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REVIEW

Progress in the utilization of water hyacinth as effective biomass material

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Abstract
Water hyacinth (*Eichhornia crassipes*) is considered a prospective free-floating aquatic plant potentially used to address current issues on food, energy, and the environment. It can grow quickly and easily in various tropical and subtropical environments as long as it has access to adequate light and water to support photosynthetic growth. Ecosystems are threatened by their invasive growth and remarkable capacity for adaptation. However, managing this plant can result in valuable products. This paper demonstrates particle technologies that might be used to utilize water hyacinths, including brake pads, fertilizer, bioenergy, animal feed, phytoremediation agents, bioplastics, and adsorbents. This study is accompanied by a discussion based on the conducted experiments and currently available literature, providing readers with a clearer understanding. Water hyacinth's capacity to absorb macro- and micro-nutrients, nitrogen, and phosphorus makes it a good plant for phytoremediation. The prospect of producing cellulose makes it prospective as a biomass energy source and livestock feeding. Further, it can be transformed into high-cellulose content particles for applications in bioplastics, brake pads, and adsorbents. The current reports regarding education of water hyacinth to student also were added. Finally, issues and suggestions for future development related to the use of water hyacinths are discussed. This study is expected to provide comprehensive knowledge on how to turn invasive water hyacinth plants into valuable products.

Keywords Aquatic plant · Ecosystem · Engineering · Environment · Particle technology · Water hyacinth

1 Introduction

Water hyacinth (*Eichhornia crassipes*) is one of the invasive species that lives and reproduces in the aquatic environment. It is a free-floating aquatic plant that typically flourishes in stagnant swamps, lakes, reservoirs, and rivers (Jirawattanasomkul et al., 2021). It poses a threat to socio-economics and biological diversities at the environmental, individual, and genetic levels (Colautti & MacIsaac, 2004). Its rapid growth creates a global concern

Extended author information available on the last page of the article because uncontrolled growth can clog water bodies and disrupt power plants. In addition, water hyacinths can prevent sunlight from reaching water bodies and lower oxygen levels, disturbing the aquatic ecology due to a lack of oxygen from the atmosphere (Madikizela, 2021).

Water hyacinth is classified as a weed or nuisance plant due to its rapid proliferation in aquatic ecosystems. Before expanding, it persists in small numbers. Water hyacinths are incredibly prevalent, especially in reservoirs, ponds, lakes, and fish farm ponds. The utilization of water hyacinths is quite broad in scope, but research is still urgently required to prevent the spread of water hyacinths and turn them into valuable goods. Various methods for using and managing water hyacinths have been reported and examined (Ajithram et al., 2021; Ali et al., 2020; Duenas et al., 2018; Elenwo & Akankali, 2019; Ilo et al., 2020; Leguizamo et al., 2017; Mishra & Maiti, 2017; Pandey, 2020; Priya & Selvan, 2017; Ting et al., 2018; Yan et al., 2017; Zolnikov & Ortiz, 2018). Unfortunately, current publications only provide incomplete descriptions of effective use in one particular case and some theoretical perspectives. This study's major goal was to demonstrate how technologies can be applied to manufacture products from water hyacinths, including animal feed, fertilizer, bioenergy, brake pads, bioplastics, phytoremediation agents, and adsorbents (see Fig. 1). Additionally, several new findings obtained in the experimental results are explained in every section. This study brought the discussion based on the literature to a close with experiments that can help readers gain a better understanding and perspective. This study is expected to provide comprehensive knowledge on using invasive water hyacinth species to produce beneficial products.

In addition, although the paper shows several applications, as shown in Fig. 1, this study is limited to discussion and description of some potential applications of water hyacinths. In fact, many applications are available such as bioenergy (i.e., biogas, biofuel, biodiesel, bioethanol), animal feed stock, water treatment, soil remediation, crafts, medicine, production of new materials and fertilizers.

The benefits of this study are being able to document the potential and sustainable application of water hyacinths to control the massive growth of water hyacinth and an environmental conservation method.

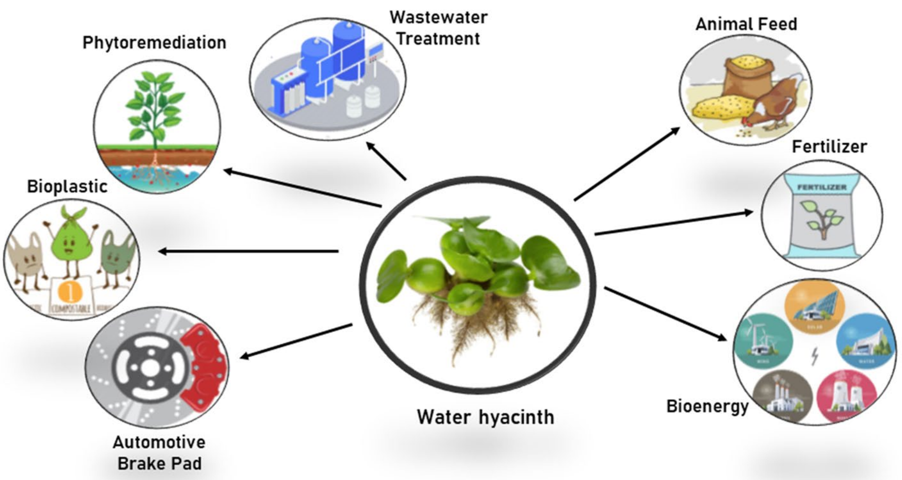


Fig. 1 Potential applications of water hyacinth

The review highlights several applications, including bioplastics, brake pads, animal feed, bioenergy, and waste water treatment (i.e., phytoremediation and adsorption), as well as important education aspects to support its management and utilization. We also added current reports regarding education of water hyacinth to student.

This study also compiles all the possible ways to control the growth of water hyacinth through a potential, safe, and sustainable holistic approach. It also focuses on the role of naturally growing plants to pave the way for further afforestation programs (Yadav et al., 2021). Therefore, the benefits of this study include comprehensive documentation of the potential and sustainable application of water hyacinth as a method of controlling the massive growth of water hyacinth and environmental conservation and deep exploration of the educational potential of water hyacinths, providing educators with ideas, methodologies, and case studies to integrate this aquatic plant into their teaching and learning activities.

This study also has a bibliometric analysis study on water hyacinth research. Thus, this research is also expected to help and become a source for other researchers in conducting and determining research topics based on related topics.

The current study's roadmap regarding water hyacinth use is explained in Fig. 2. The trend of water hyacinth research is exploring the potential use of water hyacinth (such as wastewater treatment, fertilizers, bioenergy, handicrafts, potassium sources, composite fillers, biochar, and animal feed) as an effort to control the invasive growth of water hyacinth (Hofifah & Nandiyanto, 2024; Nandiyanto et al., 2024). In detail, several research trends on water hyacinths are explained as follows:

(i) In the first ten years (1971–1980), the water hyacinth was introduced through several publications, including many publications that informed general ecology and the life history of the water hyacinth. The papers also discussed that water hyacinth is an aquatic plant that floats in tropical waters and subtropics and is known as one of the most serious pest plants; thus, it is necessary to control the inhibition of this pest

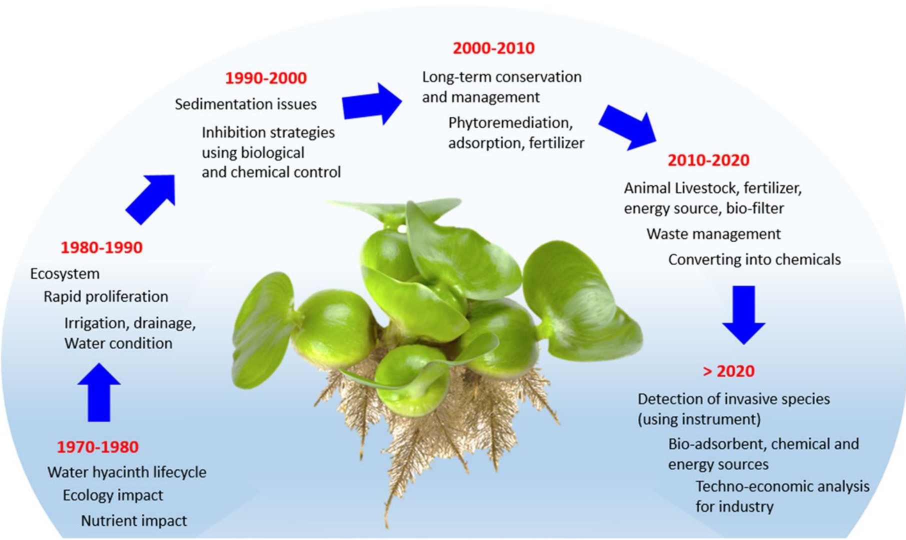


Fig. 2 The roadmap of the current study regarding the use of water hyacinths. Data was obtained using the Scopus database with keywords "water hyacinth" and "ecosystem" analyzed on July 2023

plant. In addition, they informed the macronutrient content (such as inorganic and organic) of water hyacinth, which is useful as a feed ingredient, and discussed that the waters where water hyacinth plants grow affect the physical properties of water (such as temperature, pH, dissolved oxygen (DO), and alkalinity).

(ii) In the second decade (1981–1990), the application of water hyacinth plants has been extensively studied for municipal wastewater treatment, irrigation, drainage, and water along with many other uses (such as animal feed, source of fresh water through evapotranspiration, source of methane, fertilizer, and compost). Water hyacinth plants are proven very efficient to be efficient in wastewater treatment. It can be implemented to prevent eutrophication by removing biochemical oxygen demand (BOD), NH_3, and PO_4. Not only it has the potential to recycle wastewater but also the potential application of water hyacinth in air recycling ecological systems is also informed.

(iii) In the third ten years (1991–2000), the use of macrophyte plants for municipal wastewater treatment grew rapidly. For example, water hyacinths are used to purify three effluents (nitrogen, phosphorus, chemical oxygen demand (COD), and suspended solids) containing high levels of ammonia nitrogen. In addition to water treatment, water hyacinth is used to purify chlorophenoxy acid (CPH) and s-triazine herbicides, accumulated in sediments. During this year, efforts to inhibit the growth of water hyacinth as an aquatic weed have been studied. One of the efforts to control the inhibition of water hyacinth growth was carried out through biological and chemical control.

(iv) In the fourth ten years (2001–2010), researchers have focused on the use of water hyacinth for long-term conservation for the rehabilitation and management of lakes, management of ecosystems polluted by heavy metals (such as cadmium, chromium, copper, nickel, and lead) and industrial management of wastewater (such as treating wastewater from dairy, tanneries, sugar factories, pulp and paper industries, palm oil mills, and refineries) through phytoremediation and adsorption methods. In these years, water hyacinth has been informed of its prospect of becoming a very valuable resource as a substrate for mushroom production. However, in promoting the use of water hyacinth biomass as a substrate for mushroom cultivation, it is also necessary to assess the food safety of the mushrooms produced. This is because water hyacinths and mushrooms accumulate various mineral elements. Furthermore, the potential use of water hyacinths as a source of potassium to produce potassium salts has been reported through the process of extracting and extracting potassium from water hyacinths.

(v) In the fifth ten years (2011–2020), research trends in water hyacinth span this year were still related to the utilization of water hyacinth biomass as fish and livestock feed, fertilizer, and fuel energy (such as biofuel). Water hyacinth can be harvested and used economically for fish and livestock feed. In addition to fuel energy, dry water hyacinth biomass can also be made into briquettes, which are suitable as additional fuel in coal-fired power plants. Water hyacinth was also studied to absorb petroleum hydrocarbons; thus, it can be used in the phytoremediation of polluted ecosystems contaminated by crude oil. To increase the added value of water hyacinth, this plant is also used as an alternative source in the manufacture of carboxymethyl cellulose (CMC) because it has a high cellulose content. In addition to making CMC, water hyacinths were used as a raw material for handicrafts to replace paper. Water hyacinth has also been studied for its application as an effective, efficient, inexpensive biofilter for wastewater treatment from fish farming; thus, small and medium farmers can adopt this treatment system to aim for sustainable employment from this activity.

(vi) In the sixth ten years (2021–present), most of the research trends for water hyacinth were the same as the previous year; namely, the detection of invasive plant species in aquatic ecosystems using various instruments (for example, geographic information systems (GIS) and earth observation applications (EO)), recycling of biomass (animal feed, compost, biochar, bioadsorbent, composite filler, magnetic bioadsorbent with a combination of inorganic and inorganic materials), and multifunctional engineering to reduce pollutants in the form of heavy metals, metalloids, and organic compounds. Water hyacinth has been widely studied because it can fulfill various sustainable development goals (SDGs) related to clean and safe water, land protection, ecosystem, and biodiversity conservation, climate action, increased industrialization, and public awareness. In addition to the techniques for utilizing water hyacinth plants, research trends on assessing the economic value of water hyacinth plants are no less important. This economic analysis can be used to provide evidence of the effectiveness of water hyacinth biological control. Economic analysis studies also show that robust and cost-effective economic analysis is made possible by good record-keeping and generalizable models that can demonstrate management effectiveness and improve the social efficiency of invasive species control.

