Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Evaluation of water hyacinth utility through geospatial mapping and in-situ biomass estimation approach: case study of Deepor beel (wetland), Assam, India

Koshal Rajora
Guru Gobind Singh Indraprastha University
Shipra Tyagi (shipra.usem.900680@ipu.ac.in)
Guru Gobind Singh Indraprastha University
Kiranmay Sarma
Guru Gobind Singh Indraprastha University
Arun Kumar Sarma
North East Centre for Technology Application and Research, Govt. of India
Rajendra Jena
North East Centre for Technology Application and Research, Govt. of India

Research Article

Keywords: Water hyacinths, Deepor beel, Wetland, Assam, Sentinel, Geospatial mapping

Posted Date: April 6th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2767129/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Version of Record: A version of this preprint was published at Environmental Monitoring and Assessment on October 6th, 2023. See the published version at https://doi.org/10.1007/s10661-023-11900-8.

Abstract

As an invasive species, water hyacinths (*Eichhornia crassipes*) are known to progressively proliferate and cause the ecological invasions of aquatic environment. Their incursions not only cause the disappearance of native species but gradually degrades the natural habitats of freshwater regimes. The control and management of these species is laborious task, however, transforming weed into wealth can substantially serve a sustainable approach to reduce the efforts. Therefore, the present study intends to utilise the application of geospatial techniques for mapping the water hyacinths growth in the Deepor beel (wetland) of Assam, India. Sentinel based image analysis has shown that pre-monsoon seasons has encountered massive productivity and area coverage of water hyacinth, whereas in post-monsoon seasons, productivity of water hyacinths reduces to half. Furthermore, i*n-situ* biomass estimation of the water hyacinths samples same around the productive season has been collected and analysed 6 kg (green biomass) and 1 kg (dry biomass after sun-dried). Finally, this hybrid approach evaluated the production and revenue generation from Moorhen yoga mat (handicraft item) made from the dried water hyacinths. After assuming the actual availability of 50% of total mass yield of water hyacinths, around ~ 0.8 million (8.8 lakhs) yoga mats can be commercially produced within the most productive seasons. The revenue generation from the yoga mat in the domestic and international markets evaluated around US $ 12.79 million (Rs. 105.85 Crore) and US $ 15.99 million (Rs. 132.31 crore), respectively from a single productive season. Thus, applicative intent of this study can boost potential market in Assam, renovate the weed waste of water hyacinth into wealth generation, and sustainably support the livelihoods of the local communities.

Introduction

Water hyacinths (*Eichhornia crassipes*), in freshwater ecosystems, can adapt and tolerate variations in the environment (Sainty, 1988). It offers habitat complexity and serves as a substratum for shelter and feeding grounds for myriad of aquatic species. However, its ecological significance can regressively transform into ecological invasion of the aquatic habitat. The biodiversity of freshwater regimes has been facing a great threat from such proliferation rates of “free-floating” invasive plants. Water hyacinths have been listed among 100 most invasive species (Lowe et al., 2000; Rakotoarisoa et al., 2016) and it has found to spread over entire globe from its native ecosystem in Amazonia and Brazil (Degaga, 2018). Spatial distribution and configuration of water hyacinths has deteriorated the aquatic life (Mironga et al., 2012; Meerhof et al., 2006; Murkin & Kadlec, 1986). It not only obstructs sunlight penetration into the deeper regions of the water bodies but also inhibits the photosynthesis rate for the submerged plants (Wang et al., 2007). This scenario triggers non-conducive as well as inhabitable ecological conditions that can inhibit planktonic growth and evade the flourishing diversity within aquatic life (Li et al., 2007). It also contributes to eutrophication, slows down water currents flow and deposition of debris at the bottom. The pronounced adverse impact of water hyacinths has been encountered on the zooplankton population density (Mironga et al., 2012; Chukwuka & Uka, 2007). Moreover, the massive productivity augments the hypoxic conditions which declines the dissolved nutrients, disrupts the cyclical nutrient flow, and increases turbidity of surface water bodies. Literature has also revealed that rampant growth of this fast-growing weed induces hypoxic conditions for optimum breeding of the pests and waterborne disease carriers such as encephalitis, filariasis, and mosquito, thereby excluding breeding, or nesting grounds of the aquatic species (Twongo & Howard, 1998). The physical removal of the water hyacinth is a laborious task and subsequent disposal and decomposition also poses serious environmental health concerns. Therefore, water hyacinths need a sustainable strategy for its uncontrolled growth and management.

From the prespective of aquatic weed management, remotley captured information has aided and rendered the inhibiting barriers within the utilization of remote sensing (Kwok, 2018; Thamaga, 2018). These techniques have been providing enhanced projection to detect and map the water hyacinth distribution in the water bodies in spatio-temporal manner. Several remote sensing based studies have been attempted to track the water hycaniths (Everitt et al., 1999; Hestir et al., 2008; Schmidt & Witte, 2010; Jakubauskas et al., 2002; Venugopal, 1998). Alvarez-Taboada et al. (2017) has identified the plant invaded ecosystems through the application of Sentinel 2-A, Sentinel 2-B and Landsat-8 data and are widely utilised to improve the understanding on the drivers, processes and effects of plant invasions. Oyama et al. (2015) also used Landsat 7 TM and ETM + shortwave infrared bands (SWIR bands) and utilised Floating Algal Index (FAI) and $NDWI_{4,5}$ to differentiate surface cyanobacterial blooms and aquatic macrophytes. Likewise, Landsat driven studies have been performed in data detection and mapping the spatial configuration of water hyacinth (Dube et al., 2017). The reported study by Verma et al. (2003) has also assessed and compared the areas covered with water and water hyacinths species by employing IRS LISS II and LISS III data of 1988 and 2001 in and around the northern parts of Bangalore city, India. Numeorus research has identified and analysed the alien species through multispectral and hyperspectral remote sensing platforms (Carson et al., 1995; Cuneo et al., 2009; John & Kavya 2014; Kimothi et al., 2010; Mladinich et al., 2006). Recently launched Sentinel multispectral sensors have been used and provided unconventional strides for spatio-temporal mapping of the water hyacinths’ blooming patterns (Bayable et al., 2023; Janssens et al., 2022; Schreyers et al., 2021).

Besides the ecological incursion traits, water hyacinths have been widely used to perform the nature-based soultions to the environmental concerns (Fig. 1). The innumerable utilities for a product-oriented management can serve as a raw material for animal feed, water purification, producing fertilizer, biofuel & biogas production, and artefacts (Wolverton & McDonald, 1979; Ogle et al., 2001; Honlah et al., 2019). The plant has earmarked its ecological significance in utility driven aspects such as agicultural bio-manure/ compost fertilisers as it is rich source of nutrients and fodder for animals (Alam et al., 2017; Bui et al., 2015; Gunnarsson & Petersen, 2007; Ogbuehi & Ibe, 2021), biofules & biogas production (Bhattacharya & Kumar, 2010; Kumar et al., 2020; Kunatsa & Xia, 2021; Rathod et al., 2018) and wastewater treament & water purification (Alade & Ojoawo, 2009; Laitinen et al., 2017; Anipeddi et al., 2022; Arunpandi et al., 2022). Water hyacinths have manifested its potential for commercial utilities, used as a dry plant in cold season, a rich source of biofuel and its remaining ashes used as a plant fertilizers (Reddy & Sutton, 1984).

