Polymer Bulletin
https://doi.org/10.1007/s00289-024-05469-6

ORIGINAL PAPER

Effect of moringa filler powder in *Eichhornia crassipes* fibre-reinforced polymer composites: advancement in mechanical properties and environmental sustainability

Ajithram Arivendan[1] · Sumesh Keerthiveettil Ramakrishnan[2] · Xiaoqi Chen[1] · Yuan-Fang Zhang[1] · Wenhua Gao[3] · Firda Aulya Syamani[4] · Winowlin Jappes Jebas Thangiah[5] · I. Siva[6] · S. R. Boselin Prabhu[7]

Received: 9 April 2024 / Revised: 18 August 2024 / Accepted: 19 August 2024

Abstract

This study aims to investigate the mechanical, thermal, morphological, and characterization properties of a polymer composite composed of water hyacinth plant fibres. In order to improve the mechanical properties of the composite specimens, a new powder derived from the moringa plant was used for the first time as a filler material in the water hyacinth plant-reinforced polymer composites. In this study, composite specimens were prepared using a hot compression moulding machine. The weight percentage of moringa resin filler powder and hyacinth fibre was varied during the process from 2.5 to 7.5% and 15 to 35%. The resulting tensile strength ranged from 18.24 MPa to 32.14 MPa, flexural strength ranged from 38.64 to 56.32 MPa, impact strength ranged from 1 to 3.75 J, and hardness ranged from 66 to 98 Shore D hardness. The composite sample containing 5% moringa filler powder and 30% WH fibre content achieved high mechanical strength, maximum decomposition temperatures, and high crystallinity percentages. It exhibited 11–13% higher strength compared to the other samples. Absorption studies showed weight gains of 3.42% and 4.45% for water and chemical absorption, respectively. The fracture surfaces of the composite specimens were analysed using the SEM technique. The fabricated composites could be useful for particle board and medium density fibre board applications.

Keywords *Eichhornia crassipes* · Interfacial bonding · Moringa filler powder · Mechanical properties · Characterization studies

Extended author information available on the last page of the article

Introduction

In the light of growing global environmental concerns and a heightened awareness of the importance of renewable resources, considerable effort has been devoted to the development of eco-friendly composite materials [1]. Natural fibres, including hemp, flax, jute, kenaf, and sisal, have emerged as a particularly promising option for composite reinforcements, given their superior strength and modulus relative to other materials [2]. The natural plant fibres offer an attractive option as a highly effective reinforcement for polymer matrix composites due to their unlimited availability, low density, and ease of disposal, they may not be compatible with hydrophobic polymers and their composites. As such, it is necessary to further understand diffusion behaviour, manufacturing processes, and moisture resistance [3].

Water hyacinth, a free-floating aquatic plant commonly found in tropical and subtropical regions, was originally known as *Eiccornia crassipes* from the *Pontederiaceae* family and is native to the Amazon basin. The stem of the hyacinth plant is approximately 15–25 cm in length and has sharp-edged petioles. The plant typically has large and medium roots, spongy thin leaf stalks, and petioles. The stem contains a significant amount of water, nearly 65–70%. When present in water bodies, water hyacinth gains more mass compared to the desilting stage [4]. The hyacinth plant is recognized for its rapid growth and ability to reproduce both sexually and asexually. The dispersion of hyacinth seeds is facilitated by a variety of agents, including humans, birds, and other animals. The water content of the environment is influenced by several factors, such as hydrogen potential, dissolved oxygen, dissolved solids, and salinity, which can be mitigated by plants like hyacinths. While this plant has been used as a source of raw materials for small-scale paper manufacturers, it is also used as organic feed for animals in several countries around the world [5]. Furthermore, hyacinth roots have been found to absorb high levels of mercury and other pollutants, making them an important tool in environmental remediation efforts. Several nations have been cultivating water hyacinths in waterbodies as a means of mitigating the nuisance caused by nitrogen removal from the surrounding area [6]. Water hyacinth (WH) fibre-reinforced composites have been increasingly utilized in various industries, including construction, commercial production, and automotive manufacturing, due to their lightweight properties.

This study explores a sustainable approach to the use of water hyacinth, an aquatic plant. The study involves incorporating various weight percentages of moringa filler powder with hyacinth fibre. Composite samples are then produced by combining the hyacinth plant and moringa filler powder with an epoxy matrix material using a hot compression moulding machine. In addition, a new mechanical extraction method for hyacinth fibre was developed and tested. In this work, the mechanical properties of the WH polymer composite such as tensile, flexural, impact, and hardness were tested along with its absorption, characterization, and surface morphologies. The main objective of this work is to use the fabricated composites in the commercial particle board and medium density fibre board applications.

Materials and methods

Materials

This work utilized water hyacinth plant fibres extracted in different ways, along with an epoxy polymer matrix resin (LY 556) and hardener (HY 951) purchased from Coimbatore Seenu and Company. It was mixed with the ratio of 10:1. Additionally, naturally extracted moringa filler material powder particles were used. Compression moulding techniques were employed to produce various composite samples. A quick curing process was achieved by subjecting the materials to temperatures of 120 °C and 100 °C on the machine. The hyacinth fibres have the average density of 1.15 g/cm^3.

