



Research article

Evaluation of biopots made from various parts of water hyacinth: Physical and structural characteristics

Novianti Adi Rohmanna^{a,*}, Dessy Maulidya Maharani^a, Lya Agustina^a, Hisyam Musthafa Al Hakim^a, Zuliyani Agus Nur Muchlis Majid^a, Dwija PutriPERTIWI^b, Muhammad Fitrihanur^a

^a Department of Agroindustrial Technology, Faculty of Agriculture, Lambung Mangkurat University, Banjarmasin 70123, Indonesia

^b Department of Agronomy, Faculty of Agriculture, Lambung Mangkurat University, Banjarmasin 70123, Indonesia

Article Info

Article history:

Received 18 July 2025

Revised 8 July 2026

Accepted 10 July 2026

Available online 30 September 2026

Keywords:

Biopot,

Lignocellulosic materials,

Waste valorization,

Water hyacinth

Abstract

Importance of the work: Water hyacinth (WH) is an invasive aquatic plant whose abundant biomass has potential as a renewable material for biodegradable planting pots (biopots). However, the effects of different WH components, including roots, petioles, and leaves, on biopot quality remain unclear. Utilizing WH biomass as an agricultural product could provide a sustainable approach to invasive weed management while supporting sustainable agriculture and the circular economy.

Objectives: To determine the effect of different WH components and their proportions on the physical, mechanical, structural, and morphological properties of biopots.

Materials and Methods: The biopot was produced using thermoprocessing at 150°C for 15 min based on white clay and polyvinyl acetate PVAc as a matrix. Four different compositions of raw material were tested: 100% roots; 50% roots and 50% petioles; 50% roots and 50% leaves; and 40% roots and 60% petioles. Each biopot was analyzed for physical, mechanical, structural and morphological properties.

Results: The utilization of different parts of WH affected the quality of the biopot. Biopots using equal amounts of petioles and roots had improved quality. However, over-supplementation of petioles (60%) had some weakening effects, including increased water absorption and moisture content and a decreased impact resistance index (IRI) and compressive strength of the biopots. The use of 50% roots and 50% petioles contributed positively to the biopot physical-mechanical, structural and morphological properties, with mean $\pm$ SD values for density, moisture, water absorption in 30 min, IRI and compressive strength being 0.147 ± 0.006 g/cm³, $8.23 \pm 0.06\%$, $129.57 \pm 0.66\%$, 98.5% and 107 N, respectively.

Main finding: The use of WH as a major source of biopot material could serve as an alternative for managing environmental issues associated with the spread of this aquatic weed. Biopots made from 50% WH roots and 50% petioles showed favorable physical and mechanical properties, suggesting their potential as an alternative to conventional polybags for sustainable agriculture. Further studies should evaluate WH biopot biodegradation, durability, economic feasibility and large-scale production potential.

* Corresponding author.

E-mail address: novianti.rohmanna@ulm.ac.id (N.A. Rohmanna)

Introduction

Water hyacinth [*Eichhornia crassipes* Mart. (Solms); WH] is an invasive aquatic plant commonly found in freshwater environments (Villamagna and Murphy, 2010). It grows optimally at 28–30°C and has a high reproductive rate, classifying it as an aquatic weed. Its population can double within 2 wk or even 5–7 d, depending on environmental conditions (Dölle et al., 2021). According to Dölle et al. (2020), 1 ha of water can produce approximately 500 t of WH. In particular, WH has severe environmental impacts in freshwater ecosystems, where it disrupts river ecosystems by causing deoxygenation, reducing water volume and decreasing biological diversity (Stiers et al., 2011). On the other hand, water hyacinth has attracted attention due to its high lignocellulosic content and rapid growth rate, making it a promising raw material for biodegradable products such as biodegradable pots or biopots (Dölle et al., 2021). Istirokhatun et al. (2015) reported that WH consists of 10% lignin, 25% cellulose and 33% hemicellulose. However, its utilization remains limited, primarily for compost, briquettes and paper pulp production.

Biopots were developed as an alternative to polybags and are made from biocomposites and solid waste (Fuentes et al., 2021). Conventional plastic pots contribute greatly to environmental pollution due to their non-biodegradability and the challenges of recycling (Abe et al., 2021). Therefore, the development of biopots from biomass has emerged as a promising alternative. Biopots not only support seedling growth but can also be transplanted directly into the soil, where they decompose naturally and facilitate root penetration, minimizing transplant shock and environmental impact (Castronuovo et al., 2015).

Various agro-industrial materials have been explored for biopot development, including paddy straw, oil palm empty fruit bunches and WH blends (Sari et al., 2021; Jaya et al., 2022; Pratibha et al., 2022). Compared to other natural fibers, WH is more abundant, fast-growing and rich in cellulose (Ishaya et al., 2024), making it highly biodegradable and structurally suitable for various applications. In addition, its porous nature may improve root aeration and microbial activity during plant growth. Sari et al. (2021) explored combinations of galam (*Melaleuca cajuputy*) skin and WH as fillers and tapioca flour as an adhesive, yielding biopots with water absorption rates up to 176.2% and densities in the range 0.3584–0.8767 g/cm³. However, the use of WH fiber as the main structural component in biopot production has received limited attention. Predominantly the published studies used whole WH biomass without differentiating specific plant components and frequently incorporated additional biomass materials into the biopot matrix.

To date, research has shown that the performance of biopots was influenced by the types and proportions of materials and matrix used (Abe et al., 2021). Nevertheless, limited research has examined specifically how different parts of the WH—such as roots, petioles and leaves—contribute to the functional properties of biopots. These differences are likely influenced by variations in lignocellulosic composition and fiber length among the plant parts, which can substantially affect the strength, compactness and water resistance of the resulting biopots. Despite the growing interest in WH-based

biomaterials, no studies have compared systematically the characteristics of individual WH parts for biopot production, leaving undetermined the most suitable component in terms of physical and structural properties. To address this gap, a preliminary study tested biopots made from 100% roots, petioles, or leaves, respectively. Based on these results, petiole- and leaf-based biopots were structurally fragile and failed to form stable pot shapes (Fig. 1), whereas root-based biopots had better structural integrity. Building upon these preliminary findings, this study conducted a systematic investigation of various combinations of WH parts to optimize the structural, mechanical and biodegradation characteristics of WH-based biopots for sustainable agricultural applications. Accordingly, the aims were: 1) to compare the physical and structural properties of biopots fabricated from various parts of WH; and 2) to determine the plant component with the most favorable characteristics for biopot production.