2 Method

2.1 Raw materials

Several materials were used: water hyacinth (from Cirata dam, Purwakarta, Indonesia), pure water, curcumin (extracted from turmeric purchased from a local market in Bandung, Indonesia), acetic acid, glycerol, Bisphenol A-epichlorohydrin (technical grade, P.T. Justus Kimiaraya, Indonesia), cycloaliphatic amine (technical grade, P.T. Justus Kimiaraya, Indonesia), and iron (III) chloride hexahydrate ($FeCl_3$, Sigma-Aldrich; as a model for metal ion).

2.2 Phytoremediation

Water hyacinths were washed and cleaned from impurities to ensure the absence of pests, such as insect eggs. Metal salt solution (45-ppm $FeCl_3$ in 2.5 L) was put in a glass batch reactor (dimensions of $25 \times 15 \times 14.5$ cm for length, width, and height, respectively) containing water hyacinths. The water hyacinth was exposed to the solution for two weeks at room temperature and pressure (controlled light for 12 h/d). The growth of water hyacinths was monitored (length of the petiole and the width of the leaf blade), and an aliquot sample from the glass batch reactor was taken for chemical content analysis using UV–Vis spectroscopy (Model 7205; JENWAY; Cole-Parmer; U.S.; between 280 and 600 nm). The UV–Vis spectrophotometer results were normalized and extracted using Beer Law to get the actual concentration (Pratiwi & Nandiyanto, 2021).

2.3 Nutrient analysis

Proximate analysis on the determination of moisture, ash, and crude fiber content was carried out using the gravimetric method. Analysis of fat, protein, and carbohydrate contents was performed using the Soxhlet, Kjeldahl, and Luff-Schoorl methods, respectively. Thermal Gravimetric analysis of the samples was performed on a NETZSCH Company, Germany, STA449F3 synchronous thermal analyzer (25–600 °C; a heating rate of 20 °C/min).

2.4 Energy content analysis

To analyze the energy content in the water hyacinth, 50 mg of the water hyacinth was introduced into a thermogravimetric analyzer (TG–DTA; DTG60A TA60WS, Shimadzu Corp., Japan) under atmospheric conditions (the heating rate of 10 °C/min; between 25 and 600 °C; holding time at the targeted temperature of 10 min). Information regarding TG–DTA was explained in the previous study (Nandiyanto, 2017).

An adiabatic bomb calorimeter in a pressure-resistant reactor (ASTM D 5865–13) was used to measure the calorific value of the water hyacinth (which was dried before the analysis). The water hyacinth sample was exposed to 99.5% pure oxygen for 10 min. A current passed through an ignition wire (inserted inside the bomb) ignited the sample. The reactor was submerged in water and covered by a jacket to prevent heat loss. The heat generated from the combustion was used to heat the water, and the transformed heat was measured.

2.5 Water hyacinth particle production

Water hyacinth (i.e., stems and leaves) was washed, cut into pieces, dried using sunlight for 3 h, re-dried using an electrical furnace at 150 °C for 2–3 h to remove physically attached water, saw-milled (to get particles), and put into sieve test mesh (ASTM D1921) to get fine particles with a specific size (i.e., 500, 250, 100, 74, and 60 µm)). Detailed information on the preparation of particles is reported in the previous study (Nandiyanto et al., 2018). The particle size and morphology of the material were investigated using a digital microscope. Fourier transforms infrared spectrometer (FTIR, FTIR-6600, Jasco Corp.; Japan) was used to analyze chemical content. Data obtained from FTIR was then compared to the FTIR dataset available in the literature (Nandiyanto et al., 2019, 2023b). To support the analysis of the surface area and porous structure, nitrogen sorption measurement (BET Nova 4200e; Quantachrome Instruments Corp., US; operated at 77 K) was conducted.

2.6 Bioplastic production

Water hyacinth particles were mixed with cornstarch particles (a composition ratio of 15:0.1; 15:1.0; 15:1.5; and 15:2.0), water, glycerol, and acetic acid. The mixture was heated and stirred for 20 min at 60 °C until it thickened. The thickened mixture was then poured into the mold and dried at room temperature to obtain brownish-yellow bioplastics. The prepared bioplastics were observed using a digital microscope (BXAW-AX-BC, China) to determine the morphology and structure of the bioplastics. To analyze the chemical structure of bioplastics, FTIR (FTIR-4600, Jasco Corp., Japan). A biodegradation test was done by immersing bioplastics in water. Detailed information regarding the preparation with its biodegradation analysis of bioplastics is presented in the previous studies (Nandiyanto et al., 2020a, 2020b, 2021d, 2022a, 2022b, 2022d; Triawan et al., 2020).

2.7 Brake pads production

Water hyacinth particles were mixed with bisphenol A-epichlorohydrin and cycloaliphatic amine (the mass ratios of 6/5/5; 9/5/5; 3/5/5), poured into a silicone mold (dimensions of $4 \times 3 \times 1$ cm for length, width, and thickness, respectively), and dried at room temperature and pressure for one week. Detailed information for the preparation of brake pads is reported in previous reports (Anggraeni et al., 2022a, 2022b; Nandiyanto et al., 2021b, 2021c, 2022c, 2022d, 2022e). The prepared brake pad was then put into the compression test using a micro screw mount (Model I ALX-J, China) with a digital force meter (model HP-500, serial number H5001909262), the puncture test using a shore durometer (Shore A hardness, In Size, China), and friction test using sandpaper (Dae Sung CC-80Cw, Daesung Abrasive Co., Ltd., Korea) with 5 kg mass pressure (20 min at a speed of 18 cm/s) for understanding wear rate (M) and friction coefficient (μ)). The wear rate was determined using Eq. (1):

$$M = \left(M_a - M_b\right) / t \times A \tag{1}$$

where Ma and Mb are the mass of the brake pad in initial and final conditions after the friction test (g), and t is the testing time (s). A is the cross-sectional area of the brake pad in contact with the sandpaper (cm^2).

2.8 Adsorption analysis

For the adsorbent, water hyacinth particles with a specific size were put into a 150-mL glass reactor containing curcumin solution (i.e., concentrations of 100, 80, 60, 40, and 20 ppm; as a model of dye). The suspension was mixed (at 500 rpm for 120 min) at ambient conditions with a constant pH (approximately pH 7). An aliquot of the mixed suspension was taken and filtered through a pore size of 0.22-μm nylon membrane syringe. The filtrate was analyzed using a UV–Vis spectrophotometer (Model 7205; JENWAY; Cole-Parmer; U.S.; between 250 and 500 nm). The UV–Vis spectrometry results were normalized and extracted using the Beer Law to get the actual concentration (Pratiwi & Nandiyanto, 2021). Ten adsorption isotherm models were used to evaluate the phenomenon during the adsorption process (i.e., Langmuir, Freundlich, Temkin, Dubinin–Radushkevich, Fowler–Guggenheim, Hill-Deboer, Jovanovic, Harkin–Jura, Flory–Huggins, and Halsey). The mathematical analysis and its interpretation of the models are explained in the previous studies (Ragadhita & Nandiyanto, 2021).

2.9 Education references

We collected data on the theme of education in Indonesia about water hyacinth through a literature study. Data on various articles and books indexed by google scholar were searched and collected through the vosviewer application. The keyword used was "education in Indonesia about water hyacinth". The searched data were limited to only the last 5 years. The development of research on water hyacinth education over the last 5 years obtained as many as 996 articles and book data. After that, several sample article data were taken to be analyzed and discussed.

3 Results and discussion

3.1 Current progress in the management of water hyacinth as invasive species

Invasive species are alien species that live and breed in the aquatic area until they become a threat to biological diversity (Colautti & MacIsaac, 2004). The introduced species must generally survive in small populations before becoming invasive. The invasion happened because of competition to get resources, which can significantly change the functions and processes in ecosystems (Duenas et al., 2018), transform the balance of the ecosystem, and lead to environmental damage and economic losses. Invasive species possibly reduce biodiversity, causing the extinction of species and habitats (Evans et al., 2016).

Many types of invasive species live in water bodies, such as water hyacinth (*Eichhornia crassipes*), creeping water primrose (*Ludwigia adscendens*), flowering pickerel weeds (*Monochoria vaginalis*), African water weeds (*Monochoria africana*), water lettuce (*Pistia stratiotes L.*), lesser bulrush (*Typha angustifolia*), Kariba weeds (*Salvinia molesta*), mosquito fern (*Azolla pinnata*), and yellow velvetleaf (*Limnocharis fava*). These aquatic species occupy the same niche in the water area, causing direct interactions with the ecosystem (Pandey, 2012). One of the most well-known invasive aquatic plants is the water hyacinth. It causes a lot of economic loss in agriculture and husbandry due to its quick invasion of the area. It appears randomly everywhere, competing with cultivated plants for water, sunlight, nutrients, and space. It can destroy native habitats and threaten native plants, organisms, and animals in water bodies. To control water hyacinths in the ecosystem, many researchers reported controlling nutrients (Karouach et al., 2022; Yan et al., 2017) in the water as well as adding natural enemies (e.g., *Neocetina. Spp*) (Elenwo & Akankali, 2019) and herbicides (Portilla & Lawler, 2020). However, since water hyacinths easily proliferate and have high resistance to extreme planting conditions, controlling their growth is challenging.

One of the best strategies is to make them consumable products. Water hyacinth is a free-floating aquatic plant that usually grows in swamps, lakes, reservoirs, and rivers with a steady flow (see Fig. 3a). It is a biomass that has great potential to be utilized. Many reports have documented the use of water hyacinth for numerous beneficial products. Because of its high crude protein content, water hyacinth was employed as food for ruminants, pigs, geese, ducks, and fish (Wimalarathne & Perera, 2019). Additionally, it is employed in producing bioenergy, biogas, briquettes, fertilizer, and arts and crafts. It is even well-introduced to students in their education from elementary through high school. (Harun et al., 2021). According to some publications, water hyacinths can also be used for phytoremediation to take out organic (Madikizela, 2021) and heavy metals [e.g., cadmium (Cd), arsenic (As), mercury (Hg), chrome (Cr), cadmium (Cd), and copper (Cu)] (Nazir et al., 2020; Pandey, 2016) from water. The next sections of the article give a discussion based on experimental results compared to recent literature.

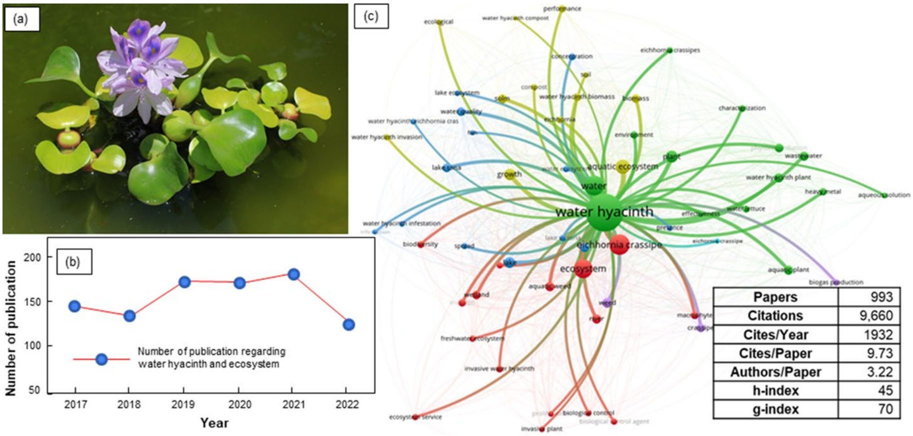


Fig. 3 **a** Photograph image of water hyacinth, **b** development of Publication number, and **c** Network visualization of Publications on "Water Hyacinth" and "Ecosystem" (from 2017 to 2022). The inserted table at the bottom right is the publication data

Information on water hyacinths has been distributed to students since elementary school due to the major concern regarding water hyacinth management. On the official website of the Indonesian Directorate General of Education, for instance, this material is included in the curriculum and even developed into a project-based learning program. In Indonesia, water hyacinths are explained to elementary school students as eutrophication and the potential used as conventional craft products. Following that, in the 2013 curriculum, water hyacinth-related learning has been given to 7th-grade middle school students. Specifically, water hyacinth is introduced in the section on biomass energy combined with information on plants, agricultural waste, forestry waste, human waste, and livestock manure treatment. The topic (regarding "Relations of Interaction and Natural Appearance") was also available to discuss the advantages of water hyacinths, including their usage as animal feed, handicraft materials, and floral arrangement support. Water hyacinth has been used to foster student entrepreneurship, encouragement, and innovation (Syamsi & Fitrihidajati, 2021). Discussion about water hyacinths was re-introduced to 10th-grade senior high school students. In extracurriculars, students are taught to convert water hyacinths into basic consumer goods, such as photo frames, flower vases, sandals, tote bags, and other souvenirs.