Water hyacinth plant fibre extraction process

During an initial stage of the investigation, it was found that hyacinth plants were present in nearby ponds. The identification process has been completed to collect and separate the plant into its various parts, including the stem, petiole, leaf, and roots [7]. Hyacinth fibre can be extracted from the parent plant using various methods, such as manual extraction, the hot water boiling method, a chemical extraction method, and retting with a conventional method [8]. All of these methods can have an impact on the final length, quantity, and quality of hyacinth fibre. The extraction process of water hyacinth fibre and moringa filler powder particles is illustrated in Figs. 1 and 2, respectively. Additionally, Fig. 3 presents the general process flowchart of the research work. This study describes a mechanical extraction technique used to extract fibres from hyacinth parent plant stems. The machine used for this technique is equipped with a 0.5 horsepower electric motor, monoblock bearings, two alternative shafts, and one permanent shaft. It is capable of processing plants with diameters of 50 cm and lengths of 55 cm. This method has been shown to result in higher fibre yield and reduced waste, with up to an 80% reduction in wastage compared to other methods. We choose the mechanical extraction machine compared to the other conventional extraction because of the effective and quality fibre yield.

Water hyacinth composite production

During the drying process of the hyacinth plant fibres, they are exposed to sunlight and air to remove moisture. The fibres are then dried in an air oven for 24 h at 65 °C. The Epoxy and Hardener LY556 and HY951 grades, which are mixed in a 10:1 ratio. The reinforcement percentages range from 15, 20, 25, 30, and 35%. The moringa resin powder varied from 2.5, 5, 7.5, and 10%. Figure 3 clearly shows that this research design procedure. The fibre and epoxy matrix materials were then poured into a rectangular mould with dimensions of 250 × 180x3 mm using a hot press compression moulding machine. A quick curing process was

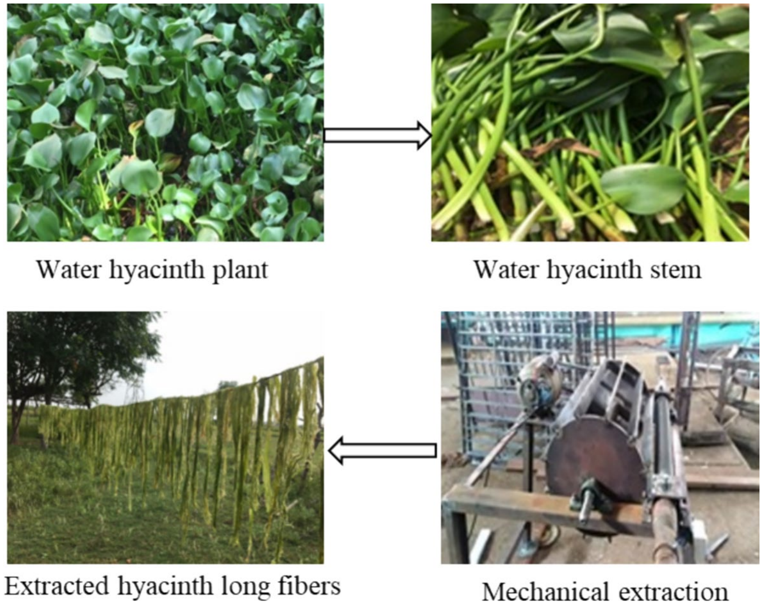

Fig. 1 Hyacinth plant fibre extraction

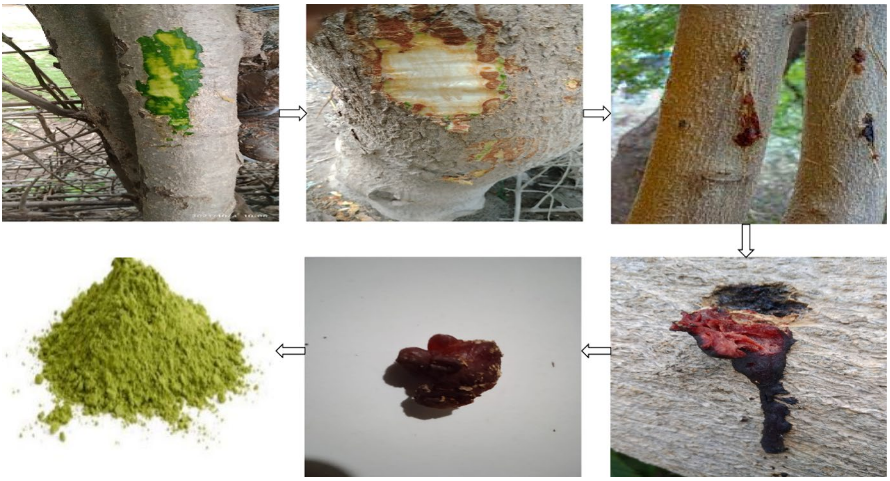

Fig. 2 Moringa resin extraction

achieved by subjecting the materials to temperatures of 120 °C and 100 °C on the machine on 1 h time period for each composite. Finally, the hyacinth fibre-reinforced polymer composite, which was produced using a compression moulding machine. Post-curing is considered a necessary step for natural fibre composites to enhance bonding and mechanical properties. In this case, the hyacinth fibre composite is dried for 24 h in a hot air oven at 70 °C. The viscosity of the

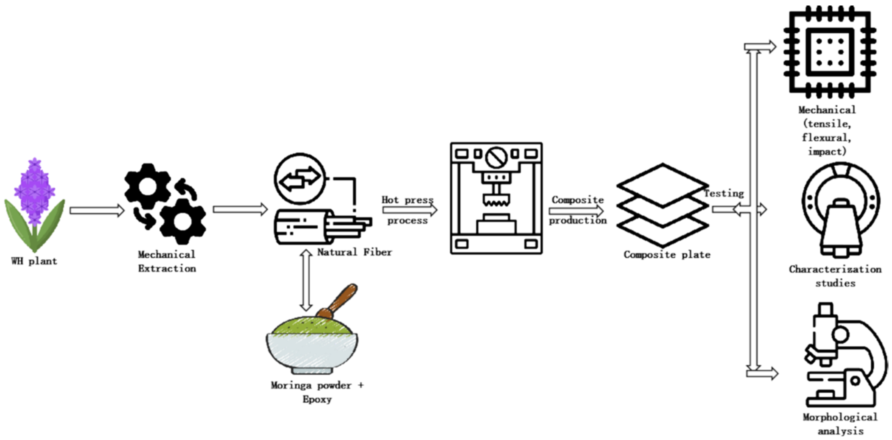

Fig. 3 Research design procedure

composite is measured at 1.15 g/cm^3 and 0.97 g/cm^3 at 25 °C at 10,000 MPa and 10 MPa, respectively. Additionally, the hardener has a density of 0.97 g/cm^3.