In India, for biofuel generation, an estimated yield of dry water hyacinth accounts for approximately 50 litres of ethanol and 200 kg of residue fibre (Gunnarsson and Petersen, 2007). Investigation reveals that aquatic macrophytes can be used for pollutant removal, as well as bio-indicators to trace heavy metals in aquatic ecosystems (Aoi & Hayashi, 1996). It acts as an ecological scrubber of heavy metals and other pollutants and is profusely used in the phytoremediation and waste water treatment processes (PN & Madhu, 2011; Roy et al., 2021). Moreover, it has also shown removal of 60–80% of nitrogen and about 69% of potassium from water and screens heavy metals and various other toxins from contaminated water (Fox et al., 2008). Furthermore, the implicit fibre usage of water hyacinths have been explored in the handicrafts making in the commercial markets such as handbags, baskets, ropes and household goods and other hand-made artifacts. Pin et al. (2021) have attempted the technological studies for checking the biomass production in the rural settings and addressing the issue of water hyacinth within the Lake Tondano, Indonesia. Likewise, Rakotoarisoa et al. (2015) have documented the profitable outputs with the usage of water hyacinth for making handicrafts at Lake Alaotra of Madagascar. In Indian context, water hyacinth is also utilized for making furniture, fibre but on a small scale production units and major markets have not been established yet. Although, an women-oriented intiative in Assam was undertaken by the industrial intervention where a product called “Moorhen yoga mat” was produced by transforming the water hyacinth into sustainable livelihood (NECTAR, 2021). A women-driven enterprise, who belongs to the fishing community and living in the fringes of the Deepor beel wetland of Assam, India. The implication of water hyacinths has been attributed within the Deepor beel, a permanent freshwater lake in southwest of Guwahati city, recognised as a Ramsar Site (a wetland of international importance), a bird wildlife sanctuary and considered as one of the largest riverine wetlands in the Brahmaputra valley. The entire region is facing threat due to unchecked urbanisation and carries load of waste waters of adjoing rivers, posing threat to the biodiversity of the wetland. From the past few years, the lake is also suffering from the excessive growth of water hyacinths, and creating a problem to residing inhabitants, as reported by the residents. Till date, no research has encountered the combination of technology, techniques, and trade to resolve the problem of invasive plant mats in the Deepor Beel region. Therefore, an attempt was undertaken to check the possibilities of satellite interventions for mapping as well as evaluating the wealth prospects of the water hyacinths.

The study was designed to remotely map the seasons that has massive productivity of the water hyacinths, thereby estimating the area coverage from satellite image processing within the Deepor beel. In addition to this, integrating the in-situ sampling and monitoring of water hyacinths’ for biomass estimations for the productive season identified. Specifically, the objectives of the concerned study intends to: i) assess the mapping of productive season and area coverage of the water hyacinths in the Deepor beel; ii) in-situ biomass estimation of the harvest of the water hyacinth within the lake; and, iii) evaluate the prospects of “weed to wealth” generation from water hyacinth utility for a handicraft item (Moorhen yoga mat). The creation of wealth from invasive weed waste can potentially mark significant stability to the socio-economic facets as well as improving the environmental conservation status of the region. The contribution is beneficial for a long-term sustainability of the Deepor beel, since the products made from such invasive plants have potential and productive markets.

Materials And Methods

Study Area

In the Brahmaputra valley, wetlands are locally known as beels (Patar, 2005) and usually found as oxbow lakes with a larger size. Deepor beel is one such lake located in the Kamrup district of Assam and designated within the 21 national wetlands of India with a geographical location lies in between 26°05–26°11 N latitude and 91°35–91°43 E longitude (Fig. 2). This wetland is a natural, permanent, freshwater lake, in a former channel of Brahmaputra positioned to the south of the present main river channel, oriented to the south-west of Guwahati city as a major storm water storage basin. This freshwater lake has been listed under Ramsar Convention in November 2002 as a Ramsar site for undertaking conservation measures based on its biological and environmental importance. Deepor beel is home to many migratory waterfowl each year in addition to a huge congregation of residential water birds. 219 species of birds including more than 70 migratory species are reported in the beel area. Also, it supports 50 fish species belonging to 19 families (Saikia & Bhattacharjee, 1987). Due to its biodiversity richness, it is also designated as Deepor Beel Wildlife Sanctuary covers an area of 4.1 km^2.

Satellite Datasets Used

For visually capturing the abundance and distribution of water hyacinths, satellite based synoptic view explicitly facilitate the *in-situ* measurements, which otherwise makes it tedious from a field measurement perspective (Schreyers et al., 2021). Satellite imagery can distinctly identify the spectral signals as well as assess the spatial spread of water hyacinth in the area of interest (AOI) i.e., Deepor beel wetland. The Sentinel-2 Multispectral sensor with Level 2A (Product type-S2-MSIL2A) images were retrieved from the European Space Agency (ESA) Copernicus Open Access Hub (https://scihub.copernicus.eu). Sentinel series can provide frequent revisit timing, high quality with 10-meter spatial resolution and standardized optical scenes for the detection of floating aquatic vegetation. The AOI scene is searched (for a cloud-free coverage) and downloaded for two sensing seasons i.e., for 22 December, 2020 and 01 May, 2021 representing post-monsoon and pre-monsoon seasons, respectively. Furthermore, a false color composite (FCC) was also used to visually observe areal accumulation of water hyacinths within the water body. The scenes for image analysis were processed on the ESA software Sentinel Application Platform (SNAP) v.8.0.

Image pre-processing and classification analysis

The pre-processing of the satellite imagery usually accounts for radiometric calibration and atmospheric corrections. The former is done to calibrate image data radiance, reflection, or brightness temperature whereas the latter corrections are performed for removing the atmospheric effect on reflectance values of images. However, these processes are priorly resolved in the Sentinel imageries. Supervised image classification process was performed in order to assign the class or grouping of the pixel depending upon their properties and similarities through Maximum Likelihood Classification technique. This method assumes that the statistics for each class in each band are normally distributed and calculates the probability that a given pixel belongs to a specific class. The highest probability threshold i.e., Maximum Likelihood was chosen so that each pixel is assigned to the class. However, if the highest probability is smaller than a threshold, the pixels as such remains unclassified (Richards et al., 1999). The data processing and mapping platform used for Sentinel imagery was an open-access software Sentinel Application Platform (SNAP) v.7.0 (Biswakarma et al., 2021). All the pre-processing operations and image classification has been performed in ENVI (Environment for Visualising Images) v.5.3 software.

The spectral resemblance of the water hyacinths and other aquatic vegetation within the water body is ambiguous in nature, however minimizing this effect is a crucial step for an accurate mapping. Masking of the area covered by water on the imagery along with field ground truthing (for the water hyacinth vegetation) can provide relatively sound results (Schreyers et al., 2021). In the electromagnetic spectrum, highest reflectance peak, for water hyacinth vegetation, is observed for the Near-Infrared (NIR) wavelengths of light (~850 nm), and absorption in the red (~660 nm). Also, water reflects largely in the green spectrum (~560) and absorbs in the vegetation-red edge bands (~705 and 740). Water pixels tend to show a peak in NIR region in some instances where water body carry sediment loads or if polluted with eutrophication. For efficiently tracing the water hyacinths growth, Normalized Difference Vegetation Index (NDVI) have been employed which are developed to easily distinguish green vegetation from other non-photosynthetically active surfaces (Rouse et al., 1974). It is used to estimate the plant biomass by measuring the amount and health conditions of the biomass on land surface. NDVI values ranges from − 1.0 to + 1.0, where the *negative* value indicates non-vegetation classes such as barren land, builtup area, road network clouds and water, *positive* NDVI value closer to zero indicates barren land, and NDVI value ranges from 0.2–0.5 indicates sparse (low) vegetation and value ranges from 0.5–1.0 indicates dense (healthy) vegetation. (Schreyers et al., 2021). The biomass of water hyacinth (vegetation pixels) present in Deepor beel lake was calculated by NDVI by a combination of NIR and red band (RED) in ENVI software v. 5.3 by equation Eq. 1:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$ Eq. 1

The overall accuracy of the image classified for water hyacinths vegetation accounts for more than ~90% after ground truthing in the field surveys. The final map creation for the seasonal mapping is illustrated by ArcGIS software v.10.6.