To support the explanation in this paper, computational literature review analysis was employed to comprehend the impacts of water hyacinth on the ecosystem as well as products that can be made from it. Detailed information for the computational literature review analysis used in this study is reported in the previous studies (Al Husaeni & Nandiyanto, 2022b). This analysis has been widely employed in numerous research fields to understand current trends in certain areas of inquiry, such as engineering and mining (Al Husaeni & Nandiyanto, 2022a; Mulyawati & Ramadhan, 2021; Nandiyanto et al., 2023a), education (Al Husaeni et al., 2023; Al Husaeni & Nandiyanto, 2023; Bilad, 2022; Nordin, 2022; Ragadhita & Nandiyanto, 2022a; Shidiq et al., 2021; Sudarjat, 2023; Wirzal & Putra, 2022), health (Hamidah et al., 2020; Saputra et al., 2022), agriculture and biotechnology (Hirawan et al., 2022; Luckyardi et al., 2022; Mudzakir et al., 2022; Riandi et al., 2022; Soegoto et al., 2022), chemistry, chemical engineering, and material science (Kurniati et al., 2022; Nandiyanto & Al Husaeni, 2021;

Nandiyanto et al., 2021a, 2022a, 2022d, 2022e; Saputra et al., 2022; Setiyo et al., 2021; Shidiq, 2021; Wiendartun et al., 2022). The analysis current progress using keywords of "Water Hyacinth" and "Ecosystem" found 993 articles. This can become the novelty in this study since the literature review analysis was completed by computational literature review analysis for searching research papers for supporting the experiments and discussion. A research matrix is shown in the attached table in Fig. 3, with a total number of citations of 9,660. The publications had 1932 citations per year and 9.73 citations per year. The collected data had an h-index of 45 and a g-index of 70, implying a relatively good level of metrics for the productivity and impact of citations from publications. Table 1 shows the popular articles (taken on January 2023 using VOSviewer with google scholar database). This data confirms the importance of research on water hyacinths to the ecosystem.

Figure 3b shows the progress in the publications between 2017 and 2022. Research has increased since 2019, implying increasing concerns regarding water hyacinths, especially facing the issues of this aquatic plant in the ecosystem. Figure 3c presents the network visualization of Publications from 2017 to 2022, showing a strong connection in different colors of the nodes in the visualization, including several groups:

1. Aquatic weed, biodiversity, biological control, biological control agent, ecological impact, ecosystem, ecosystem service, *Eichhornia crassipe*, freshwater ecosystem, invasion, invasive plant, invasive water hyacinth, macrophyte, proliferation, rivers, and wetlands.
2. Aquatic plant, aqueous solution, characterization, effectiveness, *Eichhornia crassipes*, environment, heavy metal, phytoremediation, plant, wastewater, water, water hyacinth, water hyacinth plant, and water lettuce.
3. Concentration, fish, infestation, lake, lake ecosystem, lake tana, Lake Victoria, presence, spread, water body, water ecosystem, water hyacinth *Eichhornia crassipe*, water hyacinth infestation, and water quality.

Table 1 Top articles on "Water Hyacinth" and "Ecosystem" obtained using VOSviewer with google scholar database taken on January 2023

References	Title
Ali et al. (2020)	Application of floating aquatic plants in phytoremediation of heavy metals polluted water: A review
Saha et al. (2017)	Phytoremediation of industrial mines wastewater using water hyacinth
Sindhu et al. (2017)	Water hyacinth a potential source for value addition: an overview
Kulkarni et al. (2017)	Removal of crystal violet dye from aqueous solution using water hyacinth: Equilibrium, kinetics and thermodynamics study
Mishra and Maiti (2017)	The efficiency of *Eichhornia crassipes* in the removal of organic and inorganic pollutants from wastewater: A review
Oyeoka et al. (2021)	Packaging and degradability properties of polyvinyl alcohol/gelatin nanocomposite films filled water hyacinth cellulose nanocrystals
Ting et al. (2018)	Application of water hyacinth (*Eichhornia crassipes*) for phytoremediation of ammoniacal nitrogen: A review
Nandiyanto et al. (2024)	Research trends from the Scopus database using keyword water hyacinth and ecosystem: A bibliometric literature review
Hofifah and Nandiyanto (2024)	Water hyacinth and education research trends from the Scopus database: A bibliometric literature review

4. Aquatic ecosystem, biomass, compost, ecological, Eichhornia, growth, performance, soil, water hyacinth biomass, water hyacinth compost, and water hyacinth invasion.
5. Biogas production, *Eichornia crassipe*, and weed.
6. *Eichornia crassipe*.

Based on the above results, water hyacinths have connections to the research in the aquatic ecosystem, water treatment, and lake. Compared to the environmental impact, research on managing water hyacinths is relatively less, informing the need for comprehending reports to solve issues in the water hyacinth invasion.

3.2 Phytoremediation

Water plants, especially water hyacinth, have been widely studied for phytoremediation (Pandey, 2012; Rezania et al., 2015; Ting et al., 2018) for removing organic, inorganic, and heavy metal pollutants in water. Current reports on the utilization of water hyacinths for phytoremediation for removing chemicals (such as nitrogen, phosphorous, ammonia, Fe, Cu, Cr, Zn, Pb, Cd, and Ni), as well as connection to the COD, total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS), BOD, and DO, are presented in Table 2.

Different from other reports, the present study has a novelty in analyzing directly the growth of water hyacinth under the existence of iron in the water medium. Iron ion was selected as a model since it creates agriculture, industries, and municipal problems. The permissible iron concentration in water is less than 10 ppm (Kumar et al., 2017). This study used an initial concentration of iron ions of 45 ppm. Figure 4 shows the phytoremediation results of water hyacinth under iron-contaminated water. Figure 4a is the Vis spectrum results, and Fig. 4b is the analysis of concentration using Beer Law (taken at a wavelength of 325 nm). Figure 4c is a visualization of the sample during the phytoremediation. After going through phytoremediation for 14 days, the concentration of iron decreased significantly, as shown by decreasing the visible spectrum for the solution before and after 14 days of phytoremediation (see Fig. 4a). The Beer Law analysis from the visible spectrum of the phytoremediation process replies to the decreases in the concentration from 45 to 12 ppm of iron (see Fig. 4b). The successful phytoremediation was shown by the effectiveness of iron removal in water at about 38% after two weeks of phytoremediation. The decreases in concentration are due to the ability of the roots of the water hyacinth plant to absorb pollutants accumulated in water (Newete et al., 2016). These pollutants are accumulated as dissolved materials in the accumulator plant parts (Ali et al., 2020).

The successful phytoremediation was supported by observing the growth of water hyacinths (see Fig. 5). The growth of the petiole size and leaf blade width (see Fig. 5) were obtained daily with a total elongation of more than 3 cm within 14 days. Almost no impact on the additional contaminant in the water was found, showing the metabolic stability of water hyacinths under extreme conditions (Nguyen et al., 2021). The water hyacinth plant continued to grow; however, yellow spots were found on the leaves (see Fig. 4e), which is different from the healthy leaf (presented in Fig. 4d). It is suspected that the spots are caused by an accumulation of iron absorbed (Kneen et al., 1990), but further research is still required to investigate deeply for this case. During the growth in 14 days, the total water loss due to the water hyacinths absorption and water evaporation was about 1.2 L (from a total of 5 L of the reactor). It is relatively large, informing great photosynthesis for supporting their growth by absorbing carbon dioxide, carbon dioxide, and nutrients.

Table 2 Recent studies on phytoremediation using water hyacinth

Treated water	Type of chemicals	Results	References
Wastewater from simulated wetland	Cu, Cr	Pollutant removal from the water was extremely effective. The experimental results showed that water hyacinth could remove about 65% of heavy metals	PN and Madhu (2011)
Artificial lake water	Zn, Cu, Pb, Cd	Successful phytoremediation (8 days) was obtained, and it depended on the pH condition. When using a pH of 8, the removal efficiencies of Cu, Pb, Cd, and Zn are 24, 26, and 18%, respectively. When using a pH of 6, the removal efficiencies of Cu, Pb, Cd, and Zn were 24, 26, 50, and 57%	Smolyakov (2012)
Agricultural, river, and mixed industrial drain	Zn, Cu, Ni	Water hyacinth plants were capable of accumulating higher amounts of Cu, Ni, and Zn in their roots to levels that exceeded the normal ranges stated in plants. They are recommended for the phytoremediation of metal ions from aquatic habitats or constructed wetlands. The accumulation of trace metals in root tissues was discovered to be in the following order: Zn > Cu > Ni	Hammad (2011)
Sewage wastewater stabilization ponds	Cd, Cu, Pb, and Zn	Water hyacinths can capture heavy metals and accumulate the metal components in their leaves (reaching 63%)	Michael (2019)
Synthetic waste waster	Cu	The results showed an increase in copper within the tissues of the plant's roots and shoots and a decrease in copper concentration in the solution. The maximum copper removal rate was 97.3%	Mokhtar et al. (2011)

Table 2 (continued)

Treated water	Type of chemicals	Results	References
Domestic wastewater	COD, TN, and TP	During the first week of the experiment, water hyacinth removed 80% of the COD, 75% of the TN, and 75% of the TP. The water loss ratio in the tank and its effect on biomass growth was evaluated, and it was discovered that there was a 20% or 15 L weekly water reduction and a 40% crop increase in biomass at the end of the experiment when compared to the beginning	Rezania et al. (2013)
Metallurgic, pharmaceutical, and textile wastewater	TSS, BOD, DO, nitrate-nitrogen, Cd, and Fe	Pollutant removal averages for TSS, BOD, DO, nitrate-nitrogen, cadmium, and iron were 53.03, 64.41, 65.4, 47.22, 94.67, and 30.30%, respectively, after a 5-week growth on wastewater (from different industries)	Ajayi and Ogunbayo (2012)
Domestic wastewater	COD, BOD, TN, TP, TSS, phosphate, and ammonia	Reduction for COD, BOD, TN, TP, TSS, phosphate, and ammonia of 14 h was 79, 86, 76.61, 44,84, 73.02, 38.69, and 72.48%, respectively	Valipour et al. (2015)
Domestic sewage water	Ammonia, nitrate, phosphate	The uptake of nutrients for plant growth in water hyacinth and Azolla showed a greater reduction than in the papaya. The combination of water hyacinth and papaya stem effectively reduced ammonia (67%) and nitrate (74%). Phosphate was reduced by 80% when Azolla was combined with the papaya stem	Anandha Varun and Kalpana (2015)
Nitrogen-polluted water	Nitrogen	The TN removed was 63.9%. Denitrification accounted for 72.8% of the nitrogen removed	Mayo and Hanai (2017)

Table 2 (continued)

Treated water	Type of chemicals	Results	References
Muddy fly ash pond	Cr, Cu, Cd	Phytoremediation with water hyacinth is efficient for accumulating various heavy metals (such as Cr, Cu, and Cd) from fly ash ponds	Pandey (2016)

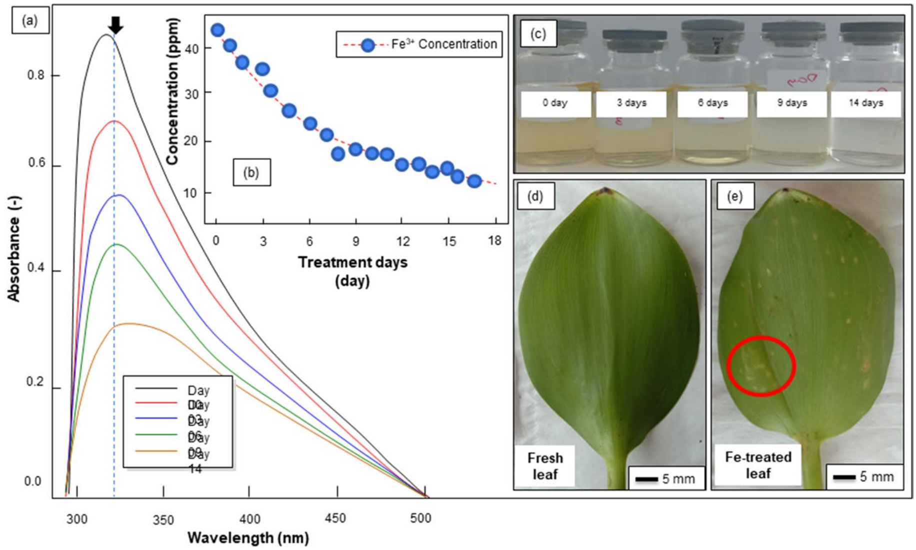


Fig. 4 **a** The result of the visible spectrum of the water hyacinth phytoremediation test under iron-contaminated water, **b** analysis of iron concentrations after phytoremediation, **c** visualization of the decrease in iron concentrations for 14 days after phytoremediation, **d** appearance of water hyacinth leaves before phytoremediation, and **e** appearance of water hyacinth leaves after phytoremediation