Mechanical properties

The mechanical strength of water hyacinth natural fibre-reinforced polymer composites was determined using a universal testing machine and Charpy impact test machine. The crosshead speed was maintained at 2 mm/min and 1.5 mm/min for tensile and flexural strength, respectively.

Absorption studies

Following ASTM D570, water absorption tests are conducted, while chemical absorption studies are carried out in accordance with ASTM C413-18. Both tests use a sample size of 20 × 20 × 3 mm.

Characterization studies

The X-ray diffraction process is performed on a BRUKER D8 advance machine with a temperature range of 10 °C–80 °C, and a precision of 0.02° per step, at an operating temperature of 25 °C. For the Fourier transform analysis, the hyacinth composite samples were evaluated using the SHIMADZU instrument, which operates within a frequency range of 4000–400 cm^{-1} and a resolution of 2 cm^{-1}. Both quantitative and qualitative methods have been employed to analyse natural fibre composite samples.

TGA

A thermal analyser with an inert gas and a flow rate of 20 ml/min was utilized to measure the weight loss of a water hyacinth composite test sample across various temperature ranges. This was done to determine the thermal and oxidative stability of the water hyacinth fibre composite sample.

SEM

The TESCAN electron microscope was utilized to examine the surface of a composite made from water hyacinth powder. The surface investigation process involved using failure samples from mechanical testing. An electron inspection was conducted using a 3 kV acceleration and different magnifications. This method was employed to monitor external contents and impurities.

Results and discussion

Mechanical strength

The mechanical strength of composite samples reinforced with water hyacinth fibre and moringa filler powder was investigated using the universal testing machine and Izod impact testing machine. The composite samples were reinforced with different weight percentages of moringa filler powder (2.5%, 5%, 7.5%, and 10%), and different weight percentages of hyacinth fibres (20%, 25%, 30%, and 35%) were used [9, 10]. The test results indicate that the epoxy resin has a tensile strength of 14.3 MPa, a flexural strength of 22.14 MPa, and an impact strength of 0.20 J. The tensile strength of the composite samples varied between 16.42 and 22.64 MPa for the 15% composite sample, between 18.26 and 24.86 MPa for the 20% composite sample, between 24.63 and 32.42 MPa for the 25% composite sample, and between 24.63 and 31.24 MPa for the 35% composite sample. The flexural strength of the composite samples varied across different percentages: at 15%, the strength ranged from 29.654 to 39.42 MPa, at 20%, it ranged from 29.52 to 42.52 MPa, at 25%, it ranged from 29.82 to 44.26 MPa, at 30%, it ranged from 38.64 to 56.32 MPa, and at 35%, it ranged from 22.62 to 41.28 MPa [11, 12]. According to the final results, the composite samples with 30% water hyacinth fibre and 5% moringa filler powder exhibited higher mechanical strength (including hardness, tensile, flexural, and impact strength) compared to the other samples [13]. Figure 4 shows that the mechanical properties of the hyacinth fibre with moringa filler powder-reinforced composites.

In general, it has been observed that the strength of fibre composites increases as the percentage of fibre weight increases up to 30%. However, it has been noted that composite samples with more than 30% reinforcement, such as 35%, may exhibit lower mechanical strength, possibly due to agglomeration caused by the primary fibre reinforcement [14, 15]. It was observed that the water hyacinth fibre

