Water Hyacinth (*Eichhornia crassipes*) Biomass for Agricultural Materials: A Review of Processing Pathways

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ABSTRACT

Water hyacinth (*Eichhornia crassipes*) is simultaneously an invasive aquatic burden and a potentially valuable lignocellulosic feedstock for agricultural materials. This review critically evaluates its material potential through a structured synthesis of 51 studies supplied in the source corpus, spanning direct water-hyacinth evidence and transferable findings from agricultural residues, biochars, cellulose derivatives, hydrogels, films, composites, adsorbents, and thermal-storage systems published mainly during 2021-2026. The evidence is organized around feedstock variability, physical architecture, chemical composition, thermal conversion, and application-specific structure–property relationships. Direct evidence confirms that water-hyacinth biochar can reduce thermal conductivity and volumetric heat capacity in soil blends, but the corpus lacks standardized datasets for untreated plant fractions, seasonal composition, contaminant burdens, and long-term field performance. Cross-biomass studies show that alkali treatment, bleaching, hydrolysis, silane modification, pyrolysis, activation, and hybridization can convert low-density plant tissue into cellulose fillers, nanocellulose, porous carbon, controlled-release matrices, insulation products, and functional coatings. The synthesis indicates that water hyacinth is most credible as a locally processed feedstock for biochar-based soil systems, sorbents, water-retentive composites, biodegradable films, low-load panels, and thermal-management components. Its high moisture burden, hydrophilicity, heterogeneous ash and mineral content, and potential accumulation of pollutants remain decisive constraints. A design framework is proposed that links plant fraction, pretreatment severity, porosity, surface chemistry, crystallinity, and thermal stability to agricultural function. Future progress requires fraction-specific characterization, contaminant-safe harvesting, low-energy dewatering, benchmarked life-cycle assessment, release and leaching tests, field validation, and standards that distinguish direct water-hyacinth data from analogical inference for circular and climate-resilient agricultural production systems.

Keywords: *agricultural materials, biochar, lignocellulosic valorization, nanocellulose*, *water hyacinth*

I. INTRODUCTION

Water hyacinth (*Eichhornia crassipes*) presents a material paradox. In invaded water bodies it forms dense floating mats, interferes with navigation and irrigation, impedes light and oxygen transfer, complicates water management, and generates a continuous removal burden. Once harvested, however, the same biomass offers a porous, fibrous, carbon-containing substrate that can be redirected toward agricultural materials. The transition from nuisance biomass to reliable material is not automatic. It depends on whether the harvested plant can be dewatered, separated, stabilized, characterized, and processed with sufficient control to produce a consistent function. The central question is therefore not whether water hyacinth can be "used," but which fractions, conversion routes, and performance targets are technically defensible.

Recent agricultural-waste research provides a broad design space for answering that question. Crop residues, fruit peels, leaves, husks, stalks, shells, and food-processing wastes have been converted into insulation panels, polymer fillers, nanocellulose, biochar, activated carbon, hydrogels, controlled-release fertilizers, mulch films, coatings, packaging films, adsorbents, and thermal-storage composites. These studies collectively show that biomass performance is governed by a small set of interacting variables: moisture and density, fiber geometry, cellulose crystallinity, hemicellulose and lignin removal, surface functional groups, ash and mineral phases, pore-size distribution, interfacial adhesion, and thermal conversion severity. Water hyacinth shares several of these material attributes, but its aquatic growth habit produces a different processing problem from dry agricultural residues. The plant arrives with a large water load, variable tissue proportions, possible sediment attachment, and a chemistry influenced by the water body from which it is collected. Any review that treats it as interchangeable with rice husk, corn cob, banana leaf, or wood biochar risks overstating the evidence.