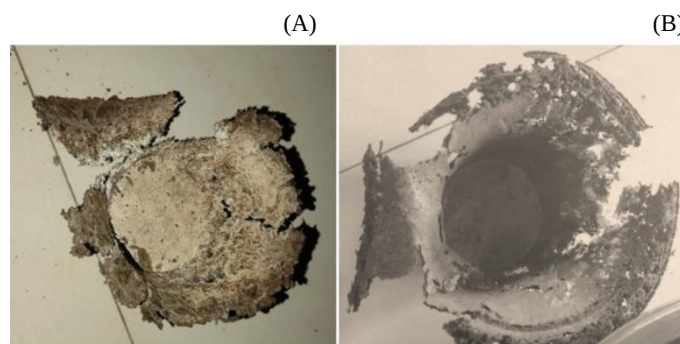


Fig. 1 Unusable biopots from preliminary study: (A) 100% petioles; (B) 100% leaves, (scale bar = 20 mm)

Materials and Methods

Materials

The adhesive used was polyvinyl acetate (PVAc), produced by PT Aica Indria, Jakarta, Indonesia. The white clay and glycerol were obtained from PT Pandu Multi Jaya, Banjarmasin, Indonesia. The WH samples were collected from the BPDAS (Central Management of Regional River Flow) in Banjarmasin, South Kalimantan, Indonesia.

Water hyacinth preparation

WH was used as the raw material. Plant samples were harvested from mature individuals with fully developed leaves and petioles characterized by uniform green coloration and the absence of decay. A single local variety commonly found in the rivers of Banjarmasin was used to ensure consistency. After collection, the WH plants were washed and separated manually into three main components (roots, petioles, leaves). Each part was chopped into 2–3 cm pieces using a machete and then processed in a mechanical chopper to reduce the particle size. Approximately 500 g of each part (wet basis) were sun-dried for 2–3 d under ambient conditions (28–32°C, relative humidity 60–70%) until the moisture content dropped below 10% (dry basis).

Subsequently, the partially dried materials were oven-dried at 70°C for 48 hr to ensure uniform drying, then ground and sieved through a 100-mesh screen. The resulting powders were stored in sealed containers prior to use. Proximate analyses were conducted to determine the moisture, lipid and lignocellulose (cellulose, hemicellulose, and lignin) contents of each WH component.

Biopot preparation

Producing biopots from WH involved using white clay as a reinforcement agent and PVAc as adhesive, with a mixture of 25% WH, 25% white clay and 50% PVAc. Initially, approximately 10 g of white clay and 20 g of PVAc were dissolved in 30 mL of distilled water and the mixture was stirred until a consistent gel formed. Subsequently, 10 g of the sample and 3 ml of glycerol were added to the adhesive solution, which was then thoroughly mixed using a stirrer to create a paste suitable for molding. Based on the results of the preliminary study (Fig. 1), the formulations of the biopot materials using different parts of WH were: A) 100% roots; B) 50% roots and 50% petioles; C) 50% roots and 50% leaves; and D) 40% roots and 60% petioles.

Each treatment was conducted in three replicates ($n = 3$). The biopot formulation was placed into an iron mold designed to achieve the desired pot shape, with an upper diameter of 9 cm, a bottom diameter of 6 cm and a height of 7 cm. Subsequently, the formulation was molded using the thermopressing method at 150°C for 15 min. Once the thermopressing process had been completed, the biopots were removed from the molds and stored in a dry container.

Physical characterization

The physical characterization of the biopots was investigated based on measuring the moisture content, water absorption and density. The moisture content was analyzed following the method described by Jaya et al. (2022). Briefly, a Pyrex Petri dish was dried for 15 min at 105°C and weighed (W_2). Biopot specimens (from the bottom of the biopot) were prepared in dimensions of 20 mm × 30 mm. The weight was recorded of each specimen placed on a Petri dish (W). Then, the specimens were dried for 15 min at 105°C and reweighed (W_1). The moisture content as a percentage was calculated using Equation 1:

$$\text{Moisture content} = (W - (W_1 - W_2) / W) \times 100 \quad (1)$$

where all weights are in grams.

The water absorption assay was adopted from Jaya et al. (2022). Briefly, biopot specimens were prepared in dimensions of 20 mm × 30 mm and weighed (W_0). Then, the samples were saturated with water for 30 and 60 min, respectively, and reweighed (W_1). Water absorption (Q) was calculated using Equation 2:

$$Q ((W_t - W_0) / W_0) \frac{W_t - W_0}{W_0} \times 100 \quad (2)$$

where all weights are in grams.

The density assay was adopted from Wahdan et al. (2022). Briefly, each specimen was weighed in grams (W) and its volume in cubic

centimeters (V) was measured using the geometric method. The density in grams per cubic centimeter (d) was calculated using Equation 3:

$$d = w/v \quad (3)$$

Mechanical characterization

The mechanical characterization of the biopots was investigated based on the impact resistance index (IRI) as a percentage and compressive strength. The IRI analysis was adopted from Wahdan et al. (2022). Briefly, the IRI of the biopots was determined by dropping each biopot from a height of 1.85 m onto a concrete surface or a metal plate and repeating the test four times. The biopot was weighed in grams before (B_a) and after (B_b) the drop test. The IRI was calculated using Equation 4:

$$IRI = 100 - (((B_a - B_b) / B_a) \times 100) \quad (4)$$

The compressive strength analysis was conducted using a concrete compression testing machine (MBT Mektan; city, country) operated with a hydraulic pump complying with ASTM C39 (ASTM International, year). The compressive strength of each specimen was calculated as the maximum load divided by the specimen's cross-sectional area. The pump's speed was controlled by adjusting the variable-speed setting.