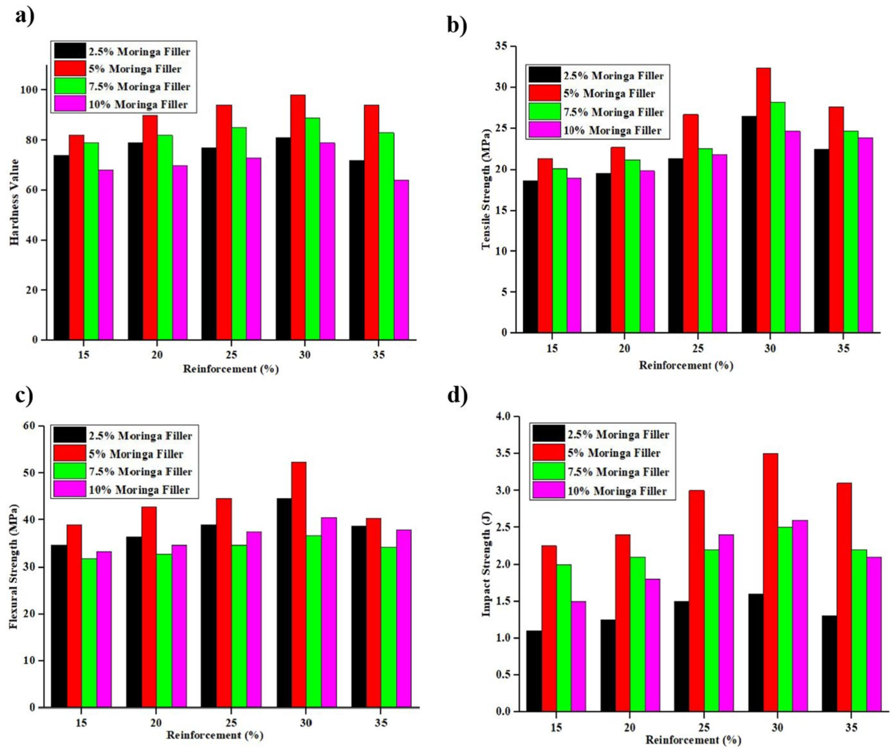

Fig. 4 Mechanical properties of the hyacinth fibre composite samples

with 5% moringa powder achieved higher mechanical strength in comparison with the other samples, based on the final strength tests [16, 17]. The hyacinth fibres have been observed to cause expansion of the nebulous cellulose within the composite samples. Hydrogen is expelled from all samples over time. The hybrid composite samples display a monoclinic crystalline lattice structure within the native cellulose of the hyacinth fibre and form a strong bond with the epoxy polymer matrix, resulting in a chain formation with the primary, filler, and secondary matrix materials. Prior to being blended with the epoxy matrix and moringa filler, the hyacinth fibre was subjected to treatment with an alkaline solution [18]. Through this treatment, the lignin particles can be removed from the hyacinth fibre, resulting in a glass-like structure of the cellulose [19]. The previous test results indicate that sisal composites achieved a tensile strength of 28.42 MPa, a flexural strength of 41.24 MPa, and an impact strength of 0.25 J. Similarly, the coir composite achieved a tensile strength of 32.628 MPa, a flexural strength of 41.26 MPa, and an impact strength of 0.5 J [20, 21]. Interestingly, the hyacinth-based composite samples exhibited higher mechanical strength compared to the sisal and coir-based composite samples [22, 23]. The hyacinth fibre (30%) with moringa filler (5%) composite exhibited significantly higher mechanical strength values when compared to the other conventional composites [24].

Absorption studies

Figure 5a,b illustrates the water and chemical absorption of a water hyacinth composite sample. It was observed that the weight percentage of the WH composites increased by only approximately 5% before reaching saturation after the 10th hour [25, 26]. This suggests that water and chemical solutions did not significantly affect the composites. This low water or chemical intake could explain the hydrophobic nature of WH fibre in composites, as the previous studies [27]. When compared to other natural fibres, such as coir, sisal, and bamboo composites, WH-based composites had a relatively lower impact on water and chemical solutions. It has been observed that water absorption at the fibre–resin interface may result in swelling and potentially lead to hydrolytic breakdown of the chemical bond between the fibre and resin. The weight percentage of the increased layer in the hyacinth fibre composite differs significantly from that of the other samples. According to studies, it has been found that jute and glass fibre composites, when reinforced with epoxy, exhibit improved water and chemical absorption properties [28]. On the other hand, it has been observed that the addition of moringa filler to hyacinth fibre composites significantly reduces their ability to absorb water and chemicals [29, 30]. For instance, coir-based composites took 28 h to reach saturation, with 8.60% of the coir composite's weight being saturated [31, 32]. Similarly, sisal composite also reached saturation point after 36 h, resulting in a 7.20 per cent weight percentage [33, 34]. However, a composite based on hyacinth fibres reached saturation quickly (within 10 h) and absorbed less water (5.40%) [35].

Characterization studies

Figure 6b illustrates that WH fibre composites with moringa filler powder exhibit different X-ray diffraction patterns. The composite sample contains with

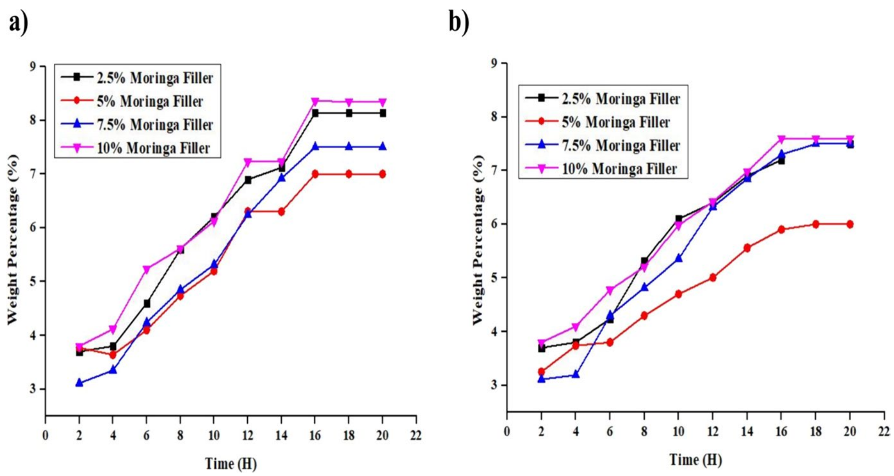

Fig. 5 Absorption behaviour on hyacinth fibre composite (**a**) water and (**b**) chemical absorption studies