In-situ sampling and biomass estimation of water hyacinths

After mapping the abundant (productive) season of water hyacinths growth in the month of May, the field measurements were conducted accordingly i.e., closest to the scene date captured from Sentinel-2. In-situ sampling for the water hyacinths has been performed for deriving biomass estimation from Deepor beel lake. The field sampling was employed through a 1 x 1 metre quadrate method, where the water hyacinths plants was collected from three sites around the lake boundaries. The water hyacinth weed plants were collected and processed manually by extracting the stems (removing the root and leave parts). The weight of the stack of the green stems was taken and noted down. Further, the height of each stem harvested in ground sampling was also estimated with an average final height of water hyacinth as the collected stems were of varying lengths. The stems collected were sun-dried in an open terrace, where each day humidity, temperature and weight were noted. Before drying, the initial green weight and subsequent weight in each day was taken till the weight measured a constant value. The average height of stem of water hyacinth was calculated by measuring the height of 50 stems of water hyacinth selected at random and an average height of water hyacinth comes out to be 0.7 meter (70 cm). The area covered by water hyacinths has been estimated from classified image. The flow chart for the working methodology is demonstrated in Fig. 3. The computations used for biomass estimation is given in the following equation Eq. 2, Eq. 3 and Eq. 4:

$$\mathrm{Volume} = \mathrm{Satellitebasedareacoveredbywaterhyacinths}\ (\mathrm{sq.\,meters}) \times \mathrm{Averageheightofthewaterhyacinths}\ (\mathrm{meters})$$ Eq. 2

$$\mathrm{Greenmass} = \mathrm{Satellitebasedareacoveredbywaterhyacinths}\ (\mathrm{sq.\,meters}) \times \mathrm{Weightperunitareaofgreenwaterhyacinths}(\mathrm{kg/sq.\,meters})$$ Eq. 3

$$\mathrm{Drymass} = \mathrm{Satellitebasedareacoveredbywaterhyacinths}\ (\mathrm{sq.\,meters}) \times \mathrm{Weightperunitareaofdrywaterhyacinths}(\mathrm{kg/sq.\,meters})$$ Eq. 4

Results And Discussion

Mapping of productive season and area coverage of the water hyacinths

The satellite mapping of seasons that contribute to abundance of the water hyacinth plant weed in the Deepor beel is crucial to assess the productive season for their substantial growth. The subsequent mapping has shown that the progressive growth of the water hyacinth in this wetland is found uniformly distributed over the lake in the pre-monsoon seasons i.e., for the month of May. It is evidently observed in pre-monsoon season, where water hyacinth covered an area of 4763800 m^2 (476 hectares) in comparison to post-monsoon season with an area of 2355100 m^2 (235 hectares) (Fig. 4). The limited growth of water hyacinths in post-monsoon might be attributed to inundation of the Deepor beel which is generally receives its source of water from local monsoonal run-offs and prudently, majority of the water flows is carried from Basistha and Kalmani rivers. Deepor beel drains into the Brahmaputra River 5 km to the north-west, through the Khonajan channel (Sharma & Sharma, 2012). The local monsoon recharges heavily occur between the months of May and September and acts a natural storm water reservoir during the monsoon for the urban landscape of Guwahati city. However, the unique physiographic settings of the lake are characterized by active hydrologic regime, where water depth goes up to 4 meters at the time of extreme flooding and during the dry seasons, the depth of the lake drops to about 1 meter (Sharma & Sharma, 2012). Therefore, accumulation of water hyacinth is subjected to the drier months where natural and anthropogenic factors might cause its massive growth in pre-monsoon season and often experience submergence of the weed plant in the monsoon and post-monsoon seasons. Furthermore, previous studies have also witnessed the substantial transformations in the ecological and social trends of Deepor beel and nearby surroundings of the region, where water hyacinths have become a huge problem to the community residing within the vicinity of the wetland. Ahmed et al. (2021) also assessed the fast decline in the lake water volume through a time series analysis in the Deepor beel lake, where findings suggested that lake storage capacity has shrank in the past two decades and stated a serious concern of rapid urbanization within the Guwahati city. Some of the surrounding land use transition activities include construction activity of railway line along the southern boundary, industrial establishment, large-scale encroachment and trespassing of the vacant land to private property around the periphery of the wetland. Unscientific fishing practise, soil erosion and brick making factories are dominant activities that has also transformed the landscape around the Deepor beel (Bezbaruah, 2007; Sharma & Sharma, 2012). The entire region is facing threat due to unchecked urbanisation, as it is fed by contaminated water and waste carried by Bharalu river, posing a significant threat to the biodiversity of the wetland, home to many aquatic species and migratory birds.

Biomass estimation of water hyacinths

For the biomass estimation of the water hyacinths, freshly collected samples were kept under the drying conditions and consecutively dried in an open sun exposure for 7 days for a fixed period of 9 hours with an optimum temperature of 38°C and humidity ranging from 66–78% (Table 1). Samples collected of the invasive weed measured an average height of 0.7 meter of stems/fibres collected from an area covered of 1 m^2. The initial green and final dry weight per unit area of the collected water hyacinths biomass were observed as 6.008 kg/m^2 and 1.111 kg/m^2, respectively under these *in-situ* conditions of temperature, humidity, and duration of solar exposure (Damtie et al., 2022) (Table 1). The volume estimation is the function of the water hyacinths' density found in the water bodies and thus, it is difficult to calculate through remote sensing and requires filed investigation. The biomass weight was reduced to about 18.5% of the total green weight. Subsequently, biomass (green and dry) was calculated from standard equations (Eqs. 2, 3 & 4) and illustrated in Table 2. Further, the estimated biomass weight observed for the productive season was combined with the area coverage of the water hyacinths derived from image analysis (Fig. 4). For pre-monsoon, estimated volume of water hyacinths is 3334660 m^3 for an average height of 0.7 meters of stem. Similarly, biomass (green) of water hyacinths extracted from the Deepor beel lake with an area 4763800 m^2 accounts for 2,86,209,10 kg, whereas after sun-dried condition, dry biomass left 52,92,581.8 kg. Thus, after a sun-dried condition, the estimation shows that around 18.5% of the dry biomass of water hyacinth is left for utility with an overall decrease of 81.5% (by mass). On an average, water hyacinth takes around 6–7 day in complete drying. The drying period can be reduced with the use of solar dryer especially when the duration of rain lasts for several months in some parts of Assam. The dried portion of water hyacinth is being served for innumerable utilities and henceforth, evaluated for wealth generation aspects in the Deepor beel region.