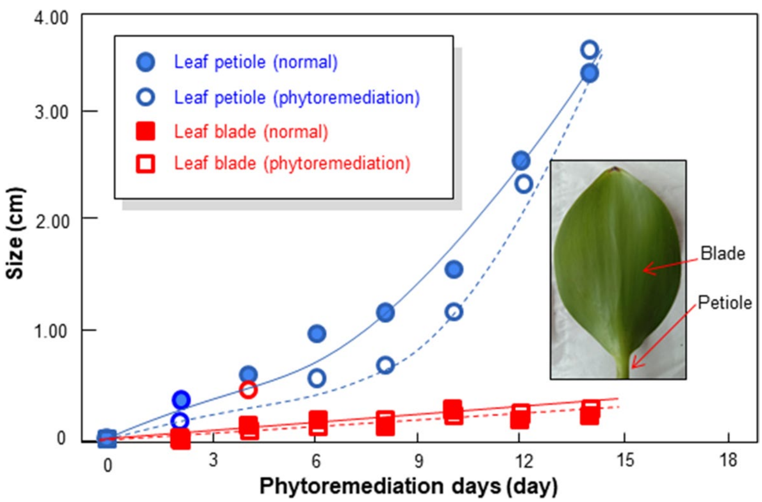


Fig. 5 Leaf growth during phytoremediation

Based on the phytoremediation process carried out in this study, iron metal absorbed by water hyacinth roots was translocated to other organs until it accumulated in these organs (in roots, petioles, and leaf blades). The results of this study correlate with the results of another study by Ndimele et al. (2013), which compared the absorption of Fe and Cu by water hyacinths, and reported that Fe and Cu could accumulate in the roots and leaves of water hyacinths. These results indicate that the potential for absorption and accumulation of Fe by water hyacinth is higher than that of Cu. The results of this study are also in line with the research of Hasani et al. (2021), who examined iron phytoremediation in the waters of former sand mines in Lampung, Indonesia. The results of research by Hasani et al. (2021) showed that water hyacinths can absorb up to 97.96% of iron in water with only 50% of water hyacinths submerged in water. Also in the phytoremediation process, the absorption of Fe metal occurs simultaneously with the absorption of nutrients. Sufficient levels of nutrients in the waters will increase the ability of photosynthesis. Thus, the absorption of nutrients and metal Fe by water hyacinth is greater. Another study examined the ability of water hyacinth to remediate kitchen waste water, and the result was that water hyacinth was able to absorb iron with the highest bioconcentration factor (BCF) of 8,363.40 compared to other metals such as nickel, zinc, and mercury contained in kitchen waste water (Parwin & Karar Paul, 2019).

3.3 Nutrition in water hyacinths

The nutritional content of water hyacinth is presented in the table attached in Fig. 6. Dried water hyacinth contains water (83.51%), ash (3.20%), fat (0.19%), protein (3.5%), carbohydrate (5.13%), and crude fiber (4.06%). Another study showed that the proximate analysis of water hyacinth contains moisture (89.20%), ash (18.20%), protein (8.20%), lipid

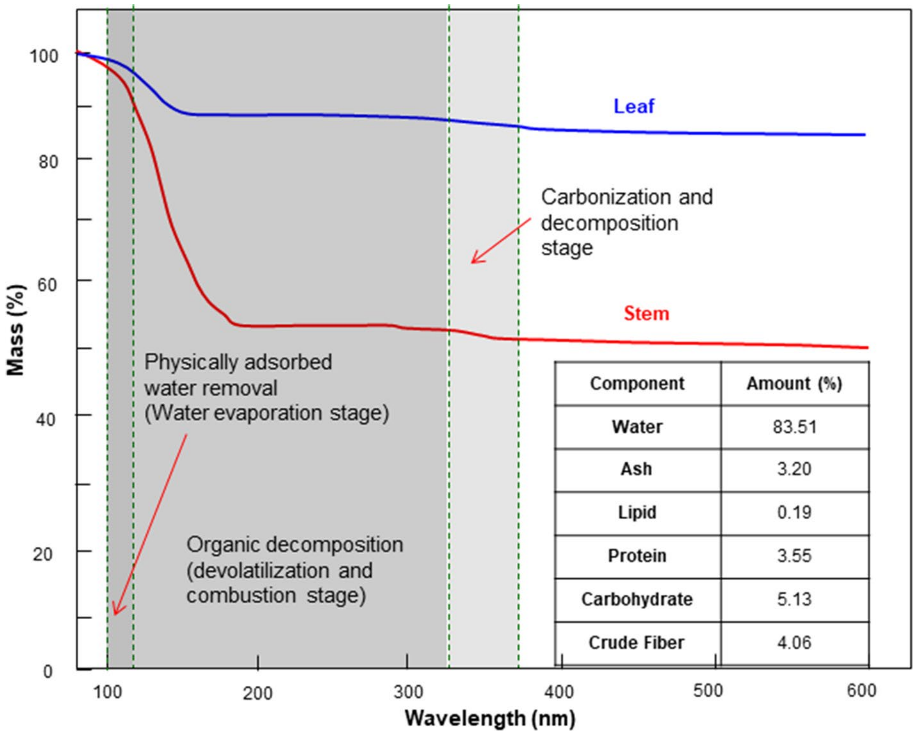


Fig. 6 Thermal analysis results of stems and leaves of raw water hyacinth

(2.20%), fiber (21.42%), and carbohydrate (49.98%). The results demonstrate that water hyacinths have a high moisture content (> 80%). The moisture content of any food is an indicator of its stability and susceptibility to microbial contamination. Because of its high moisture content, water hyacinth may have a limited shelf life. Because of the high moisture content, dehydration would raise the relative concentrations of the other food ingredients and improve the shelf-life/preservation of the water hyacinth meal (Suleiman et al., 2020). For more details, a comparison of the nutritional value of water hyacinth with other floating plants is presented in Table 3 (Banerjee and Matai, 1990). The nutrient composition (such as ash, fat, protein, carbohydrates, and fiber) of water hyacinth in this study has a lower value than some other floating plants.

Based on other studies, due to its high levels of cellulose and hemicellulose, water hyacinth is suitable to be used as an alternative to animal feed (Harun et al., 2021; Wimalarathne & Perera, 2019). This finding is also supported by other research on the use of water hyacinths for animal feed, such as goats (Abegunde et al., 2017), sheep (Mekuriaw et al., 2018), pigs (Akankali & Elenwo, 2019), ducks (Jianbo et al., 2008), rabbits (Hassan et al., 2015; Moses et al., 2021), and fish (Emshaw et al., 2021; Hailu et al., 2020). Processing water hyacinths for certain animal feed usually varies. Usually, the entire plant is utilized. However, some users remove the roots to avoid possible metal contamination (Moses et al., 2021).

The use of water hyacinth as an animal feedstock has been well-reported (Table 4). In Srilanka, water hyacinth is used as feed for ruminants, pigs, ducks, geese, and fish because of its high crude protein content (Wimalarathne & Perera, 2019). In China, for pig livestock feed, water hyacinths are usually processed through boiling, chopping, and mixing other ingredients such as vegetable scraps, rice bran, copra meal, and salt. In Malaysia, Indonesia, the Philippines, and Thailand, water hyacinths are used for pigs, ducks, and fish. However, water hyacinths are cooked without other ingredients before being fed to the animals. For catfish feed, water hyacinth is used as an additional nutrition. Water hyacinths can be used as livestock feed either in fresh form or as silage with straw instead of grass (Malik, 2007). In short, water hyacinth can be used as a supplemental feed that replaces the high-cost main feed with a cost-effective source.

Table 3 List of plant-based, non-conventional feed ingredients having the potential to be used as a feed ingredient and their nutrient composition (based on % of dry weight) (adopted from Banerjee and Matai, 1990)

Floating plant	Crude protein (%)	Ash (%)	Crude fat (%)	Crude fiber (%)	Carbohydrate (%)
Azolla pinnata	21.9	15.4	3.8	16.6	47.0
Gentiana lutea	17.2	12.9	2.2	22.7	35.0
Ipomoea reptans	20.6	16.5	4.6	27.0	54.20
Jussiaea repens	18.1	12.4	3.9	25.5	32.5
Lemma minor	20.4	17.2	3.8	15.7	43.6
Pistia stratiotes	20.5	17.0	3.8	39.6	83.07
Salvinia auriculata	14.6	12.5	2.9	45.0	20.0
Trapa bispinosa	10.8	13.6	5.1	42.8	22.30

Table 4 Utilization of water hyacinth as feeds for animals

Animals	Results	References
Duck	Feeding duck with water hyacinth improves the quality, yield (9.79%), and weight (2.36%) of eggs	Jianbo et al. (2008)
Sheep	It has impacts on nutrient intake and digestibility. Moreover, water hyacinth can be used as a substitute for Tifton-85 straw	de Vasconcelos et al. (2016)
Pig	There was a linear decrease in feed with increasing cost/weight in pigs after being fed with water hyacinth. It is due to the increased water content replaced with water hyacinth for soybean meal	Akankali and Elenwo (2019)
Indian carp (*Labeo rohita)*	Indian carp experienced a decrease in total protein diet by 20–40% compared to controls after being fed water hyacinth. The results also showed that digestibility decreased with increasing water hyacinth dietary water level	Pandey (2020)
Fish	Fermented water hyacinth-based feeds showed positive effects on the growth performance of several fish species, with additions of up to 40% being used	Pratiwi and Pratiwy (2018)
Nila tilapia	Water hyacinth with fermented can be used as a substitute for wheat bran. Fermented water hyacinth by 15% and 30% increased the growth of Nila tilapia	Hailu et al. (2020)
Goat	The weight gain of goats fed by water hyacinth has been improved by more than 2.01 kg per month. It is due to its high nutritional value that it can stimulate weight gain	Fitrihidajati and Ratnasari (2017)

3.4 Biomass energy

To meet the increasing energy demand, new energy sources must be considered. Renewable energy sources should be a viable alternative to fossil-fueled energy sources (Satriawan et al., 2021; Setiyo et al., 2021), such as hydroelectric, geothermal, wind, solar, and biomass-based power. Aquatic plants, such as water hyacinths, are promising biomass for renewable energy in future instead of land plants (Mishima et al., 2008). Currently, the literature that studied water hyacinth as a candidate energy source is summarized in Table 5.

Figure 6 shows the thermal analysis curve on dried stems and leaves of water hyacinths from 25 to 600 °C at a heating rate of 20 °C/min. Along with the TGA-DTA curves, the heating process can be divided into four stages, namely the water evaporation stage, the devolatilization and combustion stage, the carbonization and decomposition stage, and the stable stage. The details of the three stages are discussed in the following (Luo et al., 2011; Wauton & Ogbeide, 2019):

(i) Temperature between 50 and 120 °C. A decrease in the initial curve up to 47% in the stem and 23% in the leaf occurs, associated with the evaporation of moisture absorbed by the sample. The amount of water in the stem is higher than in the leaf. This is in line with the existence of water in the proximate analysis (see attached table in Fig. 6). However, the sample was raw (not dried) in the proximate analysis.
(ii) Temperature between 120 and 330 °C. The decomposition of hemicellulose, lignin, and fiber occurs. The decomposition temperatures of the original crude fiber and the pure cellulose fiber were 202 and 253 °C, respectively. The mass removal rate in this temperature range was 2% for both stem and leaf samples. This result is in line with the existence of organic components (such as lipids, proteins, carbohydrates, and fibers) in the proximate analysis (see attached table in Fig. 6)
(iii) Temperature between 330 and 380 °C. It indicates the carbonization and decomposition stage. All organic compounds were converted into carbon material (if there is not enough oxygen) and gasses (carbon dioxide and carbon monoxide if there is enough oxygen) (Nandiyanto, 2020).
(iv) Temperature higher than 380 °C. It indicates the presence of carbonaceous material (Ragadhita & Nandiyanto, 2022b).

Based on the calorific value analysis results, dried water hyacinth had a gross calorific value of 12.87 kJ/kg (0.01287 MJ/Kg) with a water content of 30%. In the literature (Cheng et al., 2010), the heating values of water hyacinth for leaves, stems, and roots are 14,930; 13,520; and 8,460 kJ/kg, respectively. The calorific value of water hyacinth was 14,550 kJ/kg (Munjeri et al., 2016). When compared with the calorific value of other aquatic plants and conventional fuels (such as diesel and gasoline), as shown in Table 6 (Arefin et al., 2021), the energy value of water hyacinths in this study is still relatively low or does not approach the calorific value of conventional fuels. The relatively small calorific value of water hyacinth is due to the water content in the water hyacinths that is relatively large, reaching 83% of raw water hyacinths (see nutrient content in the attached table in Fig. 6) and 30% for dried water hyacinth (water hyacinth adsorb water from surrounding). Therefore, additional techniques must be added to improve the calorific value since the water content is very influential on the calorific value. If the water content is high, then the calorific value is low. Less water content correlates to the obtainment of better calorific value.