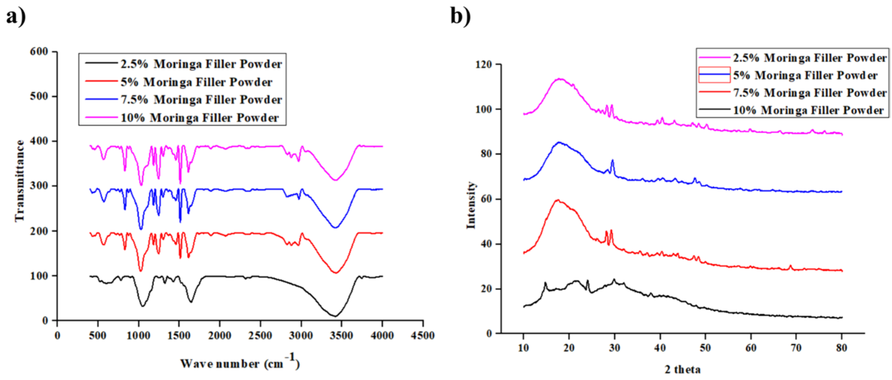

Fig. 6 Characterization studies on hyacinth composites **a** FTIR and **b** X-ray diffraction

reinforcement (fibre) materials, there is an amorphous phase in the lower intensity peaks. To determine the crystallinity index (CI), various methods are employed, such as amorphous subtraction, XRD peak height method, NMRC4 peak separation method, and XRD deconvolution method [36]. Equation 1 is used to find out the deconvolution crystallinity index of the composite samples.

$$CI = \frac{Area\ of\ crystalline\ peaks}{Area\ of\ all\ peaks} \times 100 \tag{1}$$

The term CI means the crystallinity index, A_c means area of crystalline peaks, and A_a means area of all peaks.

The composites with varying filler levels and fibre content were analysed for their crystallinity indices. It varied 46.411%, 59.32%, 54.68%, and 52.27% crystallinity indices for composites containing filler levels of 2.5%, 5%, 7.5%, and 10%, and a fibre content of 30%, respectively. The results indicate that the composite with 5% moringa filler powder and 30% fibre content exhibited the highest crystallinity index [37]. This can be attributed to the strong bonding between the fibre and epoxy matrix, resulting in improved mechanical properties of the composite. However, a decrease in CI with 30% fibre weight percentage indicated poor interfacial bonding and resulted in lower mechanical strength [38].

Fourier transform analysis was utilized to investigate the properties of WH fibres when combined with moringa filler powder composites, and it is shown in Fig. 6a. The 2.5% filler WH composite band peak at 3481.857 cm^{-1} indicates an oxygen–hydrogen (O–H) stretching of cellulose and hemicellulose [39]. Additionally, peaks between 3342 and 3466 cm^{-1} were also observed. The fibre composites of different lengths displayed additional peaks, including their raw peaks. The study found that the addition of moringa filler resulted in peaks at 3422.08 cm^{-1}, 3418.37 cm^{-1}, and 3425.680 cm^{-1} in the weight percentage of the reinforced composites [40]. The carbon–hydrogen peaks were observed at 2823.9 cm^{-1}, 2585.54 cm^{-1}, 2867.69 cm^{-1}, and 2951.13 cm^{-1} in the composites. The researchers also noted that cellulose and hemicellulose contributed to the vibration of the total hydrocarbon molecules in the reinforcement phase [41, 42]. The hemicellulose in the sample was identified through various double bond peaks, including C=O at 1590.354 cm^{-1}, 1866.472 cm^{-1}, 1742.35 cm^{-1}, and 1463.21 cm^{-1}, as well as C=H. The lignin and hemicellulose contents were reduced through proper drying and moisture removal, which was achieved by breaking the O–H bonding in the WH fibre phase [43]. As a result, the cellulose content increased by 5% of filler contents in the composite at 1532.354 cm^{-1}.

Thermal analysis

Figure 7 shows the thermogravimetric, first-order derivative, and derivative thermogravimetric curves of the WH composite. The composites containing 2.5%, 5%, 7.5%, and 10% moringa filler powder-initiated decomposition at 284 °C, 319 °C, 248 °C, and 241 °C, respectively. The moisture content trends of hyacinth fibre composites decrease before 100 °C. It is generally observed that samples with high mechanical strength can reach maximum peaks and withstand higher temperatures [44]. However, it was observed in this study that the composite sample with 5% filler powder reached the decomposition temperature peak earlier than the 7.5% and 10% composites [45]. This phenomenon can be attributed to the intermolecular effect between the polymer matrix and reinforcement material at high temperatures.

SEM (Scanning Electron Microscope)

This work examines the SEM micrograph of WH composite fractured surfaces. Figure 8a shows that the composite specimens experienced notable fibre bending and pull-out, which was caused by interfacial stresses at the fibre–matrix interface that exceeded the interfacial strength [46]. This resulted in fibre debonding from the matrix materials. The absence of epoxy resin adhering to the fibre indicates that the bond between the fibre and the matrix remained intact, it is illustrated in Fig. 8b. Additionally, the epoxy matrix was found to dominate the failure process. Furthermore, it has been noted that if the fibres are arranged loosely within the matrix, the composite sample may experience tearing [47] and shearing, it is explained in