Structural and morphological characterization

The structural and morphological characteristics of the biopots were analyzed using Fourier-transform infrared (FTIR) spectroscopy, X-ray diffraction (XRD) and scanning electron microscopy (SEM). The FTIR analysis was conducted using a IR Prestige 21 spectrometer (Shimadzu Corp.; Kyoto, Japan) to identify functional groups within the 4000–600 cm^{-1} range. The XRD analysis was performed using a PANalytical X'Pert Pro diffractometer (Malvern Panalytical; Malvern, UK) to determine the crystalline phases within a 2θ range of 10° – 90° . The SEM imaging was performed using an FEI Inspect S50 microscope (FEI Co.; Hillsboro, OR, USA) at 1,000× magnification, to examine the surface morphology of the biopot samples in detail.

Statistical analysis

All statistical analyses were carried out using SPSS software (version 29; IBM Corp.; Armonk, NY, USA). All data were replicated three times and analyzed using one-way analysis of variance and Duncan's multiple-range test at the $p < 0.05$ significance level.

Results and Discussion

Chemical properties of water hyacinth

The chemical composition of WH plays a crucial role in determining its suitability as a reinforcing material for biopot production. In this study, biopots were produced by blending WH roots, petioles and leaves with white clay and PVAc. The WH fibers served as natural reinforcement, while white clay and PVAc served as the

matrix and adhesive agents, respectively, contributing to structural integrity and binding performance. This composite formulation was developed to balance mechanical integrity and environmental degradability, making it suitable for use as a sustainable planting container.

Water hyacinth was selected as the primary raw material for biopot production due to its promising characteristics, including a relatively high lignocellulosic composition, rapid growth rate, low production cost, abundant availability, renewability, biodegradability and adequate mechanical strength (Iriany et al., 2020). In this study, the total lignocellulose content of WH (44.68–69.69%) was lower than that of oil palm empty fruit bunches (OPEFB, 89.42%) (Table 1). Nevertheless, utilizing WH as a biopot raw material represents an environmentally sustainable strategy for mitigating the ecological issues associated with its excessive proliferation in aquatic ecosystems. Previous studies have shown that lipid content in WH leaves is higher than in petioles and roots (Tadesse et al., 2022; Pokharel et al., 2024). Meanwhile, Ishaya et al. (2024) reported that WH petioles have a high moisture content. The same findings are summarized in Table 1.

Table 1 Properties of different water hyacinth components used in this study

Parameter	Water hyacinth			OPEFB
	Roots	Petioles	Leaves	
Lipid content (%)	0.13	0.46		0.46
Moisture (%)	3.76	4.84		4.84
Lignin (%)	18.54	21.74		21.74
Cellulose (%)	2.93	8.39		8.39
Hemicellulose (%)	23.21	38.96		38.96
Fiber length (mm)	4.05	7.20	0.86	-

OPEFB = oil palm empty fruit bunch (Jaya et al., 2022).

Hemicellulose in WH acts as a binder for cellulose, contributing to water absorption and thereby influencing the structural integrity and performance of the final product. Cellulose enhances mechanical strength, biodegradability, water resistance, flexibility and compatibility. Furthermore, cellulose can be chemically modified (e.g., via esterification) to improve physical and mechanical properties (Zaborowska et al., 2023). Following evaluations of the biopots, which focused on assessing their feasibility as eco-friendly alternatives to conventional plastic pots. A comprehensive characterization was carried out to investigate the physical, mechanical, structural and morphological properties of these materials. These analyses were used to determine the suitability of the materials for horticultural applications and to guide potential scaling strategies for biopot production using WH-based composites.

Physical biopot characteristics

The physical characteristics of WH (density, moisture content, water absorption) were investigated. Density is a key physical property that plays a major role in determining the rate of biopot degradation in soil. Low-density pots have a more porous structure, which promotes the diffusion of water, nutrients and microorganisms into the material, thereby accelerating biodegradation in the soil environment. The

density of biopot is presented in Table 2. The biopots formulated from equal amount of root and leaf materials had relatively higher density values than the other formulations, which may be attributed to the compositional characteristics of the raw materials, particularly their higher fiber and lignocellulose contents. The high density in biopot C may be attributed to the synergistic effect of root and leaf fibers. Although the leaf fibers had a lower lignin content and shorter fiber length, their relatively high cellulose content (33.42%) likely enhanced fiber compactness and inter-fiber bonding during thermopressing. In addition, the shorter leaf fibers (2.80 mm) may have facilitated tighter packing and reduced void formation within the matrix, resulting in a denser composite structure. Furthermore, the root fibers, with their higher lignin content (18.54%) and longer fibers (4.05 mm), likely contributed to structural rigidity and mechanical support. Therefore, the combination of dense packing from the leaf fibers and structural reinforcement from the root fibers may explain the higher density observed in Biopot C.

In general, the observed trend in density values by raw material type followed the sequence: Biopot C > Biopot B > Biopot A > Biopot D. The observed differences in the descriptive characteristics among the treatments may reflect the influence of raw material composition on the physical properties of the biopots. The biopot formulation with 40% roots and 60% petioles (Biopot D) had a relatively lower density than the other samples, which may have been due to its lower cellulose content and longer fiber morphology (Table 1), which could enhance material porosity. The petiole had the longest fiber length (7.20 mm) and the highest hemicellulose content (38.96%) among the tested materials (Table 1). At higher loading proportions (60%), long fibers tend to agglomerate and form micro-voids within the matrix, resulting in poor packing efficiency that reduce density and increase water absorption. These combined effects likely contributed to the porous structure and high-water absorption observed in Biopot D. Although long fibers (> 5 mm) can enhance load transfer efficiency, their poor dispersion and tendency to form voids within the matrix may increase porosity and reduce the overall density of the biopot. However, these characteristics should not be considered a weakness. On the contrary, lower density has been reported to improve air and water permeability, support the natural root system's aeration and stimulate nutrient absorption (Fuentes et al., 2021). Each of these factors can have a positive influence on plant growth. These findings were consistent with the principles of bioactive material design, which aim to balance mechanical stability with controlled biodegradability (Zaborowska et al., 2023).