Table 1
Drying conditions of samples and weight of water hyacinth sample

S.No.	Date	Temperature (in ˚C)	Humidity	Solar duration (in hours)	Weight (in kg)
1.	14-05-2021	38	66%	9	#6.008
2.	15-05-2021	38	67%	9	3.971
3.	16-05-2021	33	69%	9	2.682
4.	17-05-2021	35	74%	9	1.571
5.	18-05-2021	35	75%	9	1.254
6.	19-05-2021	38	78%	9	1.112
7.	20-05-2021	38	78%	9	*1.111

#Green weight *Dry weight

Table 2
Estimation of biomass of water hyacinths for pre-monsoon season

Area covered (satellite) by water hyacinth (in m^2) A	Average height of the water hyacinth (in meters) B	Weight per unit area of water hyacinth (in kg/m^2) C	Volume (in m^3) A x B	Green biomass (in kg) A x #C	Dry biomass (in kg) A x *C
47,63,800	0.7	#6.008 *1.111	33,34,660	2,86,209,10.4	52,92,581.8
#Green weight (6.008 kg); *Dry weight (1.111 kg)					

Evaluation of water hyacinth utility for wealth generation

The north eastern part of India is famous for its handcraft products as it forms one of the basic livelihood activities by providing income and employment opportunities to many people. Assam is considered as a melting spot for numerous handicraft industries like bamboo work, water hyacinth handicraft, Assam silk etc. are among various other forms of crafts, are the most important to the region (Borah, 2014). In Assam and other North Eastern states, the problem of water hyacinth has become a peril to the farmers and only utilise as an organic manure in potato cultivation/ mulching material or for cattle (for cows & buffalos) fodder. However, the efforts through an initiative project to utilise water hyacinth for making handicraft product has also been adopted for commencing its potential (NEDFi, 2008).

The combination of geospatial mapping techniques and *in-situ* biomass estimation can direct the identification for the probable usage possibilities. Any utility needs to be drawdown to the revenue generation, and livelihood support. Thus, refurbishing of this unusable weed biomass from the Deepor beel into the production of yoga mat as an artefact item can provide sustainable ways for wealth creations. The evaluation of production and cost assessment for renovating dried left biomass of water hyacinth into a handicraft product, such as Moorhen yoga mat is given in Table 3. Previous calculations have shown that, in the present study, reduced biomass of water hyacinth is observed ~ 18.5% of the green sample. For the cost approximation, if the reduced (dried) biomass of water hyacinth is left roughly around 20% i.e., if 15 kg of green sample of water hyacinth is taken, the left mass (after drying) remains around 3 kg of the total sample. As per recent interventions of the project, this yoga mat requires 3 kg of dry biomass of water hyacinths (NECTAR, 2021) and thus, around 1.7 million of yoga mats (17,64,194 of yoga mats) can be produced (Table 3). However, if actual availability of 50% of total dried biomass is assumed, around 0.8 million (8.8 lakhs) of yoga mats can be manufactured from the season that shows water hyacinth abundance. A single yoga mat costs around as per the quoted price, in domestic markets for US $14.50 (INR Rs. 1200/-) and through online selling platforms in an international market cost for US $18.13 (INR Rs.1500/-) (NECTAR, 2021).

Table 3
Evaluation of production and revenue generation from dry water hyacinth utilized for yoga mats

Dry biomass observed in-situ for 0.7 meters avg. height (in kg)	No. of Moorhen yoga mat produced (if one yoga mat requires 3 kg of dry mass)	Actual availability of 50% of total mass (dried) yield of yoga mat	Domestic sale price at US $14.50 (Rs. 1200/-) per yoga mat	International sale price at US $18.13 (Rs. 1500/-) per yoga mat
52,92,581.80	17,64,194	8,82,097	US $ 12.79 million [US $ 12,790,406.5] (Rs. 105.85 Crore)	US $ 15.99 million [US $ 15,992,418.61] (Rs. 132.31 Crore)

Therefore, revenue generation in the domestic and international markets has been evaluated around US $ 12.79 million (Rs. 105.85 Crore) and US $ 15.99 million (Rs. 132.31 crore), respectively from a single productive season from the Deepor beel alone. The export financial boost from the production of handicraft has good scope for market manufacturers and artisans/craftsman and can substantially promote “weed to wealth generation” strategy.

In Assam, long type of water hyacinth is available mostly in the stagnant water like beel/road sides pond/lake etc. and currently, these beels are under extreme threats with influencing factors such as water pollution, reclamation, habitat degradation, water hyacinth, etc. These implicit pressures cause the loss of key biodiversity of indigenous and migratory flora and fauna (Commissionerate of Industries & Commerce, 2023). The uncontrolled invasion of water hyacinths accumulates as dense mats and known to obstructs agriculture, transportation, and fishing sectors. Comparable attempt of this study can be adopted for the water hyacinths management within several other beels/lakes of Assam that are facing ecological degradation. Other than yoga mat, several other products such as baskets, bags, furniture, decorative items, and containers can be customised from the water hyacinths.

Besides from wealth generation, the concept also revives the capacity building programs for the fishing communities and women workers that are directly rely on the wetland and share this biome for their survival. The creation of alternative job prospects can imporve the socio-econmic facets of the communities involved in such programs. The ecological benefits of the hand woven yoga mat is that it is 100% biodegradeable and 100% compostable and is manufactured and designed after considering all aspects of water hyacinth plant. Government initiated project has achieved to develop 1000 craftsman through capacity building, offering market linkages, and enabling micro-credit linkages. The project inception of this innovative craft has also formed around 1300 beneficiaries, where most of them are women (NEDFi, 2012) and has transformed the lives of women in the rural and fishing communities. Therefore, the study would not only enhance the quality of wetland ecosystem by the removal of water hyacinth but its harvest also serve as a utility product and livelihood generation.

Conclusions

The present study depicts the potential of water hyacinth utility and its high economic impact for livelihood generation. This also provides a solution to the environmental issue that the invasive water hyacinth can be harvested and sustainably utilised for handicraft markets and then be locally promoted for various products and allied business. The study in Deepor beel is a case of an indicative in nature to explore the mapping of the water hyacinth which covers a large area of the Deepor beel lake. The integration of geospatial techniques has enabled the mapping of the abundance of water hyacinths and its massive area coverage in the pre-monsoon seasons as compared to the growth in post-monsoon season. *In-situ* biomass estimation and sample collection has been used to calculate the left biomass of water hyacinth as observed 18.5% of the total biomass of the weed plant, after processing under sun-dried conditions. The overall production and cost-generation has been determined by the combination of these two applications. For the productive season of water hyacinth (as mapped from satellite), the water hyacinth can be utilised in yoga mat making and other products. The study has shown that 0.8 million (8.8 lakhs) of yoga mats can be manufactured. This strategy has provided the prospects for revenue generation in the domestic and international markets and evaluated around US $ 12.79 million (Rs. 105.85 Crore) and US $ 15.99 million (Rs. 132.31 crore), respectively from a single productive season from the Deepor beel alone. The water hyacinth degrades the ecosystem of the lake; however, its massive removal can be largely operated at an industrial scale where cost of removal can be adjusted. Within the commercial framework, the prior determination of wealth prospects is highly beneficial for the people that are directly/indirectly rely on the wetland for their survival. The applicative intent of this research study, therefore, has immense possibilities for enhancing the wetland ecosystem by removing the water hyacinth, and strikingly helps in utility production in handicraft markets. The approach would engage the locals, especially women group, for generating livelihoods and sustainably support the indigenous communities.

Declarations

Acknowledgements

The authors are thankful to North East Centre for Technology Application and Research (NECTAR), Department of Science and Technology, India, for providing the timely guidance and support. The first author likes to acknowledge the Indraprastha Research Fellowship (IPRF), Guru Gobind Singh Indraprastha University (GGSIPU), India. The second author is thankful to the University Grant Commission (UGC), India in the form of Senior Research Fellowship (SRF). The authors would also like to express gratitude to the Dean, University School of Environment Management, GGSIPU for providing the research infrastructure and laboratory facilities throughout this study.