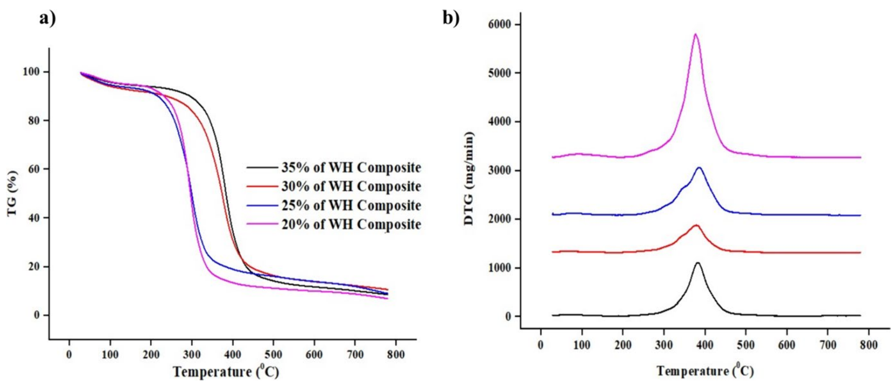

Fig. 7 Thermal behaviour of hyacinth composites

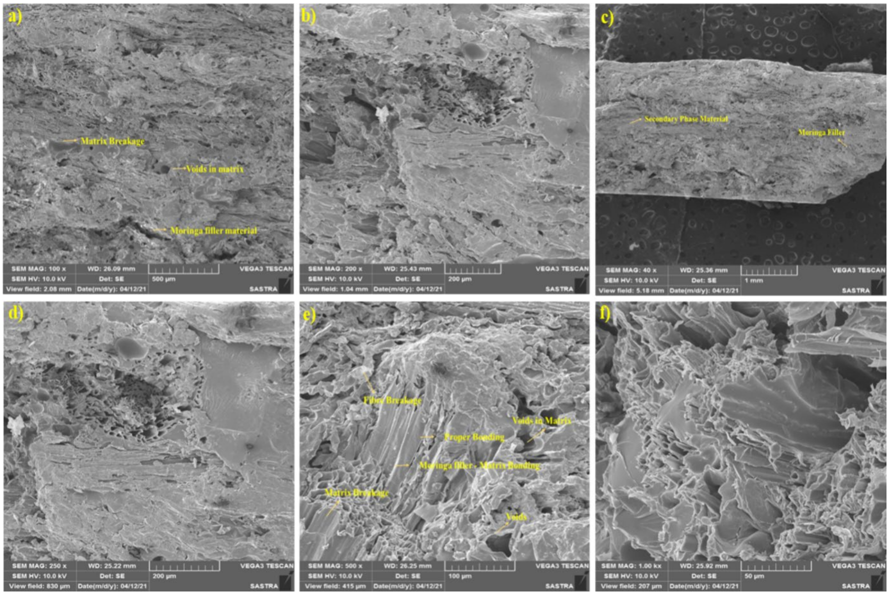

Fig. 8 Morphological studies of hyacinth composites

Fig. 8c. To address the issue of moisture on fractured surfaces of WH fibre-reinforced composites, a hot air oven set at 64 °C is utilized. This method has proven effective in removing a significant amount of wax substance. There was an agglomeration effect within the matrix phase due to the high fibre content [48]. The fibre clusters in Fig. 8d, e resulted in poor interfacial bonding between the fibre clusters and the epoxy matrix, resulting in poor mechanical properties for the composite. In Fig. 8f, fibres were pulled from the matrix phase due to failure of the composite sample under the impact load.

Conclusions

This study investigated the properties of water hyacinth fibre with moringa filler powder-reinforced epoxy composites, including microstructure, mechanics, absorption, thermal properties, and fracture surfaces, under different fibre weight percentage conditions. The mechanical extraction method produced the high yield and high quality of water hyacinth fibres within a very short time. The study found that the most effective combination of fibre and epoxy matrix is 30:70, and the highest mechanical properties, including tensile, flexural, and impact strength, can be achieved with an optimum filler weight percentage of 5%. It was observed that exceeding 30 wt% fibre and 5% filler powder resulted in a decrease in mechanical properties. Based on the absorption results, the water and chemical solutions did not affect the composites, possibly due to a change from hydrophilic to hydrophobic nature when the fibre was mixed with the epoxy. Based on the characterization studies, it was observed that the composite samples with 5% by weight of moringa filler powder exhibited higher thermal stability compared to the composites with other weight percentages. In addition, the composites have more essential functional groups than the other samples. Based on the experimental results, it appears that the moringa filler-reinforced composite may be a viable lightweight alternative to synthetic fibre-based composites for commercial particle board and medium density fibre board applications.

Author contributions A.A and X.C wrote the manuscirpts, S.K.R and Y.F.G prepared the figures, W.G supervised the manuscript, F.A.S and W.J.J.T involved the supervision and idea formation, and I.S and B.P.S.R involved the manuscript language corrections.

Funding Not applicable.

Data availability The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Declarations

Conflict of interest The authors declare no competing interests.

References

1. Mukaratirwa-Muchanyereyi N, Kugara J, Zaranyika MF (2016) Surface composition and surface properties of water hyacinth (*Eichhornia crassipes*) root biomass: effect of mineral acid and organic solvent treatment. Afr J Biotechnol 15:891–896
2. Yang X, Tang H, Li Y et al (2024) Synthesis, characterization, and thermal pyrolysis mechanism of high temperature resistant phenolphthalein-based poly (arylene ether nitrile). Polym Degrad Stab 224:110754
3. Felix Sahayaraj A, Muthukrishnan M, Ramesh M (2022) Influence of Tamarindus indica seed nano-powder on properties of Luffa cylindrica (L.) fruit waste fiber reinforced polymer composites. Polym Compos 43:6442–6452
4. Arivendan A, Jappes W, Irulapasamy S et al (2022) Extraction and characterization of natural aquatic plant fiber, powder and ash from water hyacinth (*Eichhornia crassipes*) as reinforcement of fiber, powder, and ash reinforced polymer composite. J Nat Fibers 19:9589–9599
5. Sahayaraj AF, Muthukrishnan M, Ramesh M, Rajeshkumar L (2021) Effect of hybridization on properties of tamarind (Tamarindus indica L.) seed nano-powder incorporated jute-hemp fibers reinforced epoxy composites. Polym Compos 42:6611–6620
6. Arivendan A, Chen X, Zhang YF et al (2024) Effect of pineapple leaf and ramie fiber length and weight percentage on the hybrid polymer composites dry sliding wear and air jet erosion studies. Polym Compos. https://doi.org/10.1002/pc.28151
7. Arivendan A, Thangiah WJJ, Ramakrishnan S, Desai DA (2023) Biological waste water hyacinth (*Eichhornia crassipes*) plant powder particle with eggshell filler-reinforced epoxy polymer composite material property analysis. J Bionic Eng 20:1386–1399
8. Arivendan A, Jebas Thangiah WJ, Das R et al (2023) Effect of water hyacinth (*Eichhornia crassipes*) plant into water bodies and its composite materials for commercial applications. Proc Inst Mech Eng C J Mech Eng Sci 237:5381–5390
9. Istirokhatun T, Rokhati N, Rachmawaty R et al (2015) Cellulose isolation from tropical water hyacinth for membrane preparation. Procedia Environ Sci 23:274–281
10. Tan SJ, Supri AG (2016) Properties of low-density polyethylene/natural rubber/water hyacinth fiber composites: the effect of alkaline treatment. Polym Bull 73:539–557