Furthermore, the density values of the biopots in the current study were lower than those of biopots made from OPEFB, which typically are in the range 0.177–0.264 g/cm³ (Jaya et al., 2022), suggesting that WH may offer advantages in terms of biodegradability and structural porosity for horticultural applications.

Moisture content and density are key physical properties that directly influence the quality and performance of biopots, particularly their mechanical strength, dimensional stability and biodegradability (Fuentes et al., 2021). In the current study, the moisture content was in

Table 2 Characteristics of biopots containing different amounts of water hyacinth components (roots, leaves and petioles)

Treatment	Parameter			
	Density (g/cm ³)	Moisture (%)	Water absorption (%)	
			30 min	60 min
Biopot A	0.146±0.004 ^{ab}	7.21±0.30 ^a	121.18±0.70 ^b	129.10±0.49 ^c
Biopot B	0.147±0.006 ^{ab}	8.23±0.06 ^b	129.57±0.66 ^c	124.12±0.18 ^b
Biopot C	0.154±0.006 ^a	8.47±0.04 ^{bc}	87.64±0.32 ^a	99.47±0.28 ^a
Biopot D	0.134±0.003 ^b	8.82±0.04 ^c	142.82±0.50 ^d	155.86±0.17 ^d

Biopot A = 100% roots; Biopot B = 50% roots and 50% petioles; Biopot C = 50% roots and 50% leaves; Biopot D = 40% roots and 60% petioles.

Values (mean ± SD) with different lowercase superscript letters within same column differ significantly ($p < 0.05$) among treatments.

the range 7.21–8.82% (Table 2). Biopots C and D had slightly higher and more uniform moisture content than the other formulations, likely due to their higher fiber-to-binder ratios, which improved water retention. This relatively consistent moisture distribution is beneficial because it could reduce internal stress and cracking during drying, leading to a smoother surface and more stable biopot structure. The observed moisture levels were lower than the suggested upper limit of 14% (dry basis), indicating compliance with standard guidelines (Sari et al., 2023) and were lower than the 9.85% reported by Indrianti et al. (2023). A low moisture level suggests improved mechanical stability, enhanced dimensional integrity and greater storage suitability for practical agricultural applications (Jones et al., 2013). There was a positive trend between this result and the water absorption ability of the biopots.

The variation in moisture content and water-absorption capacity of biopots is influenced by differences in the chemical composition and physical characteristics of the raw materials. For example, hydrophilic components, such as cellulose and hemicellulose, increase the water-holding capacity (Edhirej et al., 2017), whereas hydrophobic components, such as lignin and lipids, reduce moisture absorption (Martins et al., 2024). Furthermore, fiber morphology, particularly fiber length and surface roughness, affects the matrix structure and porosity, with longer fibers enhancing inter-fiber bonding and compactness, thereby reducing water retention and contributing to lower moisture levels (Abe et al., 2021). Therefore, the moisture content and water absorption observed in the current study may be attributed to both density variation and the inherent structural and chemical properties of the WH. Biopot C had the lowest water absorption among all the tested formulations, which may be attributed to the formation of a denser and more compact matrix structure resulting from the combination of root and leaf fibers. The shorter leaf fibers (2.80 mm) likely facilitated tighter fiber packing and reduced pore formation within the biopot matrix, thereby limiting water penetration. In addition, the relatively high cellulose content in leaf fibers may have enhanced inter-fiber bonding and structural compactness during the thermopressing process. In contrast, there was higher water absorption in Biopot D, which was likely associated with the high hemicellulose content (38.96%) and longer fiber length (7.20 mm) of the petiole fibers. The hydrophilic and amorphous nature of hemicellulose readily promotes interaction with water molecules, while the longer fibers may reduce packing efficiency

and increase interconnected void formation within the matrix. Consequently, these characteristics facilitated greater moisture penetration and water uptake in Biopot D.

Furthermore, studies have shown that the porous, loosely packed nature of WH fibers promotes water absorption and biodegradability (Anirudh et al., 2024). The current results were consistent with those of Indrianti et al. (2023), who reported high water absorption (136–147%) in biopots produced from OPEFB supplemented with WH, attributing this to a porous network that enhanced moisture retention and decomposition rates. These findings provide context for interpreting the role of moisture and porosity in optimizing biopot performance.

Mechanical characteristics

Two parameters that determine the mechanical performance of biopots are compressive strength and the IRI. The combined evaluation of IRI and compressive strength is important in understanding the balance between toughness and rigidity in the composite. Compressive strength represents the ability of the material to withstand static loads, whereas IRI reflects its capability to absorb impact energy. Generally, higher compressive strength is associated with a denser and more rigid structure; however, excessive rigidity may reduce energy absorption capacity and lower the IRI value (Baley et al., 2018). In contrast, composites with a higher IRI tend to dissipate impact energy more effectively through mechanisms such as fiber pull-out and matrix deformation, which may reduce compressive strength (Asmara et al., 2021). Therefore, the relationship between IRI and compressive strength provides insight into fiber-matrix interaction and the structural behavior of the composite.

In the current study, the IRI values were in the range 61.5–98.5% (Fig. 2). Biopot B (50% each of roots and petioles) had the highest IRI among the tested formulations, whereas Biopot A (100% roots) had a lower IRI value. The overall trend in IRI values followed the order: Biopot A < Biopot D < Biopot C < Biopot B. Comparable trends were reported by Asmara et al. (2021), with their high IRI values in the range 98.98–99.41% in cassava stem-based biopots, supporting the current findings. The lignocellulosic composition strongly influences the IRI of biopots, with the lower IRI value of Biopot A perhaps due to its relatively low cellulose content and less favorable fiber characteristics. According to Table 1, Biopot A was composed entirely of root fibers that had the lowest cellulose content (2.93%) compared to the leaf and the petiole fibers. The limited cellulose content may have reduced the reinforcing efficiency of the fibers, consequently decreasing the impact resistance of the composite. Furthermore, the root fibers were shorter than in the petiole, resulting in less efficient stress transfer within the matrix. In addition, Biopot A had a lower density than Biopot B (Table 2), suggesting a less compact composite structure. Furthermore, the relatively low lignin content (approximately 18%) may have weakened fiber-matrix interfacial adhesion, thereby reducing the energy absorption capacity and resulting in lower IRI performance.