Authors' Contributions: All the authors have substantially contributed to this manuscript. Koshal Rajora has designed the entire study, investigation and wrote the original draft of the manuscript. Shipra Tyagi has drafted and edited the final manuscript. Kiranmay Sarma has contributed to the visualization and final pre-proofread of the manuscript. Arun Kumar Sarma has visualized, and done the pre-proofread. Rajendra Jena has contributed to the conceptualization of the study, and final proofread of the manuscript.

Funding: No funding was obtained for this study.

Availability of data and material: The datasets used in the current study are available upon request.

Conflicts of interest: The authors declare no competing interests.

References

1. Ahmed, I. A., Baig, M. R. I., Talukdar, S., Asgher, M. S., Usmani, T. M., Ahmed, S., & Rahman, A. (2021). Lake water volume calculation using time series LANDSAT satellite data: a geospatial analysis of Deepor Beel Lake, Guwahati. *Frontiers in Engineering and Built Environment 1*(1), 107-130.
2. Alade, G. A., & Ojoawo, S. O. 2009. Purification of domestic sewage by water-hyacinth (Eichhornia crassipes). *International Journal of Environmental Technology and Management 10(*3-4), 286-294.
3. Alam, A., Srivastava, S. K., Anand, K., Sinha, P. B., & Mishra, P. K. (2017). Response of Water Hyacinth as a Source of Potassium in the Production of Potato. *International Journal of Innovative Research in Science, Engineering and Technology 6*(7), 10.

4. Alvarez-Taboada, F., Paredes, C., & Julián-Pelaz, J. (2017). Mapping of the invasive species Hakea sericea using unmanned aerial vehicle (UAV) and WorldView-2 imagery and an object-oriented approach. *Remote Sensing 9*(9), 913.
5. Anipeddi, M., Begum, S., & Anupoju, G. R. (2022). Integrated technologies for the treatment of and resource recovery from sewage and wastewater using water hyacinth. In *Biomass, Biofuels, Biochemicals,* Elsevier, pp. 293-314.
6. Aoi, T., Hayashi,T. (1996); Nutrient removal by water lettuce (Pistia Stratiotes). *Water Science and Technology 34*, 407-412.
7. Arunpandi, N., Jyothibabu, R., Dhanya, P., Jagadeesan, L., Rashid, C. P., & Sarath, S. (2022). Alarming waterweeds proliferation in the Vembanad Lake System might significantly increase water loss through transpiration. *Environmental Monitoring and Assessment*, 194(4), 303.
8. Bayable, G., Cai, J., Mekonnen, M., Legesse, S. A., Ishikawa, K., Imamura, H., & Kuwahara, V. S. (2023). Detection of Water Hyacinth (*Eichhornia crassipes*) in Lake Tana, Ethiopia, Using Machine Learning Algorithms. *Water 15*(5), 880.
9. Bezbaruah, M. P. (2007). Agricultural Development in the North-East: Status, Assessment and Prospect. *Indian Journal of Agricultural Economics 62*(1), 52.
10. Bhattacharya, A., & Kumar, P. (2010). Water hyacinth as a potential biofuel crop. Electronic *Journal of Environmental, Agricultural and Food Chemistry 9*(1), 112-122.
11. Biswakarma, P., Singh, M., Sarma, A. K., & Joshi, V. (2021). Assessment of the water inundation area due to the tropical cyclone Bulbul 2019 in the selected districts of West Bengal, India with the application of RS and GIS tools. *Proceedings of the Indian National Science Academy 87,* 628-639.
12. Borah, N. (2014). Water hyacinth craft: A livelihood initiative by NEDFi. Available at SSRN 2539958. https://dx.doi.org/10.2139/ssrn.2539958
13. Bui, X. T., Tran, C. T., Chau, T. D., & Berg, H. (2015). Reuse of sediment from catfish pond through composting with water hyacinth and rice straw. *Sustainable Environment Research 25*(1).
14. Carson, H. W., Lass, L. W., & Callihan, R. H. (1995). Detection of yellow hawkweed (Hieracium pratense) with high resolution multispectral digital imagery. *Weed Technology 9*(3), 477-483.
15. Chukwuka, K. S., & Uka, U. N. (2007). Effect of water hyacinth (*Eichornia crassippes*) infestation on zooplankton populations in Awba reservoir, Ibadan South-West Nigeria.
16. Commissionerate of Industries & Commerce. (2023). Present Handicrafts industries in Assam, Industries and Commerce, Govt. of Assam. Retrieved on 03rd March, 2023 https://industriescom.assam.gov.in/portlet-innerpage/present-handicrafts-industries-in-assam#main6
17. Cuneo, P., Jacobson, C. R., & Leishman, M. R. (2009). Landscape-scale detection and mapping of invasive African Olive (*Olea europaea* L. ssp. cuspidata Wall ex G. Don Ciferri) in SW Sydney, Australia using satellite remote sensing. *Applied Vegetation Science 12*(2), 145-154.
18. Damtie, Y. A., & Mengistu, D. A. (2022). Water Hyacinth (Eichhornia crassipes (Mart.) Solms) Impacts on Land-Use Land-Cover Change Across Northeastern Lake Tana. *Journal of the Indian Society of Remote Sensing 50*(6), 975-986.
19. Degaga, A. H. (2018). Water hyacinth (*Eichhornia crassipes*) biology and its impacts on ecosystem, biodiversity, economy, and human wellbeing. *Journal of Life Science and Biomedicine 8*(6), 94-100.
20. Dube, T., Mutanga, O., Sibanda, M., Bangamwabo, V., & Shoko, C. (2017). Evaluating the performance of the newly-launched Landsat 8 sensor in detecting and mapping the spatial configuration of water hyacinth (*Eichhornia crassipes*) in inland lakes, Zimbabwe. *Physics and Chemistry of the Earth Parts A/b/c, 100*, 101-111.
21. Everitt, J. H., Yang, C., Escobar, D. E., Webster, C. F., Lonard, R. I., & Davis, M. R. (1999). Using Remote Sensing and Spatial Information Technologies to Detect and Map Two Aquatic Macrophytes. Retrieved from http://hdl.handle.net/1834/19622
22. Fox, L. J., Struik, P. C., Appleton, B. L., & Rule, J. H. (2008). Nitrogen phytoremediation by water hyacinth (Eichhornia crassipes (Mart.) Solms). *Water, Air, and Soil Pollution 194*, 199-207.
23. Gunnarsson, C. C., & Petersen, C. M. (2007). Water hyacinths as a resource in agriculture and energy production: A literature review. *Waste management 27*(1), 117-129.
24. Hestir, E. L., Khanna, S., Andrew, M. E., Santos, M. J., Viers, J. H., Greenberg, J. A., ... & Ustin, S. L. (2008). Identification of invasive vegetation using hyperspectral remote sensing in the California Delta ecosystem. *Remote Sensing of Environment 112*(11), 4034-4047.
25. Honlah, E., Yao Segbefia, A., Odame Appiah, D., Mensah, M., & Atakora, P. O. (2019). Effects of water hyacinth invasion on the health of the communities, and the education of children along River Tano and Abby-Tano Lagoon in Ghana. *Cogent Social Sciences 5*(1), 1619652.
26. Jakubauskas, M. E., Peterson, D. L., Campbell, S. W., deNoyelles Jr, F., Campbell, S. D., & Penny, D. (2002). Mapping and monitoring invasive aquatic plant obstructions in navigable waterways using satellite multispectral imagery. In. FIEOS 2002 Conference Proceedings.
27. Janssens, N., Schreyers, L., Biermann, L., Van Der Ploeg, M., Bui, T. K. L., & Van Emmerik, T. (2022). Rivers running green: water hyacinth invasion monitored from space. *Environmental Research Letters*, *17*(4), 044069.
28. John, C. M., & Kavya, N. (2014). Integration of multispectral satellite and hyperspectral field data for aquatic macrophyte studies. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences 40*(8), 581.
29. Kimothi, M. M., & Dasari, A. (2010). Methodology to map the spread of an invasive plant (Lantana camara L.) in forest ecosystems using Indian remote sensing satellite data. *International Journal of Remote Sensing 31*(12), 3273-3289.
30. Kumar, V., Singh, J., Nadeem, M., Kumar, P., & Pathak, V. V. (2020). Experimental and kinetics studies for biogas production using water hyacinth (*Eichhornia crassipes* [Mart.] Solms) and sugar mill effluent. *Waste and Biomass Valorization* 11(1), 109-119.