11. Chukwuka KS, Omotayo OE (2008) Effects of Tithonia green manure and water hyacinth compost application on nutrient depleted soil in South-Western Nigeria. Int J Soil Sci 3:69–74
12. Kumar A, Singh LK, Ghosh S (2009) Bioconversion of lignocellulosic fraction of water-hyacinth (*Eichhornia crassipes*) hemicellulose acid hydrolysate to ethanol by Pichia stipitis. Bioresour Technol 100:3293–3297
13. Rino JJ, Suyambulingam I, Divakaran D et al (2024) Facile exfoliation and physicochemical characterization of Thespesia populnea plant leaves based bioplasticizer macromolecules reinforced with polylactic acid biofilms for packaging applications. Int J Biol Macromol 261:129771
14. Gajalakshmi S, Abbasi SA (2002) Effect of the application of water hyacinth compost/vermicompost on the growth and flowering of Crossandra undulaefolia, and on several vegetables. Bioresour Technol 85:197–199
15. Ajithram A, Winowlin Jappes JT, Siva I, Brintha NC (2021) Experimental investigation on aquatic waste water hyacinth (Eichhorniacrassipes) plant into natural fibre polymer composite–biological waste into commercial product. Proceed Instit Mech Eng E J Process Mech Eng 09544089211072378
16. Kumar P (2012) Mechanical behavior of orange peel reinforced epoxy composite bachelor of technology in mechanical engineering
17. Kumar Guna V, Ilangovan M, Maravanji Gangadharaiah A, Reddy N (2017) Water hyacinth: a unique source for sustainable materials and products
18. Supri AG, Tan SJ, Ismail H, Teh PL (2011) Effect of poly (methyl methacrylate) modified water hyacinth fiber on properties of low density polyethylene/natural rubber/water hyacinth fiber composites. Polym Plast Technol Eng 50:898–906
19. Muñoz E, García-Manrique JA (2015) Water absorption behaviour and its effect on the mechanical properties of flax fibre reinforced bioepoxy composites. Int J Polym Sci. https://doi.org/10.1155/2015/390275
20. Sampath P, Santhanam SKV (2019) Effect of moringa and bagasse ash filler particles on basalt/epoxy composites. Polimeros. https://doi.org/10.1590/0104-1428.01219
21. Kumar DR, Mohanraj P (2017) Review on natural fiber in various pretreatment conditions for preparing perfect fiber
22. Flores Ramirez N, Sanchez Hernandez Y, Cruz de Leon J et al (2015) Composites from water hyacinth (Eichhornea crassipe) and polyester resin. Fibers Polym 16:196–200
23. Abral H, Putra H, Sapuan SM, Ishak MR (2013) Effect of alkalization on mechanical properties of water hyacinth fibers-unsaturated polyester composites. Polym Plast Technol Eng 52:446–451
24. Mishra K, Sinha S (2020) Development and assessment of Moringa oleifera (Sahajana) leaves filler/epoxy composites: Characterization, barrier properties and in situ determination of activation energy. Polym Compos 41:5016–5029. https://doi.org/10.1002/pc.25771
25. Jirawattanasomkul T, Minakawa H, Likitlersuang S et al (2021) Use of water hyacinth waste to produce fibre-reinforced polymer composites for concrete confinement: Mechanical performance and environmental assessment. J Clean Prod 292:126041
26. Abral H, Kadriadi D, Rodianus A et al (2014) Mechanical properties of water hyacinth fibers–polyester composites before and after immersion in water. Mater Des 58:125–129
27. Maniraj J, Sahayaraj F, Giri J, et al (2024) Enhancing performance of prosopis juliflora fiber reinforced epoxy composites with silane treatment and syzygium cumini filler. J Mater Res Technol
28. Supri AG, Lim BY (2009) Effect of treated and untreated filler loading on the mechanical, morphological, and water absorption properties of water hyacinth fibers-low density polyethylene composites. J Phys Sci 20:85–96
29. Norizan MN, Abdan K, Salit MS, Mohamed R (2017) Physical, mechanical and thermal properties of sugar palm yarn fibre loading on reinforced unsaturated polyester composites. J Phys Sci
30. Ramesh M, Palanikumar K, Reddy KH (2013) Comparative evaluation on properties of hybrid glass fiber-sisal/jute reinforced epoxy composites. Procedia Eng 51:745–750
31. Saha M, Rahman MH, Ali MA (2011) Effect of fiber loadings on mechanical properties of water hyacinth fiber reinforced polypropylene composites. In: Proceedings of the international conference on mechanical engineering
32. Shivamurthy B, Murthy K, Joseph PC et al (2015) Mechanical properties and sliding wear behavior of jatropha seed cake waste/epoxy composites. J Mater Cycles Waste Manag 17:144–156
33. Rajini N, Jappes JTW, Rajakarunakaran S, Jeyaraj P (2013) Dynamic mechanical analysis and free vibration behavior in chemical modifications of coconut sheath/nano-clay reinforced hybrid polyester composite. J Compos Mater 47:3105–3121