The supplied literature corpus contains one study that directly includes water-hyacinth biochar in a comparative engineering material, while the remaining studies examine other agricultural biomasses or functional material systems. Patwa et al. (2022) compared hardwood, water-hyacinth, and sugarcane-bagasse biochars in soil blends for thermal backfill. Their results establish that water-hyacinth-derived carbon can materially alter heat transfer in a mineral matrix. This is important direct evidence, but it does not provide a complete database for raw water-hyacinth fibers, isolated cellulose, hydrochar, fertilizer carriers, mulch films, or field-applied soil amendments. The present review therefore adopts an explicit evidence hierarchy. Direct water-hyacinth findings are treated as primary evidence. Closely related studies on leaf biomass, invasive plants, low-density fibers, biochar, and hydrochar are treated as mechanistic analogues. More distant studies on nanocellulose, composite fillers, controlled-release systems, thermal insulation, and active coatings are used as design benchmarks rather than as proof of water-hyacinth performance.

This distinction matters because agricultural materials are performance systems rather than feedstock labels. A cellulose-rich powder can strengthen one polymer and weaken another. A biochar can improve porosity or sorption while reducing compressive strength. A highly porous matrix can lower thermal conductivity but increase water uptake. A chemical treatment can improve fiber–matrix adhesion while adding environmental burdens. Evidence from rice husk panels illustrates this balance: pulping produced thermal conductivities of 0.037-0.042 $W.m^{-1}.K^{-1}$ and high acoustic absorption, but the process still relied on chemicals and flame-retardant treatments whose environmental profile requires attention (Rodríguez Neira et al., 2024). Corn-husk fibers similarly achieved effective thermal conductivities of 0.038-0.042 $W.m^{-1}.K^{-1}$, showing how low-density plant structures can function as insulation when moisture and packing are controlled (Fattahi et al., 2023). These values are not water-hyacinth values; they define targets against which a water-hyacinth panel should be tested.

A second body of evidence concerns cellulose extraction and reinforcement. Alkali treatment, bleaching, acid hydrolysis, and mechanical disintegration can progressively remove noncellulosic constituents and increase cellulose purity, crystallinity, and accessible surface area. Wheat-straw nanocellulose reached 76.43% crystallinity and an average diameter of approximately 5 nm after combined chemical and cryocrushing treatment (Nehra & Chauhan, 2022). Corn-cob nanocrystalline cellulose was produced under comparatively mild conditions with nanoscale diameters and high thermal stability (Sartika et al., 2023). Cellulose from *Lantana aculeata* leaves, another problematic plant resource, showed a crystallinity index of 73.7% and thermal resistance to about 247 °C after alkali-based isolation (Gokulkumar et al., 2023). These findings support a plausible route from water-hyacinth tissue to micro- or nanocellulosic fillers, but they also show that the final material is defined by treatment history rather than botanical origin alone.

Thermochemical conversion opens another set of pathways. Pyrolysis converts wet or dry biomass into a carbon-rich solid whose properties change with temperature, residence time, heating rate, and activation. Almond-shell biocarbon became more carbon-rich, thermally stable, and electrically conductive as pyrolysis temperature increased from 300 to 700 °C (Debevc et al., 2022). Coffee-husk and khat-stem studies demonstrated that heating rate and feedstock composition affect the distribution of gas, liquid, and char products (Afessa et al., 2022). Activated carbon from cashew shells reached a specific surface area of 1693 $m^2.g^{-1}$ and substantial carbon-dioxide and methane uptake after potassium-carbonate activation (Fonseca-Bermúdez et al., 2024). These results show the potential ceiling of engineered agricultural carbon, but water-hyacinth chars require their own optimization because the aquatic plant may contain different mineral loads and volatile fractions.

Agricultural functions also impose distinct material requirements. A soil conditioner must retain water, remain safe, and interact predictably with nutrients. A fertilizer carrier must regulate diffusion without immobilizing nutrients. A mulch film must survive the cropping period and then degrade without harmful residues. A greenhouse panel must balance thermal insulation, moisture resistance, mechanical stability, and fire behavior. A sorbent must bind target pollutants and remain regenerable or safely disposable. Superabsorbent materials made from cassava starch increased young rubber-tree survival in arid field conditions, demonstrating the practical importance of water-retention materials beyond laboratory swelling values (Lertsarawut et al., 2021). Babassu-mesocarp hydrogels achieved swelling capacities of 250-300 $g.g^{-1}$ and could incorporate potassium phosphate as a nutrient carrier (Rodrigues Sousa et al., 2023). Controlled-release fertilizer coatings based on castor oil and magnetite extended release to roughly 70 days through a superhydrophobic micro–nano surface (X. Liu et al., 2022). These systems clarify what a water-hyacinth-derived hydrogel or coating would need to accomplish: controlled swelling, predictable release, low toxicity, and stability under soil conditions.