31. Kunatsa, T., & Xia, X. (2021). Co-digestion of water hyacinth, municipal solid waste and cow dung: A methane optimised biogas–liquid petroleum gas hybrid system. *Applied Energy 304*, 117716.
32. Kwok, R. (2018). Ecology's remote-sensing revolution. *Nature, 556*(7699), 137-138.
33. Laitinen, J., Moliis, K., & Surakka, M. (2017). Resource efficient wastewater treatment in a developing area—Climate change impacts and economic feasibility. *Ecological Engineering 103*, 217-225.
34. Li, M., Wu, Y. J., Yu, Z. L., Sheng, G. P., & Yu, H. Q. (2007). Nitrogen removal from eutrophic water by floating-bed-grown water spinach (*Ipomoea aquatica Forsk*.) with ion implantation. *Water research 41*(14), 3152-3158.
35. Lowe S., Browne M., Boudjelas S., & De Poorter M. (2000). 100 of the World's Worst Invasive Alien Species A selection from the Global Invasive Species Database. Published by The Invasive Species Specialist Group (ISSG) a specialist group of the Species Survival Commission (SSC) of the World Conservation Union (IUCN), pp. 12
36. Ogle, M. Thi Anh Dao, H., Mulokozi, G., Leif Hambraeus, B. (2001). Micronutrient composition and nutritional importance of gathered vegetables in Vietnam. *International Journal of Food Sciences and Nutrition 52*(6), 485-499.
37. Meerhof, M., Fosalba, C., Bruzzone, C., Mazzeo, N., Noordoven, W. and Jeppen, E. (2006). An experimental study of habitat choice by *Daphnia*: plants signal danger more than refuge in subtropical lakes. *Freshwater Biology 51*, 1320-1330.
38. Mironga, J., Mathooko, J., & Onywere, S. (2012). Effect of Water Hyacinth Infestation on the Physicochemical Characteristics of Lake Naivasha. *International Journal of Humanities and Social Science 2*, 103-113.
39. Mladinich, C. S., Bustos, M. R., Stitt, S., Root, R., Brown, K., Anderson, G. L., & Hager, S. (2006). The use of Landsat 7 Enhanced Thematic Mapper Plus for mapping leafy spurge. *Rangeland Ecology & Management 59*(5), 500-506.
40. Murkin, H., & Kadlec, J. (1986). Relationships between Waterfowl and Macroinvertebrate Densities in a Northern Prairie Marsh. *The Journal of Wildlife Management 50*(2), 212-217.
41. NECTAR (2021). Converting Water Hyacinth to Livelihood Option, North East Centre for Technology Application and Reach (NECTAR), Department of Science & Technology (DST), Govt. of India https://www.nectar.org.in/media-coverage/converting-water-hyacinth-to-livelihood-option Reterived on: 02. December. 2022
42. NEDFi (North Eastern Development Finance Corporation Limited) (2008). Transforming opportunities and Triggering Growth, Annual Report 2008-2009. https://www.nedfi.com/wp-content/uploads/2020/07/Annual_Report_2008_09.pdf
43. NEDFi (2012). Nurturing Entrepreneurship. Annual Report 2012
44. Ogbuehi, H. C. & Ibe, P. K. (2021). Effect of water hyacinth compost on the morpho-physiological parameters of Soybean (Glycine max l.).
45. Oyama, Y., Matsushita, B., & Fukushima, T. (2015). Distinguishing surface cyanobacterial blooms and aquatic macrophytes using Landsat/TM and ETM+ shortwave infrared bands. *Remote Sensing of Environment 157*, 35-47.
46. Patar, K.C. (2005). Preservation of wetlands. Editorial. The Assam Tribune, Guwahati, Saturday, October 1, 2005.
47. Pin, L. A., Pennink, B. J., Balsters, H., & Sianipar, C. P. (2021). Technological appropriateness of biomass production in rural settings: addressing water hyacinths (*E. crassipes*) problem in Lake Tondano, Indonesia. *Technology in Society, 66*, 101658.
48. PN, A. M. L., & Madhu, G. (2011). Removal of heavy metals from waste water using water hyacinth. *International Journal on Transportation and Urban Development 1*(1), 48.
49. Rakotoarisoa, T. F., Waeber, P. O., Richter, T., & Mantilla-Contreras, J. (2015). Water hyacinth (*Eichhornia crassipes*), any opportunities for the Alaotra wetlands and livelihoods? *Madagascar Conservation & Development 10*(3), 128-136.
50. Rakotoarisoa, T. F., Richter, T., Rakotondramanana, H., & Mantilla-Contreras, J. (2016). Turning a problem into profit: Using Water Hyacinth (*Eichhornia crassipes*) for making handicrafts at Lake Alaotra, Madagascar. *Economic Botany, 70*, 365-379.
51. Rathod, V. P., Bhale, P. V., Mehta, R. S., Harmani, K., Bilimoria, S., Mahida, A., & Champaneri, H. (2018). Biogas production from water hyacinth in the batch type anaerobic digester. *Materials Today: Proceedings, 5*(11), 23346-23350.
52. Reddy, K. R., & Sutton, D. L. (1984). Water hyacinths for water quality improvement and biomass production. *Journal of Environmental Quality 13*(1), 1-8.
53. Richards, J. A., Jia, X., Richards, J. A., & Jia, X. (1999). The interpretation of digital image data. Remote Sensing Digital Image Analysis: An Introduction, 75-88.
54. Rouse Jr, J. W., Haas, R. H., Deering, D. W., Schell, J. A., & Harlan, J. C. (1974). Monitoring the vernal advancement and retrogradation (green wave effect) of natural vegetation (No. E75-10354).
55. Roy, D., Sreekanth, D., Pawar, D., Mahawar, H., & K. Barman, K. (2022). Phytoremediation of Arsenic Contaminated Water Using Aquatic, Semi-Aquatic and Submerged Weeds. Biodegradation Technology of Organic and Inorganic Pollutants. doi: 10.5772/intechopen.98961
56. Saikia, P. K., & Bhattacharjee, P. C. (1987). A study of the avifauna of Deepor Beel: A potential bird sanctuary in Assam. Wetland and Waterfowl Conservation in Asia. D. Parisah and RC Prentice (eds.), Asian Wetland Bureau/IWRB, Kuala Lumpur pp.185-195.
57. Sainty, G.R. and S.W.L. Jacobs. (1988). Water Plants in Australia, Sainty & Associates. Sydney, pp. 65-71.
58. Schmidt, M., & Witte, C. (2010). Monitoring aquatic weeds in a river system using SPOT 5 satellite imagery. *Journal of Applied Remote Sensing 4*(1), 043528.

