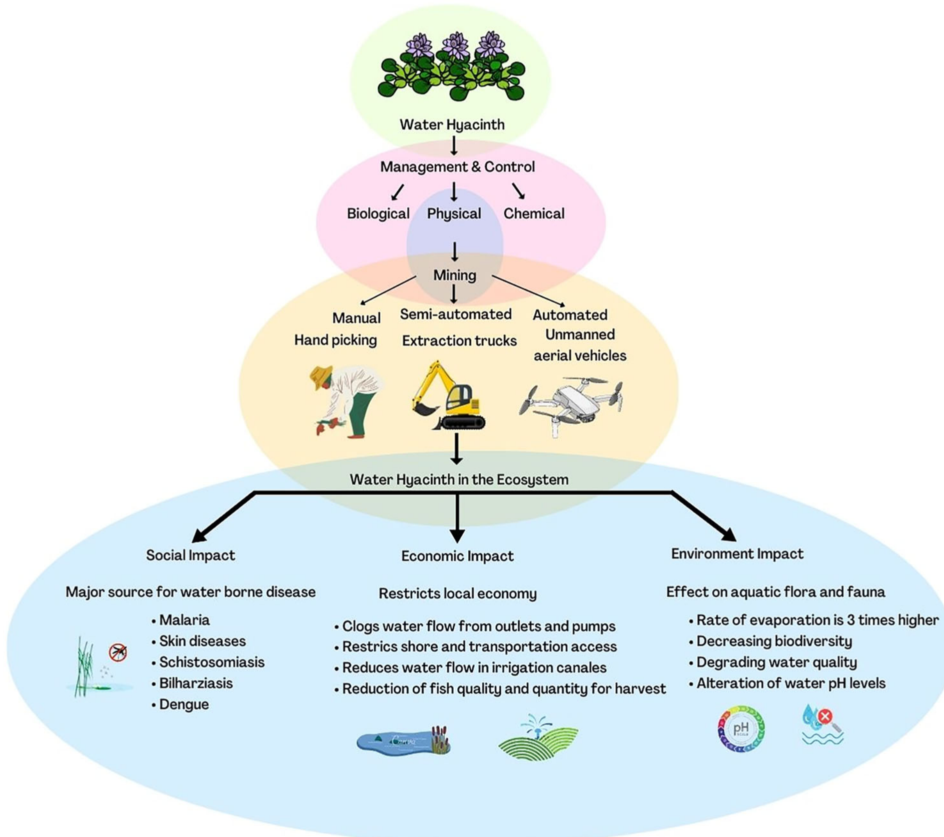


Fig. 5 Descriptive flowchart of water hyacinth management and it's interaction in the ecosystem

ensure correct mixing, heat dissipation, and enough moisture. After two months of the entire procedure, compost samples were collected for examination. The set protocol involved a total production and running cost of about USD 1000 dollars. Projected yearly revenue upwards of USD 3300 dollars was expected with 2.4 months of break even period.

Valorization of water hyacinth in various industries

Water hyacinth being a highly underutilized aquatic biomass resource presents a great source as a substrate for bioenergy production. Satisfying most biomass prerequisites, water hyacinth has been immensely used as co-fuel and briquette biomass. Numerous studies have investigated the production of bioethanol from water hyacinth using saccharification substrates and various pretreatments to maximize sugar to ethanol conversion after fermentation (Aswathy et al., 2010; M. N. Eshtiaghi, 2012). Similar studies have shown efficient results in vitro and vivo for biofuel generation using water hyacinth as a raw substrate (Bote et al., 2020; Li et al., 2021). Combustible resources are highly valued in rural regions and are of great importance in industries as well. Presently briquettes are made from coal or combustible woody material. Water hyacinth has been shown to act as an effective additive or replacer of these materials, having a smaller carbon footprint (Supatata et al., 2013). Traditionally produced biofuel from non-edible to edible agricultural waste has less practicality on a large scale with higher running costs and capital investment for pretreatment and fermentation process. The increased expenses and high energy needs for producing biofuel from currently accessible substrates should be reduced in order to generate a carbon-neutral product. One of the major drawbacks of existing processes being intensification of competition for food resources and agricultural land. Thus, water hyacinth offers to be an under/un-utilized source of biomass. Various studies suggest creating and regulating economic policies to support long term sustainability of the biofuel and bioenergy industry. The shift towards a circular bioeconomic model, particularly in countries with food security and large-scale centralized biofuel production, is crucial, especially considering water hyacinth as a decentralized economic resource, as an invasive aquatic weed (Aro, 2016; Covert et al., 2016; Tahir et al., 2019).