In contrast, the superior mechanical performance of Biopot B indicated the existence of an optimum fiber-matrix balance (50% roots and 50% petioles). Root fibers may enhance matrix compactness due to their shorter fiber morphology, whereas petiole fibers contribute to

improved stress transfer because of their greater fiber length. In Biopot B, the fibers were likely distributed more uniformly throughout the matrix, leading to improved interfacial bonding, more efficient stress distribution and fewer structural defects. Conversely, excessive incorporation of petiole fibers in Biopot D (60%) may have induced fiber agglomeration and void formation, thereby reducing the compressive resistance of the composite.

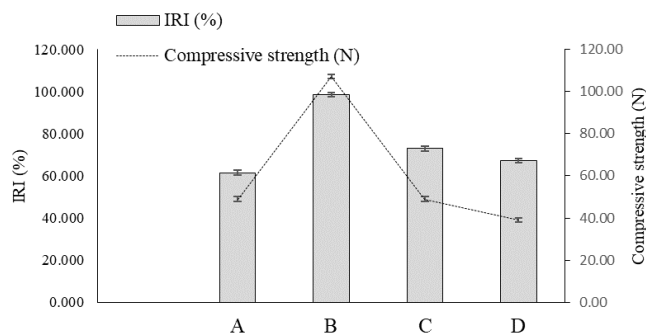


Fig. 2 Impact resistance index (IRI) and compressive strength of biopots containing different amounts of water hyacinth components (roots, leaves and petioles), where A = 100% roots, B = 50% roots and 50% petioles, C = 50% roots and 50% leaves, D = 40% roots and 60% petioles and error bars indicate $\pm$ SD.

Compressive strength represents a measure of a biopot's ability to resist axial loading without structural failure. In the current study, the compressive strength values were in the range 39.00–107.00 N (Fig. 2), with Biopot B having the highest compressive strength (107.00 N) and Biopot D having the lowest value (39.00 N). Based on these results, excessive petiole incorporation weakened the composite structure. The reduction in compressive strength was associated with both the chemical composition and morphology of the fibers. Although the petiole fibers contained relatively high lignin (which contributes to rigidity), they also had the highest hemicellulose content (38.96%) and the longest fiber length (7.20 mm). At high loading levels, these characteristics likely promoted fiber agglomeration, void formation and poor fiber dispersion within the matrix. This interpretation was consistent with the lower density and higher water absorption in Biopot D (Table 2), indicating a more porous structure with weaker fiber-matrix adhesion. Under compressive loading, these structural defects may act as stress concentration sites, accelerating material failure. Therefore, the proportion of petiole fibers should be optimized to achieve a balance between rigidity, porosity and mechanical stability.

Furthermore, the mechanical properties of biopots (mainly IRI and compressive strength) are significantly influenced by fiber length, material composition and fiber-matrix adhesion (Baley et al., 2018). Generally, shorter fibers enhance impact resistance, while longer fibers tend to improve tensile and flexural strength up to an optimal point (Sharma and Chaudhary, 2020). However, the excessively long fibers in petioles compared to roots and leaves (Table 1) may reduce compressive strength due to increased porosity (Kumar et al., 2008). This behavior was observed in Biopot D, which had a relatively moderate IRI despite having the lowest compressive strength. The

higher hemicellulose content and porous structure of Biopot D may have enhanced flexibility and energy absorption, while simultaneously weakening resistance to compressive deformation. Therefore, optimizing fiber length and material formulation is essential for producing biopots with balanced mechanical performance. The current study evaluated mechanical performance under dry conditions. Since biopots are intended for horticultural applications involving continuous moisture exposure, further studies are necessary under wet or saturated conditions to better understand structural stability during practical use.

Structural and morphological characterization

Although the presence of lignocellulosic components in WH is well established, FTIR and XRD analyses were conducted to confirm qualitatively the relative composition and structural characteristics of the different plant parts (roots, petioles, leaves) used in the biopot formulations. These analyses are crucial for ensuring the consistency and suitability of the raw materials, particularly with respect to crystallinity and functional groups, which can affect the mechanical strength, water resistance and biodegradability of the final product. The relative proportions of lignin, cellulose and hemicellulose play a critical role in determining these performance parameters.

FTIR spectroscopy was used to analyze the chemical composition of various biopot formulations composed of organic materials (roots, petioles, leaves), with white clay and PVAc added as matrix components. Spectral variations among the formulations reflect differences in functional group content. As shown in Fig. 3, the biopots had nearly identical spectral profiles. In general, their molecular structure was composed primarily of lignin, cellulose and hemicellulose. The FTIR spectra displayed a strong hydroxyl absorption band at 3200–3500 cm^{-1} , confirming the presence of lignocellulosic compounds. The peak around 1050 cm^{-1} was attributed to C–O stretching in cellulose and hemicellulose, while the peak near 1700 cm^{-1} corresponded to carbonyl groups in lignin. According to Deng et al. (2019), the absorption band at 3318 cm^{-1} indicated hydroxyl groups, the peak at 1030 cm^{-1} represented C–O stretching in cellulose and hemicellulose and the peak at 1734 cm^{-1} corresponded to C=O stretching in ketone, carbonyl and unconjugated ester groups.

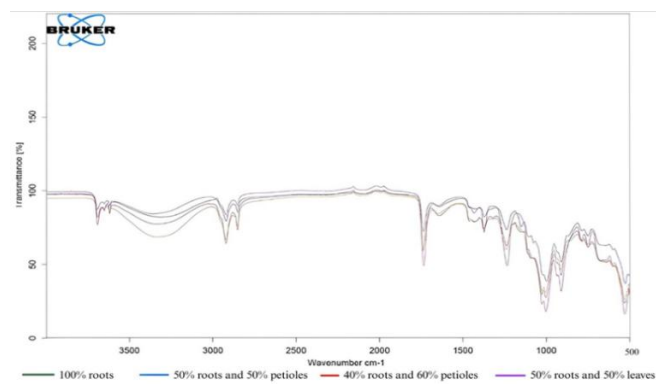


Fig. 3 Screen capture of Fourier-transform infrared spectroscopy spectra of four biopot formulations containing different amounts of water hyacinth components (roots, leaves and petioles).