Table 5 Summary study of water hyacinth as a candidate for energy sources

Product	Product characteristic results	References
Bioethanol	When using water hyacinth and water lettuce, a traditional strain of *saccharomyces cerevisiae*, produced 14.4 and 14.9 g/L of ethanol, respectively. In the simultaneous saccharification and fermentation mode, a recombinant strain of *Escherichia coli* produced 16.9 and 16.2 g/L of ethanol for water hyacinth and water lettuce, respectively, which was more effective than the separated hydrolysis and fermentation mode	Mishima et al. (2008)
Briquette	Briquettes prepared from water hyacinth contained water (7.8%), ash (12.4%), volatile matter (65.7%), and fixed carbon (21.9%). The fixed carbon content of about 20% is comparable to that of other woody and herbaceous plants. Water hyacinth biomass can be processed into convenient solid fuel pellets	Munjeri et al. (2016)
Biogas	A total biogas of 458.44 L was produced from water hyacinth with microorganisms consisting of CH_4 (68.67%), CO_2 (18.23%), and other gasses (13.10%)	Hudakorn and Sritrakul (2020)
Bio-oil	pH, water content, flash point, density, and viscosity of the fuel from water hyacinth were 2.93, 58.58%, 220 °C, 1004.3 kg/m^3, and 19.8 cSt, respectively. The bio-higher oil's heating value was discovered to be 28.35 MJ/kg, 63.02% higher than the original feedstock. The bio-oil contains no sulfur and has a low nitrogen content, indicating that environmentally friendly fuels and chemicals could be obtained by refining water hyacinth pyrolytic bio-oil	Wauton and Ogbeide (2021)

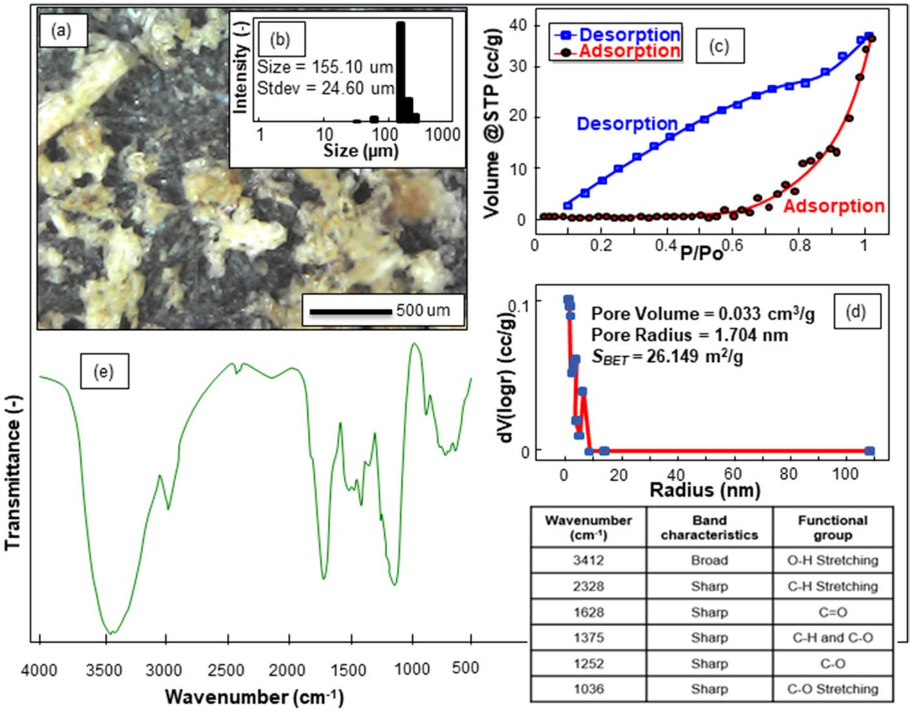
Table 6 Fuel property (calorific value) comparisons of water plants with conventional fuels (adopted from Arefin et al., 2021)

Fuel Property	Aquatic-plant biofuels				Conventional fuel		
	Azolla	*Salvinia molesta*	Water lettuce	Duckweed	Diesel	Petrol or gasoline	Biogas
Calorific value (MJ/Kg)	38.20	39.79	24.93	21.70	45.50	45.80	30.00

The calorific value is the most important quality parameter that greatly determines fuel quality (Gill et al., 2018).

3.5 Physicochemical properties of water hyacinth microparticles

Figure 7 presents the physicochemical properties of water hyacinth particles characterized by the microscope, the sieve test, and the FTIR analysis. The water hyacinth particles were prepared using a combination of drying and saw-milling process (see Fig. 7a) using a similar method to the previous studies (Nandiyanto et al., 2018). The sieve test analysis using ASTM D1921 revealed the prepared particles having sizes of between 60 and 300 µm (see



Wavenumber (cm⁻¹)	Band characteristics	Functional group
3412	Broad	O-H Stretching
2328	Sharp	C-H Stretching
1628	Sharp	C=O
1375	Sharp	C-H and C-O
1252	Sharp	C-O
1036	Sharp	C-O Stretching

Fig. 7 Physicochemical analysis of water hyacinth particles: **a** Microscope image analysis, **b** particle size distribution using ASTM D1921, **c** Nitrogen sorption analysis, **d** BJH pore size analysis, and **e** FTIR analysis results. The attached table on the bottom right shows the peaks in the FTIR analysis

Fig. 7b). The average sizes are 150 µm with a standard deviation of 24.61 µm. To confirm the pore structure in the particles, surface area analysis (Fig. 7c) with BJH pore analysis (Fig. 7d) was measured. The surface area of the particles was 26.149 m^2/g with a pore volume of 0.033 cm^3/g, and a pore radius of 1.704 nm, informing the particles were dense with no meso and macropore structure.

The FTIR analysis for understanding the chemical structure and functional groups of water hyacinth particles is presented in Fig. 7e. Detailed information regarding the dataset for FTIR is presented in previous studies (Nandiyanto et al., 2019, 2023b). Detailed peaks are shown in the paneled table in Fig. 7. The typical absorption peaks of water hyacinth-based particles appear at 3412.19, 2928.04, 1627.97, 1375.29, 1251.84, and 1035.81 cm^{-1}. The broad absorption peak at 3412.19 cm^{-1} is the absorption of the OH group, confirming the particles contain water and can easily adsorb more water. The sharp absorption at 2928.04 cm^{-1} is the C-H bond on CH_2 in cellulose (Tibolla et al., 2014). The presence of stretching C–O of the cellulose structure is observed in the absorption region of 1035.81 cm^{-1} (Sundari & Ramesh, 2012). The absorption at 1627.97 cm^{-1} indicates the presence of C=O bonds which indicates the presence of lignin and hemicellulose. The peak in the 1375.29 cm^{-1} region corresponds to the C–H and C–O groups of the aromatic ring in lignin. Then, the presence of ester, ether, or phenolic compounds was indicated by a peak at 1251.84 cm^{-1} (Nguyen et al., 2021; Tibolla et al., 2014). In addition, a broad peak between 2000 and 2300 corresponds to nitrogen content (Nandiyanto et al., 2019, 2023b). The data is in good agreement with the nutrition data (the attached table in Fig. 6) that showed the highest content of water hyacinth is water (83.51%), followed by ash content (3.20%), fat content (0.19%), protein content (3.5%), carbohydrate content (5.13%), and crude fiber (4.06%).

3.6 Bioplastics

The synthesis of bioplastics based on biodegradable materials has generated a lot of interest. Starch-based bioplastics are one of the most interesting materials. Many reports indicate the successful fabrication of starch-based bioplastics (see Table 7). However, the manufacture of starch-based bioplastics (without reinforcing materials) has weaknesses such as mechanical properties, hydrophilicity, and resistance to water and humidity. Therefore, to overcome this problem, bioplastics with reinforcing materials using water hyacinth are added. Different from other reports, to minimize the possible existence of void spaces between the water hyacinth particles, the experiment was supported by the additional glycerol and starch, which is the novelty of the production of the present bioplastic.

Figure 8a depicts the appearance of bioplastics made from cornstarch combined with water hyacinths. The color appearance of the final bioplastic product is brownish. The morphology of bioplastics has an inhomogeneous and agglomerated surface structure. Figure 8b depicts the appearance of bioplastics after three weeks of immersion. Mold was found on the surface of the bioplastics, accompanied by discoloration and cracks of the bioplastics (see Fig. 8b in the red and orange circle areas).

Figure 8c describes the compressive strength of bioplastics made from water hyacinth combined with cornstarch. Water hyacinth's content directly impacts the compressive strength (from 43 to 69 MPa). Additional cornstarch can give the highest compression test since cornstarch binds the water hyacinth particles. However, too much cornstarch can negatively impact the decrease of mechanical strength. Water hyacinth has fibers that can bring better mechanical properties. However, too less cornstarch resulted in inhomogeneous

Table 7 Development of starch-based bioplastics (without reinforcing agent)

Source of starch	Type of plasticizer used	Results	References
Water Hyacinth and bengkuang starch	Glycerol	Bioplastics have been successfully produced with the highest thermal stability and exhibited characteristics of low moisture absorption	Syafri et al. (2019b)
Water Hyacinth	Glycerol and Chitosan Solution	Bioplastics were successfully synthesized by combining starch and isolated cellulose in various compositions with chitosan and glycerol. The bioplastic prepared with a starch/cellulose of 8/2 in a 5% of matrix performed better, with a higher tensile strength of 1.67 MPa. It was more easily degraded than the other bioplastics prepared under different conditions	Pratama et al. (2020)
Water Hyacinth and sago starch	Glycerol	Water hyacinth and sago starch-based bioplastics were fabricated and characterized. Tensile strength and thermal stability increased when adding water hyacinth and sago starch. The maximum tensile strength is 10.23 MPa. Water absorption was less (23.01%). The incorporation of fiber in the matrix slows biodegradation in the soil	Syafri et al. (2019a)
Water hyacinth, native cassava starch, magnesium stearate, and beeswax coating	Glycerol	The properties of 5% of water hyacinth powder starch foam with beeswax coating are sufficient to replace conventional polystyrene foam packaging for fruits with high moisture content. The best mechanical properties, the lowest water content, and the most uniform cell size distribution were found in starch foam with water hyacinth powder of 5%. Furthermore, the beeswax coating improves the hydrophobicity of the starch foam composites, resulting in a product with low water solubility that maintains its shape after immersion in water	Chaireh et al. (2020)

Table 7 (continued)

Source of starch	Type of plasticizer used	Results	References
Water hyacinth ant commercial tapioca starch	Glycerol	Bioplastics with a 10% of water hyacinth fiber filler had the highest tensile strength (6.68 MPa) and the highest tensile modulus (210.95 MPa). On the other hand, this combination makes the lowest stress fracture by 7.30%. Tensile strength values increase by 549%, and tensile modulus increases by 973%. Bioplastics with 10% of water hyacinth had the highest thermal resistance and the lowest moisture absorption	Abral et al. (2018)
Water hyacinth cellulose nanocrystals and polyvinyl alcohol	Gelatin	The production of film-based water hyacinth nanocrystal-based cellulose (diameters of 20–50 nm) had a tensile strength of 13.8 MPa. Cellulose nanocrystal constituent increased film stability from 380 to 385 °C. A storage modulus of 3 GPa was observed when 5% of cellulose nanocrystal was added. The water absorption, water vapor permeability, and moisture absorption of the films decreased when C.N.C. was added to the PVA-gelatin mixture. The rate of moisture absorption decreased from 22.50 to 19.05%. The water vapor permeability decreased when 10% of cellulose nanocrystal was added	Oyeoka et al. (2021)
Water hyacinth, eggshell, sodium hydroxide, sodium hypochlorite, cassava starch, metal trays	Glycerol	The biodegradable plastic containing 30% eggshell and 70% water hyacinth increased durability and elasticity while decreasing water solubility. It also had lower durability, elasticity, and higher ductility and solubility. The bioplastic composed of 50% eggshell and 50% water hyacinth had the lowest durability and moderate elasticity, ductility, and solubility	Caraig et al. (2022)

Table 7 (continued)

Source of starch	Type of plasticizer used	Results	References
Water hyacinth and cassava starch	Glycerol	The bioplastic with the best characteristics is a composition ratio of water hyacinth and binder of 40:60 by weight. The characteristics of the bioplastics that were successfully made showed the values of density, water absorption, tensile strain, and flexural strength were 0.83 g/cm^3, 141.66%, 54.80 MPa, and 3.24 MPa, respectively	Limboonruang and Phun-Apai (2018)