Current eradication control tactics may not be long-term viable. It is vital to employ economically self-sustaining ways for harvesting, mining, and using water hyacinth. With the limitations of using mechanical harvesting, biological or chemical control measures, low-cost and periodic

Table 2 Several value-added products made with water hyacinth as a bio-resource

Product	Source	Economic output	Remarks	Reference
Feed	Water hyacinth shoot	The nutritional characteristics of water hyacinth render it an outstanding substitute and supplement for animal feed.	High cellulose, hemicellulose and crude protein content.	(Abegunde et al., 2020; LU et al., 2008)
Biofertilizer/ compost	Water hyacinth shoot	It can be immediately used for biofertilization, composted, or broken down anaerobically.	Rich in inorganic substances such as potassium (K), phosphorous (P), and nitrogen (N) as well as organic nutrients	(M. N. Islam Et Al., 2021; Lu et al., (2017); Villamagna & Murphy, 2010)
Textile and crafts	Water hyacinth shoot	It is utilized as a supportive, additive, and alternative material in textiles.	Greater biocompatibility is achieved with adequate dried fiber length and flexibility.	(Alzate et al., 2022; Arivendan et al., 2022)
Bioenergy	Water hyacinth shoot	It serves as a precursor substrate for hydrolysis, enabling the production of fermentable sugars, as well as methane, hydrogen, and ethanol.	By treating water hyacinth beforehand, biomass can be efficiently converted to biofuel and bioenergy.	(Adwek et al., 2019; Ezama, 2019)
Bioactive Agents	Water hyacinth leaves	It is utilized as an additive in both agriculture and the pharmaceutical industry to create antibacterial, antifungal, and anticancer products.	Shows significant inhibitory effects with both gram positive and gram negative strains. Also, effective in inhibition of breast cancer and cervical cancer cells.	(Krismariono et al., 2022; Lenora et al., n.d.; Ratnani et al., 2024; Taqi et al., n.d.)

hand harvesting and valorization of produced biomass emerged as a business concept incorporating rural adolescents. Such waste-to-wealth ventures may be adequately supported by applicable government policies and would give alternative livelihoods in India's rural hinterlands. Water hyacinth-derived biomass has the potential to be an important component of circular bioeconomic systems because of its high yield, cheap upkeep, and self-renewing qualities, shown in Table 2. Its worldwide presence nonetheless, inadequate management and control exist. By putting in place suitable management and monitoring procedures, new avenues for bioeconomic growth may become available. In addition to developing a new bioresource for circular bioeconomic growth, smart weed mining techniques and global and regional dispersion monitoring are required to address the complicated multilayer problem (Fig. 5) (Bajpai & Nemade, 2023; Ilo et al., 2021; Maturi et al., 2022). The harvesting or mining of the nutrient-rich water hyacinth will be biodegradable since 58.6% of the biomass is composed of cellulose and hemicellulose (Serafini et al., 2024). Because of its hygroscopic character and moisture retention ability, the created compost would be an excellent soil addition, particularly for sandy soil (Sharma et al., 2015). It should be noted that a variety of common heavy metals can bioaccumulate in water hyacinths from polluted sources. Water hyacinth extracted from industrial wastewater bodies should not be used as a soil conditioner, as it is claimed to be used for fish feed, paper, and biofuel production (Akinwande et al., 2013) emphasized the potential application as ruminant feed. Biomass high in nutrients might be used as animal feed in developing nations without access to a variety of dietary supplements (Jafari, 2010). Countries like Thailand and Malaysia use fresh water hyacinth boiled with rice grain, vegetable waste, and copra cake as feed for pigs, ducks, and lake fish (Malik, 2007). Biomass, often combined with coconut coir and jute, can be used for various handicrafts. In Assam, the Assam Livelihood Mission has used water hyacinth flower colors as organic dyes to create colorful handbags using this biomass (Barua et al., 2018). Water hyacinth's rapid growth prompted studies into its possible application in biofuel generation. Water hyacinth biomass may also be utilized to grow mushrooms (X. Chen et al., 2010). Two main industrially most relevant sectors are bioenergy and textile, use of water hyacinth as a bioresource for industrial applications has been discussed in the following sections, with depiction of potential business models that could be inherited into the existing pipelines.