59. Schreyers, L., van Emmerik, T., Nguyen, T. L., Phung, N. A., Kieu-Le, T. C., Castrop, E., Bui, T.K.L., Strady, E., Kosten, S., Biermann, L. & van Der Ploeg, M. (2021). A field guide for monitoring riverine macroplastic entrapment in water hyacinths. *Frontiers in Environmental Science 9*, 716516. http://dx.doi.org/10.3389/fenvs.2021.716516
60. Sharma, B. K., & Sharma, S. (2012). Deepor Beel- A RAMSAR site of India: An interesting hot-spot with its rich Rotifera biodiversity. *Acta Zoologica Academiae Scientiarum Hungaricae 58*(2), 105-120.
61. Thamaga, K. H., & Dube, T. (2018). Testing two methods for mapping water hyacinth (Eichhornia crassipes) in the Greater Letaba river system, South Africa: discrimination and mapping potential of the polar-orbiting Sentinel-2 MSI and Landsat 8 OLI sensors. *International Journal of Remote Sensing 39*(22), 8041-8059.
62. Twongo, T., & Howard, G. (1998). Ways with weeds. *New Scientist, 159*(2142), 57-57.
63. Venugopal, G. (1998). Monitoring the effects of biological control of water hyacinths using remotely sensed data: a case study of Bangalore, India. *Singapore Journal of Tropical Geography 19*(1), 91-105.
64. Verma, R., Singh, S. P., & Raj, K. G. (2003). Assessment of changes in water-hyacinth coverage of water bodies in northern part of Bangalore city using temporal remote sensing data. *Current Science,* 795-804.
65. Wang, H., Lu, J., Wang, W., Huang, P., & Yin, C. (2007). Spatio-temporal distribution of nitrogen in the undulating littoral zone of Lake Taihu, China. Eutrophication of Shallow Lakes with Special Reference to Lake Taihu, China, 97-108.
66. Wolverton, B. C., & McDonald, R. C. (1979). Water hyacinth (*Eichhornia crassipes*) productivity and harvesting studies. *Economic Botany* 33, 1-10.