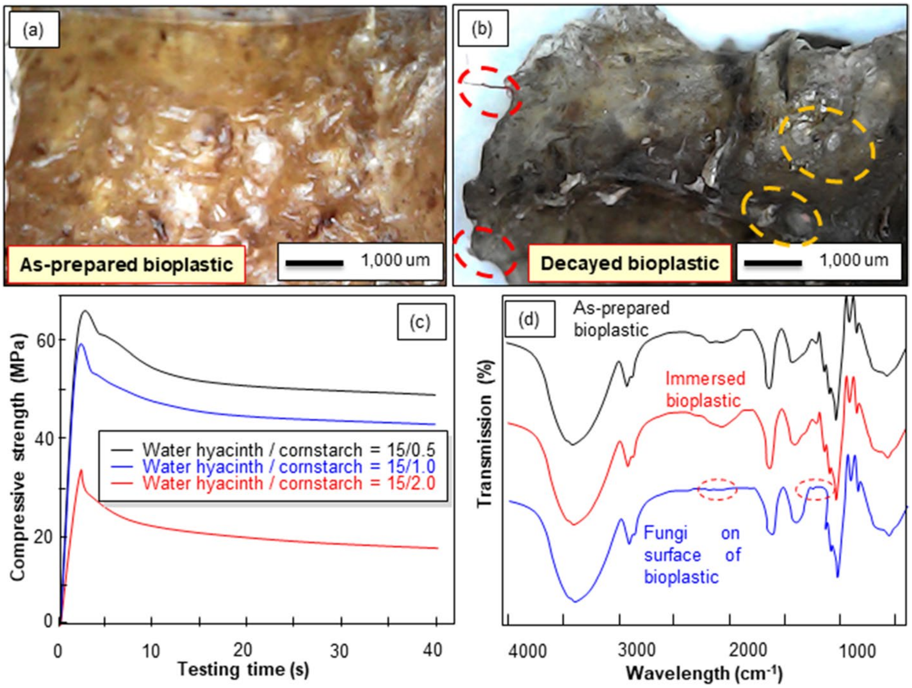


Fig. 8 **a** Microscope image of bioplastic sample made from corn starch and water hyacinth, **b** Microscope image of bioplastic surface with fungus for three weeks, **c** Mechanical properties of various composition bioplastics, and **d** FTIR results of bioplastics made from corn starch and water hyacinth, bioplastic immersed in water for seven days, and bioplastic surface with fungus for three weeks

bioplastics. The lack of homogeneity in bioplastics weakens the interfacial bond between the fiber surface and the matrix, potentially decreasing the mechanical properties of bioplastics (Sumrith & Dangtungee, 2019). Another study showed that organic growing bags with a composition of 155 g of coconut fiber and 505 g water hyacinth (A3B3) has a compressive strength of 0.020 kg/cm^2 (0.00196133 MPa) (Lutfi et al., 2020). Based on the research results of Lutfi et al. (2020), the bioplastics produced from the previous research show better mechanical characteristics. A puncture test was carried out to confirm the compressive test results. Bioplastics using water hyacinth/cornstarch ratios of 15/0.5; 15/1.0; 15/2.0 had puncture test results of 54.57; 57.71; and 65.71, respectively. The addition of water hyacinth affects the hardness of bioplastics. Bioplastics become brittle and stiff when water hyacinths s are used in large quantities. Furthermore, water hyacinth contains cellulose and lignin, a dry, hard, and easily brittle material (Sumrith & Dangtungee, 2019).

Figure 8d is the FTIR analysis results for the bioplastic during the biodegradation process. The change in the immersed bioplastic after 14 days was found at the peak of about 2100 cm^{-1}, informing the decomposition of some chemical structures. The possible released component is the nitrogen compound (Nandiyanto et al., 2019, 2023b) used by fungi for its growth. The results of this study are also in line with the results of a study by Rop et al. (2019), which stated that cellulose water hyacinth used as a polymer hydrogel can biodegrade and has the potential to absorb and retain water.

The results of the biodegradability testing of bioplastic are shown in Fig. 9. The tests were carried out using the immersion method in water. The test results showed that mass loss was found. More additional cornstarch led to the obtainment of less mass loss, which is because cornstarch has impacts on the formation of denser structures in the bioplastics. The decay dimension of the bioplastics under various compositions of water hyacinth and cornstarch are almost the same. Although there are some differences, the values are not so high (between 0.15 and 0.17 g/cm^2). The dissolution and decomposition of bioplastics in water are confirmed by the FTIR pattern (Fig. 8d) and the appearance of fungi on the surface (Fig. 8b). The cellulose, lignin content, and some nutrients (as shown in the attached table in Fig. 6) in the water hyacinth's body lead to the water hyacinth prospectively consumed by microorganisms for their growth (Ilo et al., 2020). Also, the ability of water hyacinth components to adsorb water and other chemical components makes the prepared bioplastics easily degraded, in which detailed information regarding the prospective water hyacinth particles for adsorbing chemical components is explained in the next section of this paper. The higher capability of bioplastic in adsorbing water correlates to a better biodegradation rate (Chaiwarit et al., 2022).

3.7 Brake pads

Brake pads are a type of composite material usually composed of reinforcement material embedded in a matrix along with some other backing material. The reinforcement constituents in brake lining pad composites impart the desired high friction properties required by automotive pads to function properly as motion stoppers (Idris et al., 2015). Currently, fabrication and performance evaluation of composite materials for wear resistance

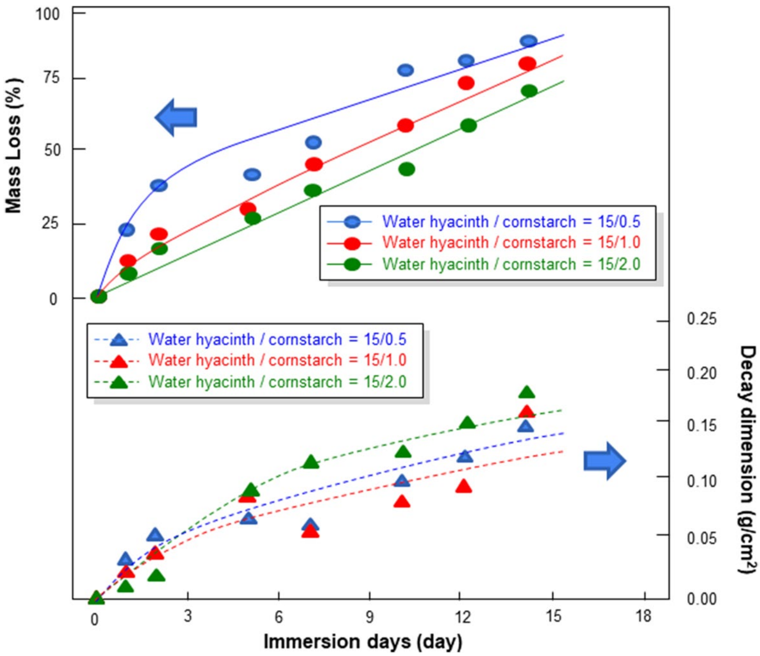


Fig. 9 Biodegradability of the bioplastics

applications utilize agro-waste as reinforcement material. Bio-reinforcement has long been regarded as a potential candidate to replace inorganic reinforcement in composite-based materials, thereby assisting in resolving environmental issues and gaining an economic advantage (Supri et al., 2011). Water hyacinth has been widely used as a reinforcing material in composite due to its cellulose, hemicellulose, and lignin contents. Several studies reported the potential of water hyacinth as a filler and reinforcement material in various types of composite materials, summarized in Table 8. Several studies have reported using water hyacinth as a reinforcement for brake linings, biobased composites, concrete confinement, and others. But, this study focuses on using water hyacinth as reinforcement for brake pads. Different from other reports, as presented in Table 8, the present brake pads were produced by compacting water hyacinth with resin and hardener. The possible hardening process at room temperature is the main idea for not adding heat during the polymerization. Thus, the water hyacinth particles as the main reinforcing agent for the brake pad can be maintained, and the optimal mechanical properties of the brake pad from water hyacinth can be obtained.

Figure 10a shows the as-prepared brake pads from water hyacinth particles with epoxy resin. Figure 10b shows a microscope image of the prepared brake pads. The mixed water hyacinth particles packed with the epoxy matrix were found. Various amounts of water hyacinth were used and tested to evaluate the compressive strength of the prepared brake pads (Fig. 10c) and mass loss during the friction test (Fig. 10d). The results of the compressive test of each sample are shown in Fig. 10c. The compressive strength of the brake pads prepared using the ratios of water hyacinth/resin/hardener of 3/5/5; 6/5/5; and 9/5/5, respectively, peaked at 424.9; 408.6; and 431.6 MPa. The brake pads from the 3/5/5 ratio reached a steady of 290 MPa, while other brake pads were stable at around 250 MPa. The puncture test confirmed all samples to have 84%. All samples could withstand the applied pressure. The brake pads remain strong. No cracks were found, and only a few indentations were left in contact with the pressing surface, informing that water hyacinth particles are a good reinforcing component for composite. The reinforcing material on the brake pads could withstand the compressive loads given collectively (Nandiyanto et al., 2022a). These characteristics occur because epoxy resin's polymerization at room temperature strongly binds water hyacinth powder. Water hyacinth with cellulose fibers (57%), hemicellulose (25.6%), and lignin (4.1%) (Tanpichai et al., 2019) bring better mechanical properties to the brake pads. However, too much water hyacinth added to the composite has no big impact on the mechanical properties. It is because there is an optimum condition for compact interaction and binding between water hyacinth and resin.

Figure 10d shows the mass loss curves during the friction test. In the friction test, water hyacinth brake pads were rubbed against sandpaper as a brake disk model. The friction between the brake pad and sandpaper converts kinetic into heat energy. Dust was produced from this friction, resulting in wear and a decrease in the mass of the brake pads. The brake pads prepared using the ratios of water hyacinth/resin/hardener of 3/5/5; 6/5/5; and 9/5/5 had wear rates of 4.76; 5.09; and 2.91, respectively. The presence of more water hyacinth contributes to a lower mass loss rate (see Fig. 10d). Water hyacinth particles as reinforcement increase the bond strength between polymer resins. The abundant water hyacinth reinforcement embedded in the resin increases the force and energy required to decompose the brake pad matrix into smaller particles. Thus, more content of water hyacinth particles on the brake pads reduces the level of wear of the brake pads. However, too much amount of water hyacinth had issues with the existence of a high wear rate. The more amounts of water hyacinth particles correlate to the inhomogeneous surface. Indeed, this condition

Table 8 Summary of studies about water hyacinth application as a reinforcing component in composite

Main filler	Supporting component	Application	Result	References
Water hyacinth	Epoxy resin	Brake lining	The tensile strength of the polymer reaches 13.54 MPa, and the flexural strength is 22.45 MPa. Mechanical strength increases as the amount of water hyacinth added increases, but when the amount of water hyacinth is more than 30%, mechanical strength decrease (due to the agglomeration effect of water hyacinth)	Arivendan et al. (2022)
Water hyacinth fiber	NaOH, silane treated, and bio-epoxy	Bio-based composite	The tensile strength value of the silane-treated water hyacinth-reinforced bio-based epoxy composite is 65.3 MPa, which is higher than that of the untreated composite (25.7 MPa)	Sumrith et al. (2020)
Treated water hyacinth fabric sheets	Epoxy resin	Reinforcement for concrete confinement	The mechanical characteristics of the water hyacinth fiber-reinforced polymer composite are found to be suitable for strengthening concrete. The usage of water hyacinth fiber-reinforced polymer composites is rewarded by their environmental friendliness	Jirawattanasomkul et al. (2021)

Table 8 (continued)

Main filler	Supporting component	Application	Result	References
Water hyacinth fiber	Yam bean starch, and glycerol	Thermoplastic starch bionanocomposite	The bio-nanocomposite's maximum modulus elasticity and tensile strength were 443 and 11.4 MPa, respectively. The composite show good dispersion and compact structure	Asrofi et al. (2018)
Water hyacinth	NaOH, 3-aminopropyl) tri ethoxy silane, and epoxy resin	Bio-based epoxy composite	The tensile modulus of 1% silane-treated water hyacinth fiber showed good mechanical properties. The tensile strength is directly impacted by the fiber orientation. In comparison to traditional epoxy, the addition of water hyacinth fibers increases impact characteristics under all circumstances	Sumrith and Dangtungee (2019)
Water hyacinth	Methyl methacrylate resin	Prosthetics Socket	Natural fibers that are readily available and renewable have the potential to lessen risks for individuals engaged in the manufacture of artificial limb sockets without compromising the strength of the sockets or harming the users. The wall thickness, fiber orientation, and lamination of fiber-matrix resin all substantially impacted socket strength	Widhata and Ismail (2019)

Table 8 (continued)

Main filler	Supporting component	Application	Result	References
Water hyacinth treated with benzene diazonium-chloride, sodium hydroxide	Polypropylene	Polypropylene composites	Water hyacinth/polypropylene composites showed excellent mechanical properties. Additional chemically treated composites showed a satisfactory improvement in all mechanical properties except tensile strength	Saha et al. (2011)
Water hyacinth fiber	Polyester resin	Resin composite	The best outcomes were obtained from composites with water hyacinth concentrations between 5 and 10%. The investigation found adding water hyacinth to the polyester resin had no detrimental influence on the composite's mechanical and thermal qualities	Flores Ramirez et al. (2015)