Bioenergy generation from water hyacinth

A case study on the local people's perception on problems related to water hyacinth peculiar to the local communities

Table 3 Biogas production plant business model scheme prepared using resourced data from non-government and government resources

Scope of project			Cost (USD)
1.	Initial investment	Raw materials, labor and overheads (85 cubic meter per day)	$60000
2.	Operation and maintenance cost	Monthly	$5000
3.	Annual Income	Electricity Supply 130 unit at USD $0.073 per unit	$3600
		Slurry USD $18 per day	$6100
		Clean Development Mechanism (CDM) benefit	$900
4.	Cost and benefit	Total profit monthly	$6100
		Total annual income generated*	$11000
		Total investment for 5 yr. run**	5.4

*Annual income = $2.45 per unskilled labor per day for 22 days a month for 12 months, rate as per MGNREGA guidelines

**Cost benefit ratio = total profit/total income generated

and the usability of water hyacinth as a potential source of energy production, fertilizer production and several other benefits. In lieu of the same, responses of around 30 people which included students, farmers and fishermen among others were recorded as the motive of the study. The research yields intriguing findings on the socio-economic applications of water hyacinth WH. For example, the majority of participants (53.1%) mentioned usage as animal feed or fodder, mulching material (22.2%), craft items such basket manufacturing (11.1%), and application as bio-fertilizer (13.6%). Water hyacinth can be used for fertilizer, compost, or green manure, can improve soil fertility and crop productivity. It has the ability to replace costly inorganic fertilizers and lessen the danger of deforestation. This increases environmental awareness and may encourage biofuel production as a climate change mitigation option. However, collecting water hyacinth for biofuel production may compete with other feasible socio economic initiatives, such as agricultural fertilizer manufacturing. Low-cost items must be considered for effective biofuel manufacturing. Communities surrounding Lake Victoria may profit from inexpensive biofuels (Adwek et al., 2019).

India has identified water hyacinth as a potential feedstock for biogas production. Anaerobic digestion, where microorganisms break down organic waste without oxygen, is used to produce biogas from water hyacinth. This biomass source is a sustainable energy source. The Sanatana Dharma College's Centre for Research on Aquatic Resources (CRAR) and the Sardar Patel Renewable Energy Research Institute (SPRERI) have developed effective bio-methanation methods using bubble gun technology. The government's "Programme on Energy from Urban, Industrial, and Agricultural Waste/Residues" aims to integrate water hyacinth biomass in biogas generation, generating power, biogas, and bioCNG from various wastes (Dwi Nugraha et al., 2021). Table 3 depicts a potential business model for setting up a biogas plant in South Asia.

Textile and handicraft from water hyacinth

A common issue in India is a strong need for inexpensive raw materials for the paper and pulp sector. With a turnover of more than USD 8.5 billion, India's paper and pulp sector employs up to 5 lakh direct and 15 lakh indirect workers. Several strategies are given for using water hyacinth fibers in the manufacturing of handmade paper. Various initiatives and research efforts demonstrated the scientific validity and usefulness of the aforementioned procedure and produce (Datta et al., 2021b; Simpson et al., 2020b). Water hyacinth is widely used in paper manufacturing in India's rural regions, potentially transferring to other enterprises aiming to extract beneficial plant products from it (Lahon et al., 2023; Sundar Bhattacharya & Paul, 2012). As a result, adopting a water hyacinth-based product may allow for the acquisition of a low-cost raw material for use in handmade paper.