34. Sumrith N, Techawinyutham L, Sanjay MR et al (2020) Characterization of alkaline and silane treated fibers of ‘water hyacinth plants’ and reinforcement of ‘water hyacinth fibers’ with bioepoxy to develop fully biobased sustainable ecofriendly composites. J Polym Environ 28:2749–2760
35. Okia DO, Ndiema CK, Ahmed MS (2016) Physical and chemical properties of water hyacinth based composite briquettes. World 4:28–36
36. Dilfi KFA, Balan A, Bin H et al (2018) Effect of surface modification of jute fiber on the mechanical properties and durability of jute fiber-reinforced epoxy composites. Polym Compos 39:E2519–E2528. https://doi.org/10.1002/pc.24817
37. Mu Q, Wei C, Feng S (2009) Studies on mechanical properties of sisal fiber/phenol formaldehyde resin in-situ composites. Polym Compos 30:131–137. https://doi.org/10.1002/pc.20529
38. Alvarez V, Vázquez A, Bemal C (2005) Fracture behavior of sisal fiber-reinforced starch-based composites. Polym Compos 26:316–323. https://doi.org/10.1002/pc.20103
39. Fang L, Chu Y, Zhu X et al (2024) Low-velocity multiple impact damage characteristics and numerical simulation of carbon fiber/epoxy composite laminates. Polym Compos 45:2517–2531. https://doi.org/10.1002/pc.27936
40. Kazi AM, Waddar S (2022) Characterization of interwoven roselle/sisal fiber reinforced epoxy composites. Polym Compos 43:1421–1428. https://doi.org/10.1002/pc.26462
41. Jiang Y, Liu L, Yan J, Wu Z (2024) Room-to-low temperature thermo-mechanical behavior and corresponding constitutive model of liquid oxygen compatible epoxy composites. Compos Sci Technol 245:110357
42. Su Y, Iyela PM, Zhu J et al (2024) A Voronoi-based gaussian smoothing algorithm for efficiently generating RVEs of multi-phase composites with graded aggregates and random pores. Mater Des 244:113159
43. Song JH, Mun SD, Kim CS (2011) Mechanical properties of sisal natural fiber composites according to strain rate and absorption ratio. Polym Compos 32:1174–1180. https://doi.org/10.1002/pc.21136
44. Periasamy D, Manoharan B, Niranjana K et al (2024) Recycling of thermoset waste/high-density polyethylene composites: examining the thermal properties. Polym Compos 45:2739–2748. https://doi.org/10.1002/pc.27953
45. Kazi AM, Devika D, Waddar S (2021) Characterization of Roselle fiber composites for low load bearing structures. Polym Compos 42:2589–2597. https://doi.org/10.1002/pc.26004
46. Tewari R, Singh MK, Zafar S (2021) Utilization of forest and plastic wastes for composite manufacturing using microwave-assisted compression molding for low load applications. J Polym Res 28:1–14
47. Wan Ramli WMA, Abdul Majid MS, Ridzuan MJM et al (2020) The effect of nanomodified epoxy on the tensile and flexural properties of Napier fiber reinforced composites. Polym Compos 41:824–837. https://doi.org/10.1002/pc.25413
48. Ajithram A, Winowlin Jappes JT, Siva I, Brintha NC (2022) Influence of extraction methods on mechanical, absorption and morphological properties of water hyacinth (*Eichhornia crassipes*) natural fibre composites: Environmental threat to successive commercial products. Proceed Institut Mech Eng L J Mater Des Appl 236:1614–1622

Authors and Affiliations

Ajithram Arivendan[1] · Sumesh Keerthiveettil Ramakrishnan[2] · Xiaoqi Chen[1] · Yuan-Fang Zhang[1] · Wenhua Gao[3] · Firda Aulya Syamani[4] · Winowlin Jappes Jebas Thangiah[5] · I. Siva[6] · S. R. Boselin Prabhu[7]

✉ Ajithram Arivendan
ajithrampdf@gmail.com

✉ Xiaoqi Chen
xqc@scut.edu.cn

✉ Yuan-Fang Zhang
zhangyuanfang@scut.edu.cn

Sumesh Keerthiveettil Ramakrishnan
sumesh2311@gmail.com; keerthiveettil.sumesh@fs.cvut.cz

1 Shien-Ming Wu School of Intelligent Engineering, South China University of Technology, Xingye Ave, Guangzhou 511442, Guangdong, China

2 Faculty of Mechanical Engineering, Department of Materials Engineering, Czech Technical University in Prague, Karlovo Namesti 13, Prague 02 12000, Czech Republic

3 State Key Laboratory of Pulp and Paper Engineering, South China University of Technology, Wushan Road, Guangzhou 510640, Guangdong, China

4 Research Center for Biomass and Bioproducts, National Research and Innovation Agency, Cibinong, West Java 16911, Indonesia

5 Department of Mechanical Engineering and Centre for Composite Materials, Kalasalingam Academy of Research and Education, Virudhunagar, Tamil Nadu, India

6 Department of Mechanical Engineering, Mohan Babu University, Sree Sainath Nagar, Tirupati 517102, Andhra Pradesh, India

7 Department of Electronics and Communication Engineering, Surya Engineering College, Kathirampatti, Mettukadai 638107, Tamil Nadu, India