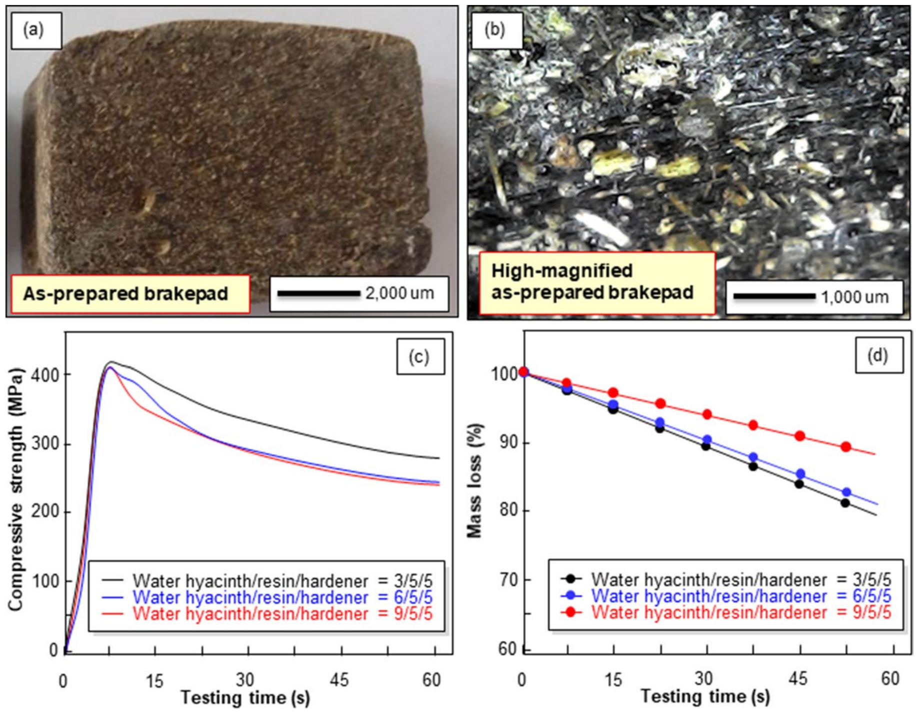


Fig. 10 As-prepared brake pads from water hyacinth particles and epoxy resin: **a** a photograph image, **b** a high-magnified microscope image of the surface of the brake pad, **c** compressive tests, **d** mass loss during friction test

makes an unstable structure when friction is applied. The heat generated during the friction test raises the surface temperature of the brake pads, softening the resin (Nandiyanto et al., 2021b). When the resin is softened, the water hyacinth-resin bonding decreases. The results obtained from compression and friction tests are in line with the results of Arivendan et al. (2022). Their experiments are the same as those found in this study. The strength of the mechanical brake pads they make increases with the increasing amount of water hyacinth added, but when the amount of water hyacinth is more than 30%, the mechanical strength decreases (due to the agglomeration effect of water hyacinth). When compared with the results of other studies, Flores Ramirez et al. (2015) used water hyacinth fiber in a polyester resin composite with a concentration of 5–10% and explained that the addition of water hyacinth to polyester resin did not adversely affect the thermal composite and could even strengthen the mechanical qualities. These results are the same as the results from previous study in that water hyacinth fiber strengthens brake pads based on a polymer resin matrix. The cellulose, hemicellulose, and lignin contents in water hyacinths cause this fiber to have good strength. Thus, further research is needed to analyze brake pads' optimum composition of water hyacinth particles.

3.8 Adsorbent

Water hyacinth contains cellulose, hemicellulose, and lignin which have hydroxyl functional groups, making it potentially used as an adsorbent in an aqueous solution. Many reports showed water hyacinth's successful adsorption process (see Table 9). They explained the successful adsorption; however, they did not mention what phenomena were taking place during the adsorption process. The novelty of this study was to demonstrate the effectiveness of the adsorption process using water hyacinth microparticles and to explain their adsorption mechanism.

Figure 11 displays the adsorption ability of water hyacinth particles for adsorbing curcumin. Figure 11a presents the result of the visible spectrum analysis, showing the concentration decreases along with the adsorption process time. Figure 11b shows a curve of decreasing curcumin concentration, which is confirmed by the physical appearance of decolorization in Fig. 11c.

Curcumin was used as a model for adsorptive. Its molecular size (about 1.4 nm) effectively describes the phenomena during adsorption. This study used three particle sizes to ensure the mechanism happening during the adsorption process. Then, to support the adsorption analysis, 10 isotherm models such as Langmuir, Freundlich, Temkin, Dubinin–Radushkevich, Fowler–Guggenheim, Hill-Deboer, Jovanovic, Harkin Jura, Flory–Huggins, and Halsey were used. The calculation was also compared to the nitrogen sorption analysis, shown in Fig. 7c, d, which confirmed the particles have no macro and mesoporous structure. Thus, all adsorption processes will be done on the outer surface of the adsorbent. Detailed isotherm parameters gained from the experiments are presented in Table 10. Detailed fitting analysis for understanding the calculation of isotherm adsorption is explained in the previous studies (Ragadhita & Nandiyanto, 2021).

Based on the adsorption results, the suitability of the adsorption isotherm model was analyzed by comparing the coefficient values of each adsorption isotherm model. The isotherm model was tested by regression analysis to get the correlation coefficient value (R^2). Based on the value of R^2 in the range of more than 0.80, sequentially, the five most suitable models were the Jovanovic isotherm ($R^2 = 0.9672$) > Harkin–Jura ($R^2 = 0.9258$) > Langmuir ($R^2 = 0.9144$) > Freundlich ($R^2 = 0.8264$) > Halsey ($R^2 = 0.8264$) (see Table 9). Meanwhile, the other five models (such as Temkin, Dubinin–Radushkevich, Fowler–Guggenheim, Hill-Deboer, and Flory–Huggins) are not recommended to explain the adsorption process (see Table 9).

An illustration of the adsorption process on the surface of water hyacinth-based bio adsorbent is depicted in Fig. 12. Based on the Jovanovic, Langmuir, and Halsey models, the adsorption process follows monolayer coverage. Based on Freundlich and Harkin–Jura's models, the adsorption process forms multilayer and monolayer coverage. Due to the formation of monolayer and multilayer coverage, the adsorption process follows a cooperative process (see the value of $1/n > 1$ in the Freundlich model). Therefore, during the adsorption process, physical and chemical interactions occur simultaneously. Physisorption occurs because of weak van der Waals bonds between the adsorbent surface and the adsorbate. Physically, the adsorbate diffuses across the adsorbent surface without any interaction with the adsorbent. Chemisorption occurs among the adsorbates in forming the upper layer, forming cooperative adsorption.

The results of this study are in line with the fact that water hyacinth has the potential to be used as an adsorbent material for absorbing waste in water (such as organic or inorganic waste) as reported by Mohammad et al. (2022). Mohammad et al. (2022) reported

Table 9 Summary of studies about water hyacinth application for water pollutants removal

Pollutants model	Results	References
Cr and Zr	Water hyacinth performs well in removing Cr and Zn accumulated in water with absorption efficiencies of 84 and 95%, respectively, for 11 days of incubation	Mishra and Tripathi (2009)
Methylene Blue Organic Dye	Water hyacinth was able to remove organic dyes (such as methylene blue) in water with an efficiency of 95.45% under pH 12, dye concentration of 300 mg/L, and a dose of water hyacinth of 3 g/L	Prasad and Yadav (2020)
Remazol Brilliant Blue Organic Dye	Water hyacinth root powder was successfully used as a cheap, effective, and efficient bio-adsorbent to remove remazol brilliant blue organic dye	Kulkarni et al. (2018)
Congo Red Organic Dye	Congo red dye from aqueous solution. The best dye removal was achieved using water hyacinth as a bio-adsorbent at pH 5, concentration of 100 ppm, and contact time of 150 min. The biosorbent's adsorption capacity is 53.76 mg/g	Parvin et al. (2019)
Cd, Cr, and Ni	Water hyacinth biochar and nano-biochar efficiently remove metal compounds in the aqueous solution. Nano-biochars were more effective than biochar in this regard. The removal efficiency of the sorbents by biochar or nano-biochar was greater than 85% in all studied sorbents. However, the sorbents investigated less removal of Ni	Elbehiry et al. (2022)
Alizarin Yellow and Rhodamine B	The greatest removal of alizarin yellow and rhodamine B was observed at pH 2. The results showed that increasing contact time, initial dye concentration, and temperature improved dye adsorption. The contact time for alizarin yellow and rhodamine B reached equilibrium in 120 and 90 min, respectively. According to the Langmuir model, the maximum adsorption capacity values for alizarin yellow and rhodamine B were 37.04 and 23.98 mg/g, respectively	Sawasdee and Watcharabundit (2022)
Hexavalent Chromium	Adsorption by activated carbon derived from water hyacinth has been shown in studies to be an alternative and efficient technique for removing hexavalent chromium, with an adsorption capacity of 50 mg/L	Macalalad et al. (2021)
As (III), As (V)	Dried water hyacinth root powder shows the best performance for removing As (III) and As (V) followed by banana pseudostem, sugarcane bagasse, and Jute. A prototype filter made from water hyacinth could remove arsenic from drinking water	Brima and Haris (2014)

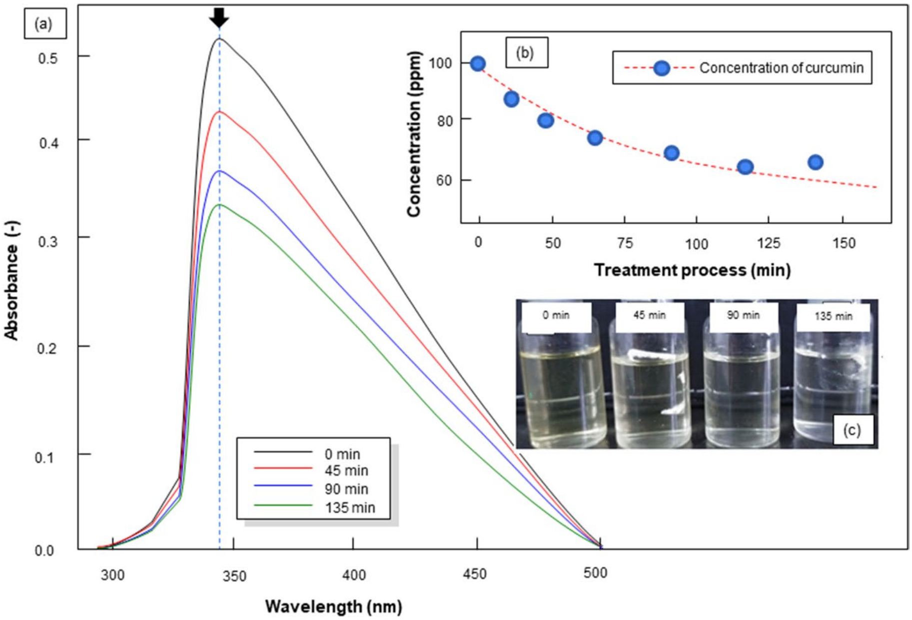


Fig. 11 Adsorption ability of curcumin solution by water hyacinth **a** results of the visible spectrum of water hyacinth adsorption test under curcumin solution, **b** analysis of curcumin concentrations after adsorption, **c** visualization of the decrease in curcumin concentrations during the adsorption process

the adsorption process in wastewater contaminated with medicinal waste with activated carbon derived from water hyacinths. Research results from Alam et al. (2015) showed that the adsorption was fast, and the equilibrium time was estimated to be 120 min. The pH of the drug solution strongly impacts on the amount of drug adsorbed, where the optimal pH value is 8. The percentage of drug adsorbed at the original pH approaches obtained at the optimal pH. Then, the adsorption isotherms were fitted with the Langmuir, Freundlich, and Redlich-Peterson isotherm models, and the Langmuir model showed the best fit describing drug adsorption as one of the monolayer forms on adsorption sites that are energy equal and homogeneously distributed. An important adsorption parameter is the adsorption capacity of Langmuir, where the Q_{max} value is 122.47 mg/g. Kumar and Chauhan (2019) also elaborated on the development of chemically modified dry hyacinth roots (DWHR) as an adsorbent to remove chromium (VI) from synthetic aqueous solutions whose results showed that The DWHR removed chromium (VI) from the synthetic aqueous solution at maximum removal efficiency of 95.43% from the conducted batch adsorption at optimized parameters (i.e., pH 3.0, adsorbent dose = 14.0 g/L, adsorbent size = 150 μ, adsorbate concentration = 10.0 mg/l, temperature = 25 ± 5 °C, agitation speed = 200 rpm) after 2 h contact time. The DWHR has a maximum adsorption capacity of 1.28 mg/g. Other researchers also investigate the effect of different parameters, i.e., adsorbent dosage, contact time, pH of the solution, initial dye concentration, and temperature, in adsorption studies of congo red dye solutions using carbon synthesized adsorbents from water hyacinth stem and leaf. The results showed that the observed Langmuir isotherms were the most suitable, with maximum adsorption capacity of 14.367 mg/g and 13.908 mg/g at 50 °C and contact time of 60 min, and initial dye concentration of 50 mg/L (Extross et al., 2023). Based on the results of several studies that have been described, the use of water hyacinths as an