The North Eastern Development Finance Corporation Ltd and the North Eastern Council are partnering to use water hyacinth for value goods production, addressing the high cost and unpredictable availability of raw materials for Cane and Bamboo Crafts craftsmen, thereby promoting sustainable living and utilizing current workers' skills. The invasive aquatic weed in the region provides an excellent solution for this purpose (Balasubramanian et al., 2013; Borah, 2014). Assam, a region rich in flora and wildlife, has been utilizing the "Water Hyacinth" species, also known as "Pani Meteka," to create useful crafts. This natural resource can yield up to 657 tons of dry matter per hectare in water with high sewage concentrations, and is sold in local and national markets. The Water Hyacinth Craft Products under ASOMI® Brand, developed by Assam State Rural Livelihoods Mission, trained over 600 rural artisans to create various crafts, including bags, mats, shades, lamps, and carts. The project generated an income of over 6.4 million up until 2020. Another initiative under the North Eastern Development Finance Corporation (NEDFi) conducted a

Table 4 Handicraft business model scheme prepared using resource data from non-government and government resources

Scope of project			Cost (USD)
1.	Initial investment	Raw materials, labor (unskilled 20–25) and overheads	$11000
2.	Production Cost	Monthly. Assuming production cost is USD $0.24 per unit and 5000 units produced.	$1000
3.	Sales Revenue	Monthly (sale price USD $0.60) (Sales revenue - Production cost)	$3000
4.	Profit	Monthly profit	$2000
5.	Return on Investment	Per month. (Fixed cost*/contribution margin**)	16.67%
6.	Break-even point	Sale with constant production line (12 months)	60,000 units
7.	Cost and benefit	Total profit	$22000
		Total annual income generated***	$18000
		Total investment	$11000
		Cost benefit ratio for 5 yr. run****	1.48

*Fixed cost = initial investment

**Contribution margin= sales revenue-variable cost

***Annual income = $2.45 per unskilled labor per day for 22 days a month for 12 months, rate as per MGNREGA guidelines

****Cost benefit ratio = total profit/total income generated

pilot program with water hyacinth as a craft to promote sustainable livelihood in the region, where training to more than 5000 artisans by UNIDO (United Nations Industrial Development Organization), Thailand, gave opportunity to local artisans to collect and produce crafts for water hyacinth (Balasubramanian et al., 2013).

Invasive floating plants such as water hyacinth are a big concern in tropical nations such as Thailand, prompting a number of efforts to combat the problem. One such idea uses water hyacinth as a raw material for the handicraft sector because of its great elasticity and mechanical strength. The initiative focuses on four major components: using unutilized or underutilized trash to reduce the environmental impact of invasive weeds, preserving original Thai art forms and promoting local craftsmanship, creating a unified work environment, and creating jobs to generate income for the underemployed. Table 4. depicts a potential business model for setting up a handicraft business in south Asia.

A wide range of biobased products are now employed in the bioenergy, biofuel, textile, agricultural, culinary, and pharmaceutical industries. Bio-plastics, biofuels, bio-textiles, and bioadhesives are produced using various resources like starch, cellulose, seaweed, shellac, gelatin, wood, algae, vegetable oil, cotton, wool, silk, bamboo, soy silk, wood pulp, jute, and bananas (Ahmad et al., 2015). Bio-based textiles, such as recycled paper, cloth fibers, and yarn, are primarily used in industries and have specialized roles. These materials are biochemically, physically, and biologically treated to improve their tensile strength, tear resistance, burst strength, folding endurance, porosity, fiber size, and optical properties. Table 5 shows a comparison between physical properties and cost of common materials used for textiles and water hyacinth (Lotfi et al., 2021; Sulardjaka et al., 2022; Tanpichai et al., 2019).

High value products from water hyacinth

The water hyacinth plant is utilized as a feedstock for various high-end products like compost, organic acids, biogas, biofuel, industrial enzymes, and biofertilizers. Co-culturing techniques improved cellulase and xylanase production, reducing costs and promoting their use in bioethanol production, ultimately lowering the overall cost of ethanol production (Manivannan & Narendhirakannan, 2015). Water hyacinth has been successfully used as a lignocellulosic substrate to produce xylanase and thermostable xylanase, followed by bioethanol (Shyama Prasad Saha et al., 2012; Uday et al., 2016). A group used water hyacinth as a raw material and methane sulfonic acid as an acidic catalyst to generate levulinic acid as effectively as feasible (Lai et al., 2011). They also looked at the effects of process factors and composition. Another group devised a technique for extracting fatty acids from water hyacinth, which they then put into a methane digester to generate biogas. Because of its high cellulose concentration, low cellulose diameter, and high fibrosity, water hyacinth is an ideal reinforcing material for polymer composites (Ganesh et al., 2005). Table 2 contains a detailed overview of numerous studies to produce high-value byproducts from water hyacinth.