The 100% root formulation (Biopot A) produced strong absorption around 3300 cm^{-1} (–OH groups, typical of lignocellulose) and a distinct band at 1630 cm^{-1} (C=O or H–O–H bending). In contrast, the combinations of root and petiole (50% roots and 50% petioles and 40% roots and 60% petioles, respectively) had decreased intensity in these regions, indicating a lower content of polar groups in the petioles. The root-leaf formulation (50% of each, Biopot C) had similar –OH absorption to the refined root sample but with increased intensity at $2900\text{--}3000\text{ cm}^{-1}$, suggesting the presence of lipid or waxy compounds derived from leaves. Absorption bands in the $1500\text{--}500\text{ cm}^{-1}$ range were more complex, reflecting greater functional-group diversity in the leaf components. White clay contributed to bands at $1000\text{--}1100\text{ cm}^{-1}$ (Si–O–Si or Si–O–Al), while PVAc was identified by bands around $1730\text{--}1750\text{ cm}^{-1}$ (C=O ester) and $2850\text{--}2950\text{ cm}^{-1}$ (C–H stretching of CH_3 and CH_2). Although minor, these signals confirmed the successful integration of PVAc. Overall, the FTIR analysis indicated that the composition of the biomass and the matrix additives influenced the chemical profile of the biopots.

The FTIR results supported the physical and mechanical behavior observed in the biopots. The formulations containing higher proportion of petioles had relatively lower intensity of hydroxyl-associated absorption bands, suggesting reduced surface polarity. Nevertheless, the high hemicellulose content and elongated fiber morphology of the petioles likely promoted moisture retention and the formation of a porous structure, which contributed to the high water absorption and low compressive strength observed in Biopot D. In contrast, the root-leaf formulation (Biopot C) had stronger absorption in regions associated with lipid and wax compounds, which may have contributed to reduced water penetration despite the high cellulose content of leaves.

The XRD analysis was conducted to evaluate the crystalline structure of the lignocellulosic material in the WH-based biopots (Fig. 4). The characteristic cellulose I diffraction peaks at $2\theta \approx 16^\circ$ (110) and 22° (200) indicated the semi-crystalline nature of the plant-derived cellulose. The root-dominant samples had sharper, more intense peaks, reflecting higher crystallinity and suggesting a greater proportion of crystalline cellulose, which would contribute to improved stiffness and tensile strength. In contrast, the formulations with higher proportions of petiole or leaf had broader, less defined peaks, indicative of increased amorphous fractions derived from hemicellulose and lignin. Lower crystallinity in these samples could be associated with reduced mechanical stability and structural cohesion in the biopots.

The higher crystallinity in the root-dominant and balanced root-petiole formulations may explain their superior compressive strength and structural integrity. Generally, crystalline cellulose regions improve stress transfer efficiency and matrix stiffness (Abe et al., 2021). Conversely, the broader diffraction peaks in Biopot D suggested increased amorphous content and reduced structural ordering, which may contribute to weaker fiber-matrix adhesion and lower resistance to compressive loading. In addition, the mechanical strength of biopots is influenced by their fiber morphology, which is a key factor affecting the structural integrity of material, with a robust material composition

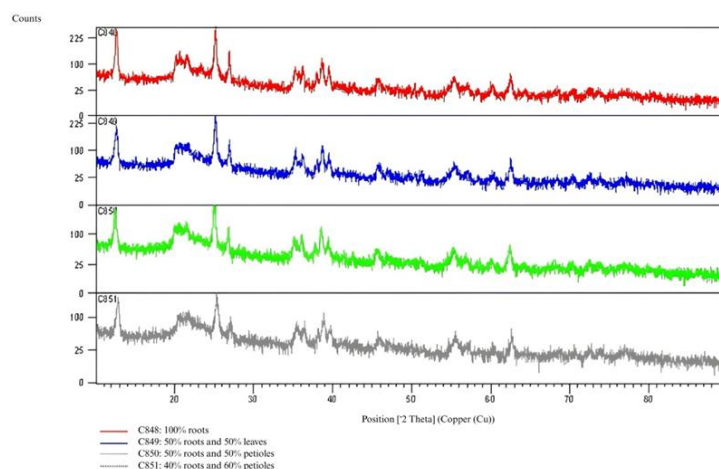


Fig. 4 XRD patterns of four biopot formulations containing different amounts of water hyacinth components (roots, leaves and petioles).

producing a biopot that is sturdy and durable, particularly in its ability to resist both tensile and compressive forces. Fig. 5 compares the biopot surface morphology across different components of WH. Using both petioles and roots as raw materials produced biopots with a more compact, uniform structure. The biopots formulated with 50% roots and 50% petioles had better morphological characteristics than the other variants. However, increasing the petiole concentration to 60% (Biopot D) reduced mechanical performance, which may have been due to the higher fiber content in the petioles compared to the roots and leaves. Inadequate mixing at higher fiber concentrations could have led to fiber agglomeration, potentially weakening the structural cohesion of the biopot.

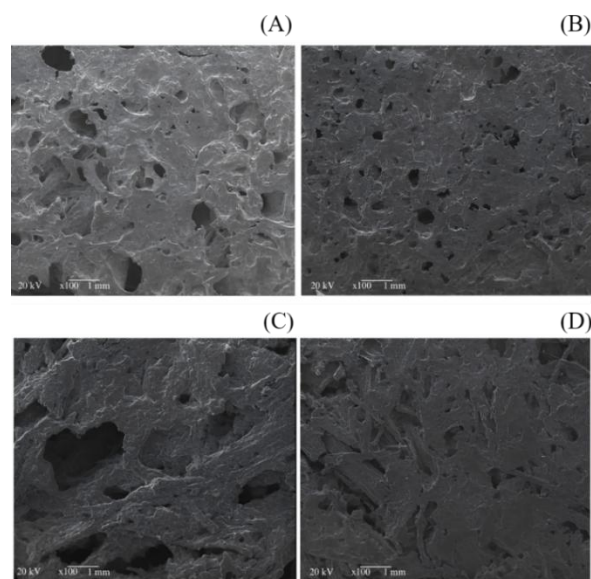


Fig. 5 Scanning electron micrographs showing morphological characteristics of four tested biopot formulations: (A) 100% roots; (B) 50% roots and 50% petioles; (C) 50% roots and 50% leaves; (D) 40% roots and 60% petioles. Scale bar = 1,000 μm .