Table 10 Adsorption parameters based on standard isotherm models

Isotherm model	Parameters	Value	Note
Langmuir	q_m (mg/g)	256.41	Maximum capacity adsorption
	$K_{.L.}$ (L/mg)	1.701×10^{-3}	Maximum capacity adsorption
	R^2	0.9144	Monolayer existence on the surface of the adsorbent ($R^2 > 0.80$)
Freundlich	$K_{\cdot f.}$ (mg/g)	0.111	Adsorption capacity of the adsorbent
	$1/n$	1.0198	Cooperative adsorption process
	n	0.980	Physisorption ($n > 1$)
	R^2	0.8264	Multilayer existence on the surface of adsorbent ($R^2 > 0.80$)
Temkin	$B_{\cdot T.}$ (kJ/mol)	108	Physisorption ($\beta_T < 8$ kJ/mol)
	$A_{\cdot T.}$ (L/mg)	0.064	Temkin equilibrium binding constant
	R^2	0.6757	Nonuniform distribution adsorbate in the adsorbent surface ($R^2 < 0.80$)
Dubinin–Radushkevich	B	− 6.6155	Dubinin–Radushkevich isotherm constant
	$q_{\cdot m.}$ (mg/g)	746	Adsorption capacity
	R^2	0.6811	The adsorbent surface does not contain micropores ($R^2 < 0.80$)
Fowler–Guggenheim	$K_{\cdot F.G.}$ (L/mg)	1.289×10^{-3}	Fowler–Guggenheim isotherm constant
	W (kJ/mol)	1.001	Attractive force between the adsorbed molecules; the process is exothermic
	R^2	0.1192	Monolayer existence on the surface of the adsorbent ($R^2 < 0.80$)
Hill-Deboer	K_1 (L/mg)	0.0012	Hill-Deboer isotherm constant
	K_2 (kJ/mol)	2.403	Attractive force between the adsorbed molecules and the process is exothermic
	R^2	0.1635	Monolayer existence on the surface of the adsorbent ($R^2 < 0.80$)
Jovanovic	$K_{\cdot J.}$ (L/g)	0.0032	Jovanovic isotherm constant
	$q_{\cdot m.}$ (mg/g)	93.84	Maximum uptake of adsorbate
	R^2	0.9672	Monolayer existence on the surface of the adsorbent ($R^2 > 0.80$)
Harkin–Jura	$A_{\cdot H.}$ (g^2/L)	57.47	Harkin–Jura isotherm constant
	$B_{\cdot H.}$ (mg^2/L)	1.931	Relating to the surface area of the adsorbent
	R^2	0.9258	Multilayer existence on the surface of adsorbent ($R^2 > 0.80$)

Table 10 (continued)

Isotherm model	Parameters	Value	Note
Flory Huggins	$K_{.F.H.}$ (L/g)	1.243	Flory Huggins constant
	$n_{.F.H}$	0.0139	The adsorbate occupies more than one active adsorbent zone ($n_{FH} < 1$)
	R^2	0.051	Multilayer on the surface of the adsorbent ($R^2 < 0.80$)
Halsey	$n_{.H.}$ (L/mg)	3.762	Halsey constant
	$K_{.H}$	3.583	Halsey constant
	R^2	0.8264	Multilayer existence on the surface of the adsorbent ($R^2 > 0.80$)

$q_{.m.}$ is the capacity of the adsorbent monolayer, $K_{.L.}$ is the Langmuir adsorption constant, $K_{.f.}$ is the Freundlich constant, *1/n* is the interaction of adsorbate-adsorbent, *n* is the value indicating the degree of linearity between the adsorbate solution and the adsorption process, $B_{.T.}$ is the Temkin constant, $A_{.T.}$ is the binding equilibrium constant, β is the Dubinin–Radushkevich isotherm constant, $K_{.F.G.}$ is the Fowler–Guggenheim constant, *W* is the adsorbed adsorbate at the active site representing the interaction between the adsorbate and the adsorbent, K_1 is the Hill-Deboer constant, K_2 is the energetic constant of the interactions between adsorbed molecules, $K_{.J.}$ is the Jovanovic constant, $A_{.H.}$ is the Harkin Jura isotherm constants, $B_{.H.}$ is the value relating to the specific surface area of adsorbent, $K_{.F.H.}$ is the Flory–Huggins model equilibrium constant, $n_{.F.H.}$ is the number of adsorbates occupying adsorption site, n_H is the Halsey model constants, $K_{.H.}$ is the Halsey model constants. Detailed calculation is reported in the previous literature (Ragadhita & Nandiyanto, 2021)

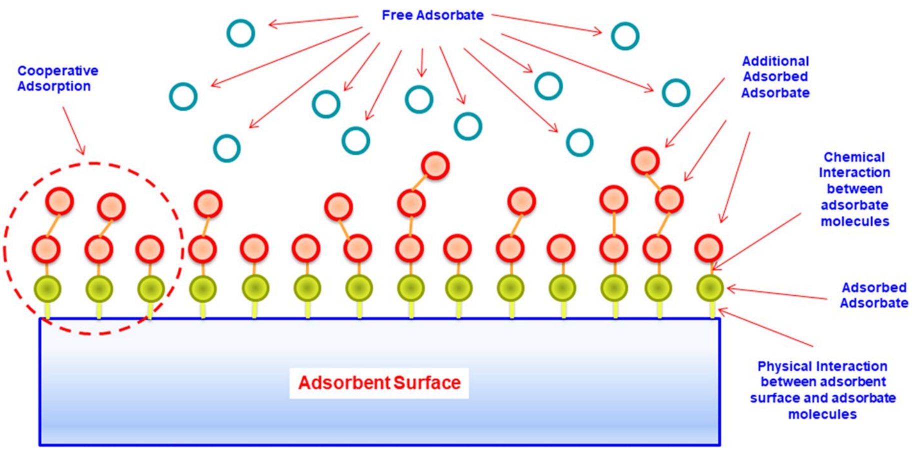


Fig. 12 Adsorption process between water hyacinth-based adsorbent and curcumin (as adsorbate)

adsorbent in this study has better results than previous studies in terms of its relatively larger adsorption capacity.

3.9 Education for water hyacinth

Education for understanding of water hyacinth and its impact on environment is provided at various levels of education. In Indonesia, it starts from kindergarten to tertiary education and even the community, in which this can be obtained from the official website in Indonesian directorate general of education (see https://ayoguruberbagi.kemdikbud.go.id/artikel/mengajarkan-cara-mengolah-sampah-eceng-gondok-di-masa-pandemi/). Most of territory in Indonesia consists of water, and water hyacinth plants do grow in water areas. This plant is important to be taught because it has several advantages and disadvantages in realistic life. This plant can be processed into various products and can even become a commercial products that can increase income and national economic growth. To elementary school students, water hyacinths are introduced as a eutrofication and possibly used as traditional crafting materials. Then, the education of water hyacinth has been reported more in class VII in middle school based on the 2013 curriculum. Water hyacinths have been introduced in the section of biomass energy, which can be from plants, agricultural waste, forest waste, human waste, and livestock manure. Water hyacinths also were introduced in topic 5 for "relations of interaction and natural appearance", in which the topic discussed the benefits of water hyacinths including their uses for animal feed as well as handicraft materials and flower arrangement support. This topic is important for improving student creativity as well as student encouragement and entrepreneurship. Discussion about water hyacinths was re-introduced in class X. In extracurricular school, students are taught to use water hyacinths for simple products, such as photo frames, flower vases, sandals, tote bags, and other souvenirs. Another discussion on water hyacinths is reported in the use of biomass energy. Education about water hyacinth has been also implemented in various countries. Although most countries provide education about these plants at the research level, unlike Indonesia, they start from various levels of education, confirmed by few research developments on water hyacinth found with specific discussions at every level of education.

Detailed information regarding the education of water hyacinth is explained in detail in literature (Fiandini et al., 2023).

4 Summary

Water hyacinth is considered to be a promising valuable species in future. With the support of available technologies, water hyacinths can be converted from invasive species that endanger the ecosystem into prospective and valuable products. A summary of the current progress in utilizing water hyacinths is presented in Fig. 13, which can be done in three general ways, including the combustion process, the direct use, and the drying process with particle preparation. The processes are the following:

(i) Direct utilization of water hyacinths can be useful for phytoremediation because water hyacinth has an excellent performance in absorbing pollutants such as metals (i.e., Pb, Zn, Ni, Hg, Cr, and As), organic pollutants, and inorganic pollutants (i.e., nitrogen and phosphorus) in water (see R1).

(ii) Direct combustion is carried out to generate energy because water hyacinth has enormous potential to be used as an energy source due to its low lignin and high cellulose and hemicellulose contents (see R2). For some cases, direct burning of water hyacinth plants is not recommended due to their low density, low calorific value per unit volume, and high water content, informing the need for pretreatment, such as an additional drying process. Other processes derived from direct burning are by adding treatments to produce briquette (see R3), which effectively increase the thermal value of water hyacinth biomass. Furthermore, water hyacinth's direct combustion process (also known as the carbonization process) produces carbon material (see R4). The carbonization process removes non-carbon compounds, thus, organic components and cellulose decompose into carbon. This carbon material derived from

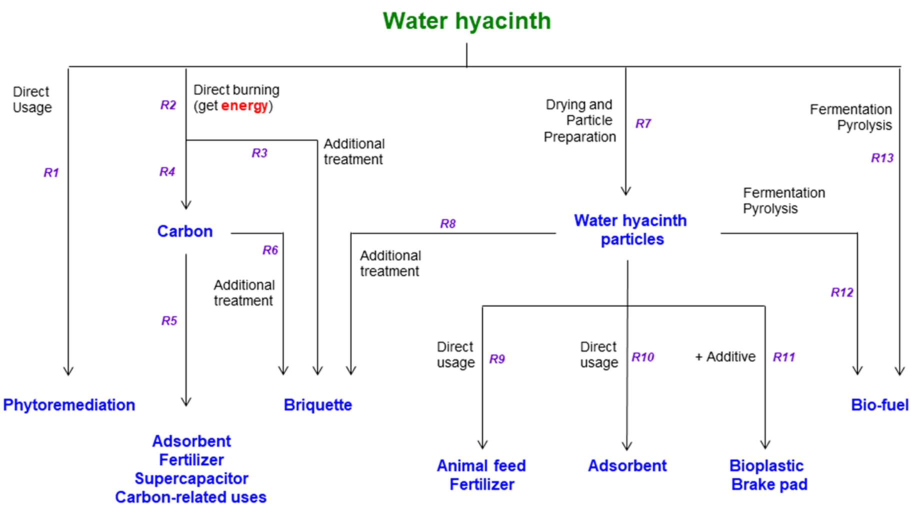


Fig. 13 Summary of the current progress in the utilization of water hyacinth

water hyacinth can be used as an adsorbent, fertilizer, and even supercapacitor and other carbon-related applications (see R5). Also, the carbonization process can be combined with the briquette production technique to produce briquettes (see R6).

(iii) Additional drying and particle preparation process can also be used to convert water hyacinth into other useful products (see R7). Drying is a process carried out to remove the water content contained in the substance to get excellent sub-products for the next treatment. For example, the dried water hyacinth and its powder form can be used for components in the briquette production process (see R8). Chopped and dried water hyacinth, and further proceeding into powder forms, can be used for animal feed and fertilizer (see R9). The water hyacinth that has been dried and/or ground can be used directly for adsorbent (see R10). In addition, mixing additives with water hyacinth is known to produce new and sustainable materials such as bioplastics and brake pads (see R11). To make bioplastics, water hyacinth needs to be added with plasticizer additives such as glycerol. Meanwhile, water hyacinth needs to be added with additives such as resin and catalyst to make brake pads. The dried water hyacinth can also be used for bio-fuel using fermentation or pyrolysis process (see R12).

(iv) Water hyacinth has a significant amount of carbon content. Cellulose and hemicellulose can be fermented or put into pyrolysis to obtain bio-fuel (see R13). Utilization of water hyacinth through drying and particle preparation can also be done to support this fermentation and pyrolysis process (see R12).

This paper is expected to become integrated information for demonstrating how to utilize invasive water hyacinth species to become useful products. Indeed, this is prospective for solving current issues regarding food, energy, and the environment (wastewater treatment). This must be supported by transferring education to student to support more innovations in future.

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Data availability All authors confirm that the data supporting the findings of this study are from authors' experiments and all relevant data are included in the article.

Declarations

Conflict of interest All authors confirm that there is no conflict of interest. All authors also confirm that the work has not been published previously, is not under consideration for publication elsewhere, and is approved by all authors.

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