Table 5 Descriptive table comparing mechanical and chemical properties of Biobased materials and water hyacinth

	Mechanical properties							Chemical properties					
Bio-based material	Tensile strength (MPa)	Young's modulus (GPa)	Tensile modulus (GPa)	Elongation %	Fiber Dia. (μm)	Fiber length (mm)	Fiber density (g/cc)	Cellulose %	Hemi-cellulose %	Lignin %	Moisture %	Major producers	Cost (USD/ton)
Cotton	250–600	250–800	5–13	3–10	10–45	10–60	1.5–1.7	80–90	5–7	< 2	< 9	China, India and USA	1500–4500
Jute	350–800	6–80	8–80	1–2	20–350	1.5–120	1.3–1.6	60–70	13–20	10–13	< 13	India and Bangladesh	400–1500
Bamboo	140–300	150–00	10–30	2.5–4	25–50	1.5–5	0.6–1.3	25–65	25–35	5–35	70–0	China, India and Indonesia	300–600
Coconut (Coir)	15–300	90–230	2.5–7	15–60	10–480	20–150	1.15–1.7	30–45	0.1–20	40–50	< 8	India, Vietnam and Sri Lanka	200–600
Banana	500–900	5–45	10–35	1.5–9	12–40	300–900	1.2–1.9	60–70	10–20	5–10	8–15	India, China, Indonesia and Brazil	2000–5000
Flax	300–2000	40–80	27–103	1.2–3.5	12–600	5–900	1.3–1.8	60–70	18–22	2– 5	8–15	Russia, Canada and China	900–3000
Hemp	200–900	20–60	23–90	1–4	25–500	5–60	1.4–1.7	68–75	15–23	3.7 – 10	6–12	China, France and Italy	700–1200
Water hyacinth	50–400	5–50	10–50	2–10	2.3–50	80–350	1–1.7	45–60	20–30	< 4	75–90	Globally present	400–1500

Phytoremediation and effluent treatment using water hyacinth

Wastewater treatment is a major concern for industrial sectors, as untreated wastewater contributes to ecosystem destruction and soil degradation. Water hyacinth, an aquatic macrophyte, has been used in phytoremediation due to its ability to absorb heavy metals and other contaminants. A laboratory-scale method for heavy metal removal from glass industry wastewater, utilizing water hyacinth and data kinetic modeling, has been developed, with potential reductions of up to 90% in heavy metals like Cadmium, Copper, Iron, Manganese, and Zinc (Singh et al., 2022). A study investigated the phytoremediation capabilities of water hyacinth, highlighting its ability to bioaccumulate heavy metals. The findings revealed that it absorbed 166.25 ppm of cadmium from the water (Nazir et al., 2020). Based on water hyacinth capacity and rate of removal, another research rated heavy metal removal in the following order: Cu > Zn > Ni > Pb > Cd (Liao, Chang 2004). Water hyacinth may remove heavy metals from distillery effluent in 15 days, including iron, zinc, sodium, potassium, magnesium, and calcium (Bathla, 2016). Research findings suggest that water hyacinths can achieve over 80% removal efficiency for antibiotics such as oxytetracycline hydrochloride, tetracycline hydrochloride, chlortetracycline hydrochloride, and sulfadiazine within 20 to 25 days. (Yan et al., 2019), while another study demonstrated a 14-day investigation on the absorption and elimination of herbicides such as Mesotrione and anticipated with a clearance effectiveness of 96–98% (Chen et al., 2019). A novel magnetic hybrid biomaterial system for removing metals and medicines from aqueous environments utilizing water hyacinth was also created, with up to 50% metal adsorption in 5 min, 90% ibuprofen adsorption in 5 min, and good catalytic activity in the reduction of 4-nitrophenol of up to 100% in a few seconds (Lima et al., 2020). A new phytoremediation kit, combining water hyacinth and two bacillus species, has been developed to effectively remove inorganic and polycyclic aromatic hydrocarbons from industrial wastewater, with high metal removal capacities ranging from 60 to 80% (Mahfooz et al., 2021).