Biopots made from roots (Biopot A) and from a mixture of roots and WH leaves (Biopot C) had open pore cavities, in contrast to those made from the root-petiole mixtures (Biopot B and Biopot D), which had a more compact and homogenous morphology due to the balanced incorporation of root and petiole fibers. This difference could be attributed to the anatomical characteristics and chemical composition of each part of the WH plant, with the roots and leaves having a looser, more porous tissue structure (Fig. 6), especially the leaves, which contain numerous intercellular spaces (aerenchyma) that naturally promote the formation of cavities (Shokry et al., 2020). In contrast, the petioles of the WH had a thicker structure and a higher lignin content. Lignin is a rigid and dense component of plant cell walls that reduces the likelihood of forming open pores in the final product.

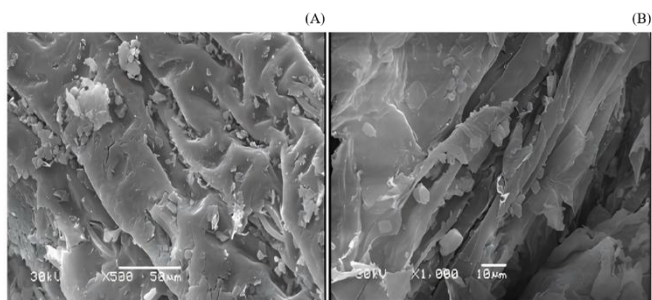


Fig. 6 Scanning electron micrographs showing morphological characteristics of water hyacinth: (A) petiole; (B) root.

Source: (Shokry et al., 2020)

Additionally, the leaves and roots had a relatively high initial moisture content and underwent greater shrinkage during drying, leading to the formation of gaps or cavities within the biopot structure, resulting in a more porous morphology. In addition, the softer texture of the leaves and roots facilitated crushing and mixing, ultimately producing biopot raw materials that were less dense. In contrast, the more rigid and fibrous petioles tended to retain their shape and density during molding, resulting in a more compact biopot structure with minimal open pores. Moderate incorporation of petiole fibers improved the matrix compactness and structural uniformity, as observed in Biopot B. However, excessive petiole loading (Biopot D) likely reduced fiber dispersion efficiency and promoted void formation despite the inherently rigid nature of petiole tissues.

Conclusions

This study demonstrated that the selection and proportion of WH components played a crucial role in the physical, structural and mechanical properties of the tested biopots. The biopot formulations containing equal amounts of roots and petioles demonstrated promising performance in terms of strength, porosity and structural integrity. In contrast, increasing the petiole proportion to 60% resulted in increased water absorption and reduced mechanical stability. Morphologically, the biopots containing roots and leaves had a more porous structure. Overall, based on the results, WH fibers, particularly from the roots and

petioles, may be considered as potential raw materials for biopot production. The current research has provided new insight into the role of WH parts in biopot formulation, offering guidance for future material design in sustainable agriculture. Further research is suggested to fully establish the viability and sustainability of these biopots involving biodegradation behavior, durability, degradation kinetics, economic feasibility studies and large-scale production assessments to better determine the practical applicability of these biopots.

Conflict of Interest

The authors declare that there are no conflicts of interest.

Acknowledgements

This research was supported by Lambung Mangkurat University from the Budget Implementation List (DIPA) of Lambung Mangkurat University 2024, Number: SP DIPA-023.17.2.677518/2024.

References

- Abe, M.M., Branciforti, M.C., Brienzo, M. 2021. Biodegradation of hemicellulose-cellulose-starch-based bioplastics and microbial polyesters. *Recycling* 6: 2–21. doi.org/10.3390/RECYCLING6010022
- Anirudh, M.K., Lal, A.M.N., Harikrishnan, M.P., et al. 2024. Sustainable seedling pots: development and characterisation of banana waste and natural fiber-reinforced composites for horticultural applications. *Int. J. Biol. Macromol.* 270: 132070. doi.org/10.1016/j.ijbiomac.2024.132070
- Asmara, S., Rahmawati, W., Suharyatun, S., Kurnia, B., Listiana, I., Widyastuti, R.A.D., 2021. Producing organic pot from cassava stem waste for water spinach (*Ipomea reptans* Poir) as waste management strategy. *IOP Conf. Ser.: Earth Environ. Sci.* 739: 012039 doi.org/10.1088/1755-1315/739/1/012039
- Baley, C., Lan, M., Bourmaud, A., Le Duigou, A. 2018. Compressive and tensile behaviour of unidirectional composites reinforced by natural fibers: influence of fibers (flax and jute), matrix and fiber volume fraction. *Mater. Today Commun.* 16: 300–306. doi.org/10.1016/j.mtcomm.2018.07.003
- Castronuovo, D., Picuno, P., Manera, C., Scopa, A., Sofo, A., Candido, V. 2015. Biodegradable pots for Poinsettia cultivation: agronomic and technical traits. *Sci. Hortic.* 197: 150–156. doi.org/10.1016/j.scienta.2015.09.025
- Deng, Z., Xia, A., Liao, Q., Zhu, X., Huang, Y., Fu, Q. 2019. Laccase pretreatment of wheat straw: effects of the physicochemical characteristics and the kinetics of enzymatic hydrolysis. *Biotechnol. Biofuels* 12: 120. doi.org/10.1186/s13068-019-1499-3
- Dölle, K., Tong, J., Wang, Q. 2020. Water hyacinths—biomass production potential at a waste water treatment plant. *J. Adv. Biol. Biotechnol.* 23: 1–10. doi.org/10.9734/jabb/2020/v23i230138