Figures

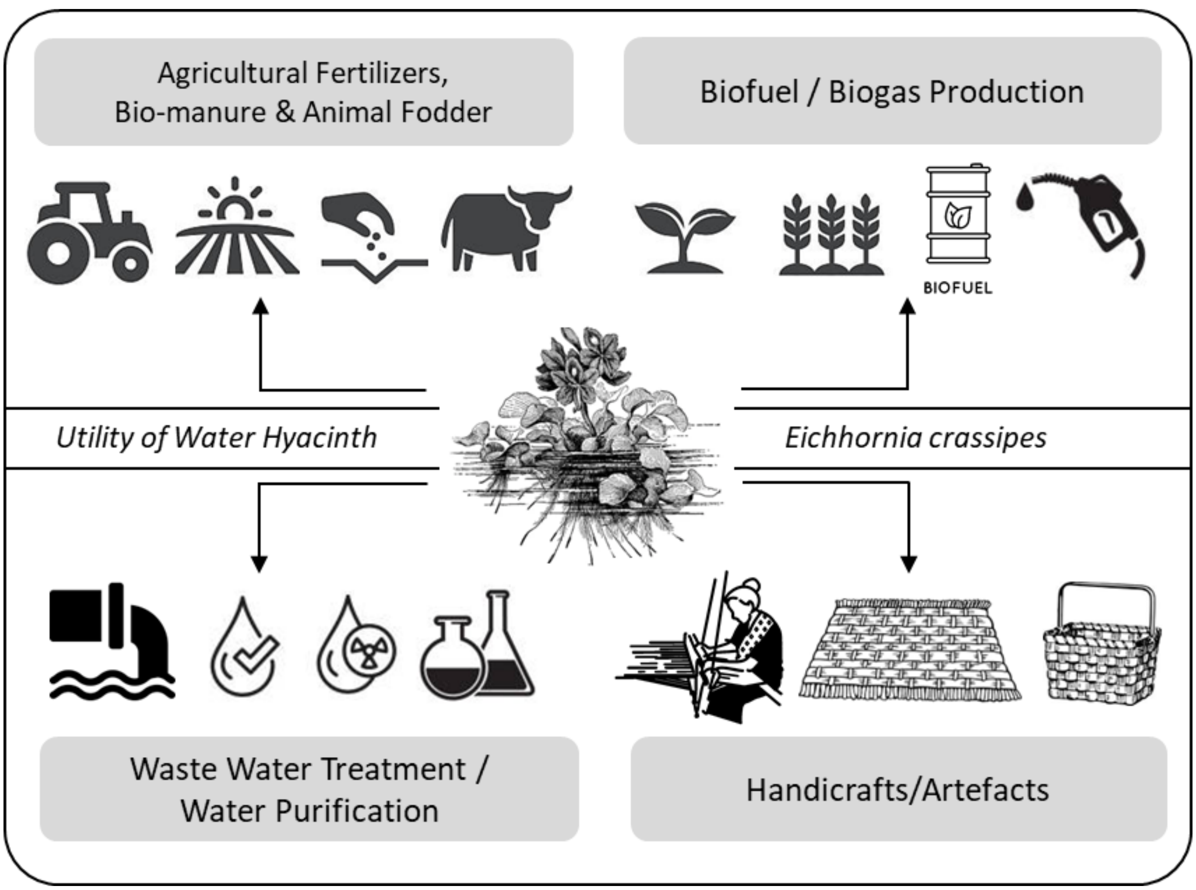

Figure 1

Schematic illustration for water hyacinths' utility

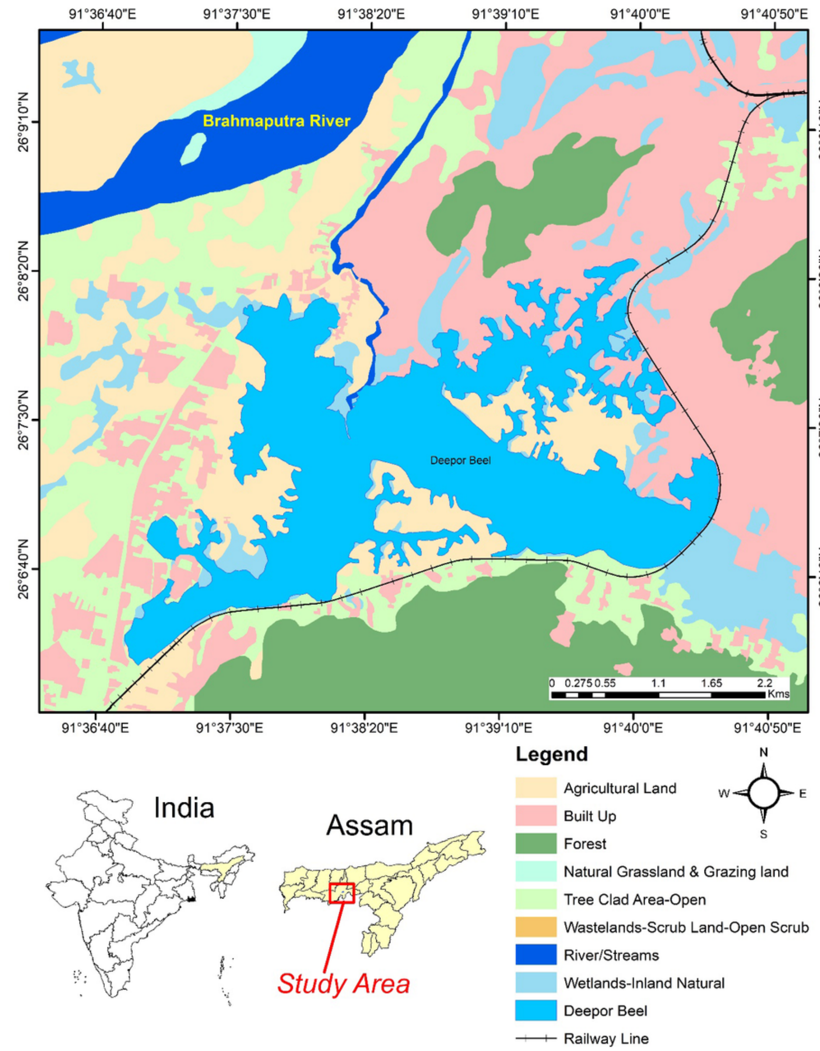

Figure 2

Location map of Deepor beel of Assam, India

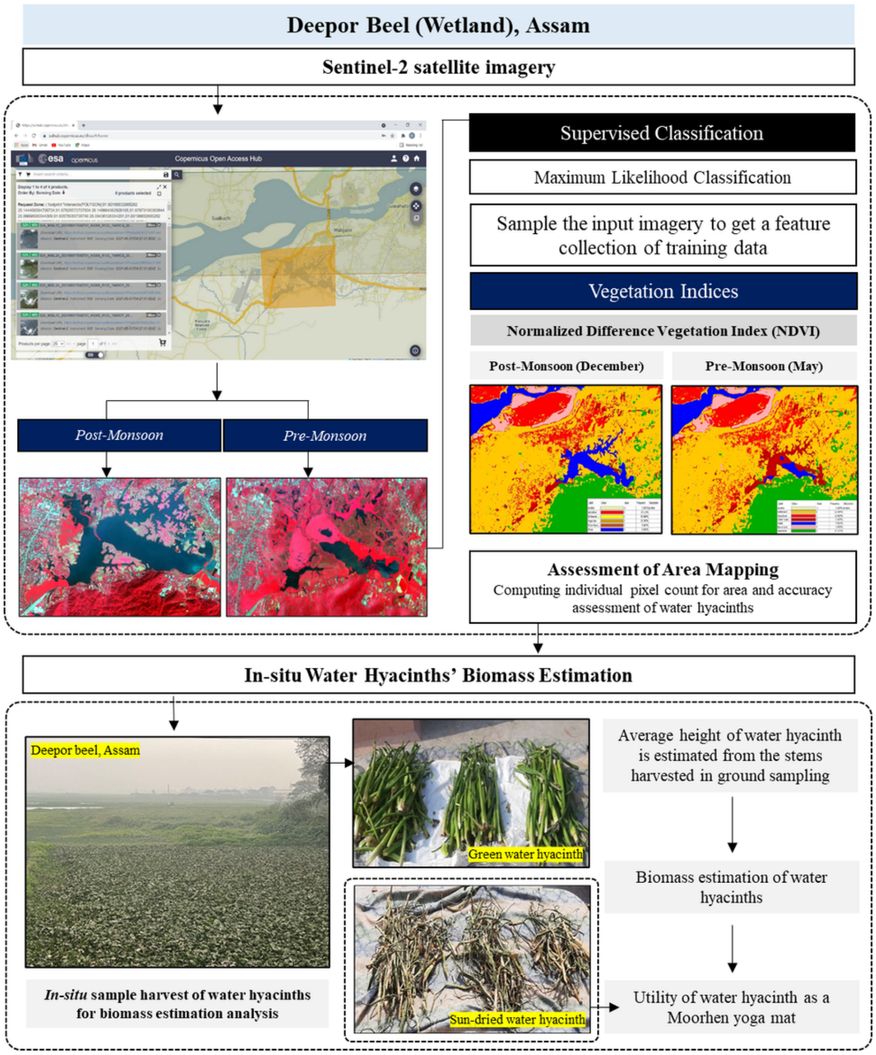

Figure 3

Flow diagram of the working methodology

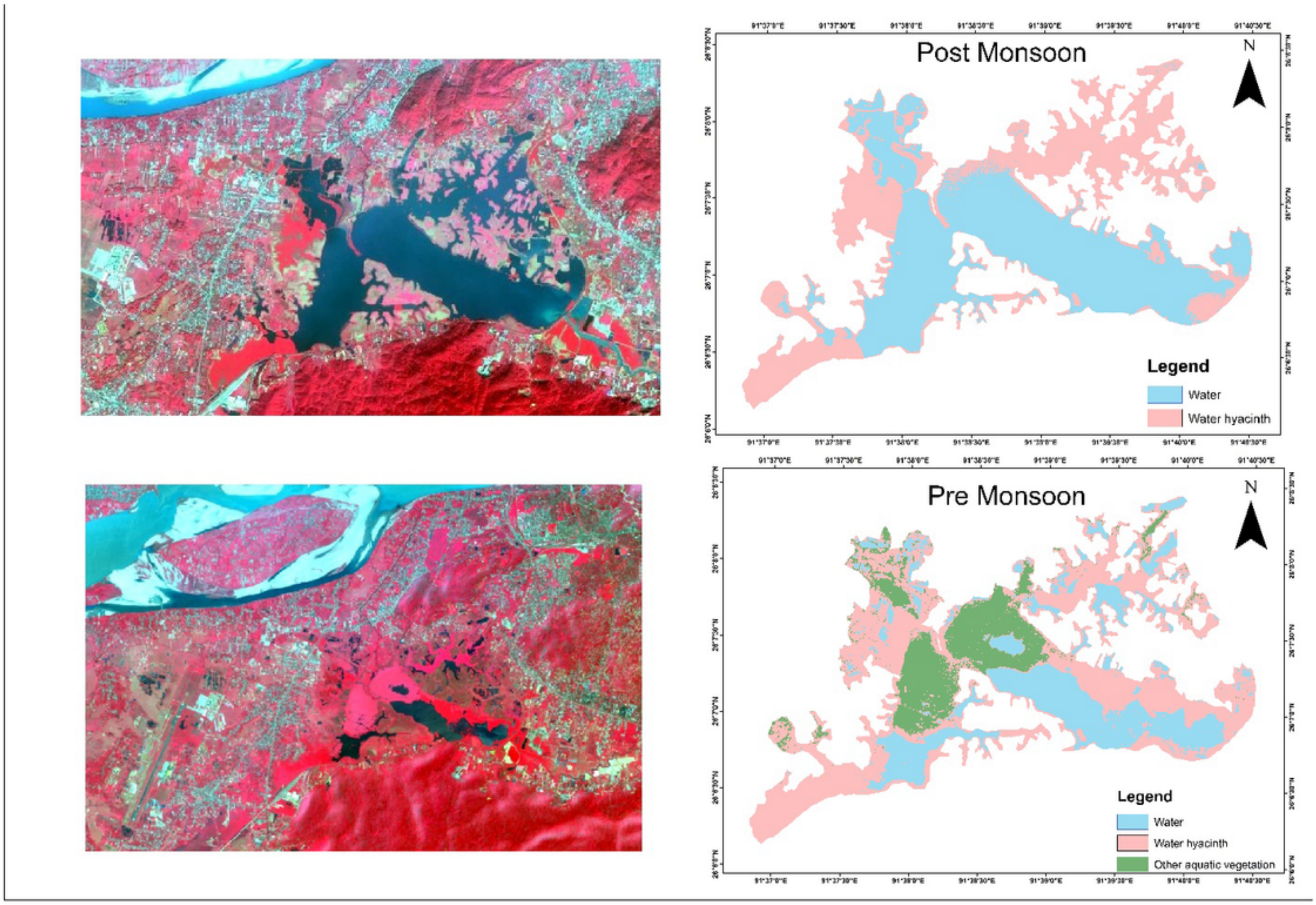

Figure 4

Map of area covered by water hyacinths in post- and pre-monsoon seasons