Green electronics and nanoparticle synthesis

Structural properties of charcoal in activated form enhance conductivity in electronic components like supercapacitors. Water hyacinth, a cellulosic biomass source, can be used to produce carbon-based products like microspheres, activated carbon, carbon nanodots, and biochar. Using treated water hyacinth to produce carbon microspheres revealed an impregnation ratio of 1:1 through electrochemical measurements. The maximum specific capacitance was achieved at a microwave power of 630 W, along with electrochemical stability (Kurniawan et al., 2015). A novel approach for generating silver nanoparticles from water hyacinth leaves has been devised for colorimetric heavy metal sensing, with great selectivity for mercury ions and outstanding sensitivity to other metal ions (Oluwafemi et al., 2019). Studies have demonstrated successful biochar production from water hyacinth for applications in supercapacitors, biosensors, and printed electronics conducting ink (Mo et al., 2020; Saning et al., 2019; Zheng et al., 2020).

Bioactive agents

It has been documented that Eichhronia crasspies contain some useful properties that can be exploited in the biological field. Here, the antibacterial and anticancer properties of hyacinth extract are detailed. A research group reported the water hyacinth extract of E. crassipes was found to possess antibacterial activity. The ethanolic extract was tested against two standard strains, S. aureus and E. coli. Results showed good antibacterial activity, which was better in the case of S. aureus than E. coli (Taqi et al., n.d.). Another evidence of antibacterial activity was also reported where ethanolic extract of Eichhornia crassipes was tested against bacterial plaque from gingivitis patients, a common gum disease. It was found that there was a decrease in the number of plaque bacterial colonies. Minimum inhibitory concentration reported of hyacinth extract was 3.125% having killing efficacy greater than 90% (Krismariono et al., 2022).

Water hyacinth has been found to possess anticancer properties, as demonstrated by a study on the MCF-7 breast cancer cell line. The E.crassipes ethanolic extract significantly inhibited cell growth, with cytotoxicity increasing with concentration. At 100 µg/ml, over 80% of cells were dead, making it a valuable antiproliferative and cytotoxic agent (Taqi et al., n.d.). Methanolic extract of water hyacinth was also tested against human cancer cell line (HeLa). With the increase in concentration of extract, the percentage viability decreases. Growth inhibition was 17% at 200 µg/ml. It was confirmed mild anti-cancerous in this case (Lenora et al., n.d.). The bio activity of water hyacinth is because of the chemical compounds like flavonoids, alkaloids, tannins, saponins, terpenoids, phenols, glutathione and other metabolites. Not only this, water hyacinth is effectively used as a fungicide, pesticide, herbicide, algaecide, anti-termite, antioxidant and antiviral agent (Ratnani et al., 2024).

Conclusion

In order to transition to a circular bioeconomy, waste formation must be reduced or biological resources must be used as an alternative. Additionally, biological resources must be used to generate end waste. The growing interest in exploring new bioresources for bioenergy, bioremediation, and bio-textiles is focusing on valorizing these resources. Water hyacinth, an underutilized, self-replicating aquatic weed, presents an opportunity for valuing these resources. This self-replicating weed requires little economic input for development, maintenance, and harvesting, which mitigates its detrimental socioeconomic and environmental effects. The use of water hyacinth can lead to the establishment of sustainable development networks at the local, regional, and national levels. A distinctive opportunity is clearly evident: water hyacinth has the potential to impact various sectors of the economy because of its overlapping mechanical and chemical properties, which can partially or fully replace existing standard biomaterials. Its localized availability facilitates the establishment of both on-site and off-site processing facilities, reducing costs associated with mobile stations. An untapped pathway of enabling water hyacinth into the existing centralized production and manufacturing pipelines can render an opportunity for transitioning to decentralization of bioenergy, biofuel, textile, agricultural, culinary, and pharmaceutical industry, which in-turn boosts local economy.

Presently, many localized small-scale industries are set up with the help of governmental aid and major private business holdings have been established across the Indian subcontinent that promote and employ water hyacinth to develop biobased products. However, a major barrier for such industries has been efficient valorization of water hyacinth due to limited scope of its monitoring and mining, which has led to confinement of this resource to small-scale industrialization. To bridge this gap between localized small-scale industries and national bio-based large scale industries a need for effective monitoring and mining is essential. The monitoring and novel approaches to aquatic weed mining are covered in this review, with an emphasis on the efficient collection, processing, and use of biomass. This water hyacinth cycle bioeconomic application might help the Indian subcontinent develop sustainably and solve bioeconomic issues.

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Compliance with ethical standards

Conflict of interest The authors declare no competing interests.

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