- Dölle, K., Wang, Q., Tong, J. 2021. Water hyacinths (*Eichhornia crassipes*)—application for secondary wastewater treatment and biomass production. J. Adv. Biol. Biotechnol. 24: 52–61. doi.org/10.9734/jabb/2021/v24i130196
- Edhirej, A., Sapuan, S.M., Jawaid, M., Zahari, N.I. 2017. Cassava/sugar palm fiber reinforced cassava starch hybrid composites: physical, thermal and structural properties. Int. J. Biol. Macromol. 101: 75–83. doi.org/10.1016/j.ijbiomac.2017.03.045
- Fuentes, R.A., Berthe, J.A., Barbosa, S.E., Castillo, L.A. 2021. Development of biodegradable pots from different agroindustrial wastes and byproducts. Sustain. Mater. Technol. 30: e00338. doi.org/10.1016/j.susmat.2021.e00338
- Indrianti, E., Rahmadi, A., Thamrin, G.A.R. 2023. Physical properties of the biodegradable pot (biopot) from oil palm empty bunches, *Eichhornia crassipes*, *Gliricidia maculata*, organic fertilizers and tapioca adhesive. J. Sylva Scientiae. 6: 758–763.
- Iriany, A., Sari, O.A.W., Hasanah, F. 2020. Optimization of biopot compositions made from water hyacinth and coconut coir for improving the growth and yield of chili (*Capsicum annum* L.). Int. J. Recycl. Org. Waste Agric. 9: 287–296. doi.org/10.30486/IJROWA.2020.1894411.1048
- Ishaya, A.A., Elinwa, A.U., Mohammed, I.Y. 2024. Water hyacinth plant fiber characterization. Int. J. Res. Sci. Innov. 22: 1172–1190. doi.org/10.51244/IJRSI
- Istirokhatun, T., Rokhati, N., Rachmawaty, R., Meriyani, M., Priyanto, S., Susanto, H. 2015. Cellulose isolation from tropical water hyacinth for membrane preparation. Procedia Environ. Sci. 23: 274–281. doi.org/10.1016/j.proenv.2015.01.041
- Jaya, J.D., Elma, M., Sunardi, S., Nugroho, A. 2022. Physical and mechanical properties of biodegradable pot derived from oil palm empty fruit bunch and sodium alginate. Braz. Arch. Biol. Technol. 65: e22210789. doi.org/10.1590/1678-4324-202210789
- Jones, A., Zeller, M.A., Sharma, S. 2013. Thermal, mechanical and moisture absorption properties of egg white protein bioplastics with natural rubber and glycerol. Prog. Biomater. 2: 12. doi.org/10.1186/2194-0517-2-12
- Kumar, K.S.S., Nair, C.P.R., Ninan, K.N. 2008. Effect of fiber length and composition on mechanical properties of carbon fiber-reinforced polybenzoxazine. Polym. Adv. Technol. 19: 895–904. doi.org/10.1002/pat.1056
- Martins, J.R., Llanos, J.H.R., Abe, M.M., Costa, M.L., Brienzo, M. 2024. New blend of renewable bioplastic based on starch and acetylated xylan with high resistance to oil and water vapor. Carbohydr. Res. 537: 109068. doi.org/10.1016/j.carres.2024.109068
- Pokharel, N.P., Dhakal, K., Panth, P., Koirala, R. 2024. Effect of different additives on nutrient parameter and palatability of ensiled water hyacinth (*Eichhornia crassipes*). Agric. Food Sci. Res. 11: 36–42. doi.org/10.20448/aesr.v11i2.5699
- Pratibha, Saha, S., Hariprasad, P. 2022. Paddy straw-based biodegradable horticultural pots: an integrated greener approach to reduce plastic waste, valorize paddy straw and improve plant health. J. Clean. Prod. 337: 130588. doi.org/10.1016/j.jclepro.2022.130588
- Sari, N.M., Violet, Nisa, K., Ajar, S. 2021. Characteristics and testing of organic pots based on waste glam [sic] skin (*Melaleuca cajuputy* [sic]) and water hyacinth (*Eichhornia crassipes*) polybag substitute. J. Hutan Trop. 9: 310–315.
- Sari, N.M., Violet, Nisa, K., Noor, M.J. 2023. Testing of organic pots based on materials of glam skin waste (*Melaleuca cajuputi*), hyacinth (*Eichhornia crassipes*) and manure. Russ. J. Agric. Socio-Econ. Sci. 137: 119–128. doi.org/10.18551/rjoas.2023-05.12
- Sharma, A., Chaudhary, R. 2020. Review of effect of fiber length on the mechanical properties of bio-composites. In: International Conference of Advance Research and Innovation. Meerut, India, pp. 67–70.
- Shokry, H., Elkady, M., Salama, E. 2020. Eco-friendly magnetic activated carbon nano-hybrid for facile oil spills separation. Sci. Rep. 10: 10427. doi.org/10.1038/s41598-020-67231-y
- Stiers, I., Crohain, N., Josens, G., Triest, L. 2011. Impact of three aquatic invasive species on native plants and macroinvertebrates in temperate ponds. Biol. Invasions 13: 2715–2726. doi.org/10.1007/s10530-011-9942-9
- Tadesse, S., Berhie, H., Kifle, B., Tesfaye, G. 2022. Production and characterization of bio-diesel from water hyacinth (*Eichhornia crassipes*) of Lake Koka, Ethiopia. Am. J. Appl. Chem. 10: 62. doi.org/10.11648/j.ajac.20221003.11
- Villamagna, A.M., Murphy, B.R. 2010. Ecological and socio-economic impacts of invasive water hyacinth (*Eichhornia crassipes*): a review. Freshw. Biol. 55: 282–298. doi.org/10.1111/j.1365-2427.2009.02294.x
- Wahdan, N.F., Okafor, Asmara, S., Kuncoro, S. 2022. Utilization of cassava stem waste and oil palm empty fruit bunches (OPEFB) as basic material for organic seedling pots. J. Agric. Biosyst. Eng. 1: 401–412.
- Zaborowska, M., Bernat, K., Pszczółkowski, B., Kulikowska, D., Wojnowska-Baryła, I. 2023. Assessment of biodegradability of cellulose and poly(butylene succinate)-based bioplastics under mesophilic and thermophilic anaerobic digestion with a view towards biorecycling. Waste Manage. 168: 413–422. doi.org/10.1016/j.wasman.2023.06.022