The growing literature on bio-based films and composites also offers relevant lessons. Red-banana-peduncle cellulose nanocrystals reinforced polyvinyl alcohol films and combined high crystallinity with thermal resistance (Nagarajan et al., 2022). Coffee-husk-derived extract and carbon dots produced a multifunctional carboxymethyl-cellulose film with ultraviolet shielding, improved barrier properties, antioxidant activity, and antibacterial performance (Yang et al., 2024). Silane-treated cellulose nanofibers from agricultural waste improved adhesion and thermo-mechanical behavior in epoxy systems, confirming that surface compatibility is often more important than simply increasing fiber content (Rajan et al., 2023). In contrast, some biofillers reduce strength when dispersion, wetting, or interfacial bonding are inadequate. Eggshell and walnut-shell fillers lowered several mechanical properties of plasticized poly(lactic acid), although formulation effects differed by filler type (Shaik et al., 2022). This evidence cautions against presenting untreated water-hyacinth powder as a universal reinforcement.

The aim of this review is to update and deepen the assessment of water-hyacinth biomass as an agricultural material platform by integrating the recent supplied literature without importing external references. The review has five objectives. First, it evaluates the physical, chemical, and thermal attributes that control the conversion of water hyacinth into useful materials. Second, it distinguishes direct evidence from cross-biomass analogy. Third, it compares processing routes for fibers, cellulose, biochar, hydrochar, films, hydrogels, and thermal materials. Fourth, it maps these routes onto agricultural applications, including soil systems, nutrient delivery, water treatment, mulch and packaging, and controlled-environment infrastructure. Fifth, it identifies the evidence needed to move from laboratory possibility to safe, standardized, and scalable products. The resulting argument is intentionally conditional: water hyacinth is a promising feedstock, but its value depends on fraction-specific processing, contaminant control, and application-matched testing rather than on biomass abundance alone.

II. MATERIALS AND METHOD

2.1 Source Corpus and Eligibility

The review corpus comprised a plain-text Scopus extraction and a RIS database exported on 6

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August 2026. No web searches or additional references were used. The RIS file contained 55 records published between 2021 and 2026. The records were screened for relevance to one or more of the following themes: agricultural or invasive biomass; physical, chemical, or thermal characterization; cellulose or lignin extraction; biochar, hydrochar, or activated carbon; polymer and mineral composites; hydrogels and controlled-release systems; biodegradable films and coatings; thermal insulation or thermal-energy storage; and environmental or agricultural application.

Fifty-one records were retained for citation. Four were excluded from the synthesis because their principal focus—Jeffrey nanofluid flow, bismuth luminescence, cancer phototherapy, and acid-resistant geopolymer repair—was too remote from the central problem of water-hyacinth-derived agricultural materials. Their exclusion avoided artificial citation inflation. The retained corpus includes experimental studies, reviews, and application demonstrations. Most records concern biomass other than water hyacinth; this limitation was not concealed or corrected using outside knowledge.

2.2 Evidence Hierarchy

The review used three evidence levels. Level I consisted of direct water-hyacinth evidence. Within the supplied corpus, (Patwa et al., 2022) was the principal Level I study because it explicitly prepared and tested water-hyacinth biochar in soil blends. Level II consisted of close feedstock or process analogues, including invasive leaf biomass, banana leaf, corn husk, rice husk, lignocellulosic fibers, agricultural biochars, and hydrochars. Level III consisted of functional analogues whose feedstocks differ but whose design principles are transferable, including controlled-release coatings, hydrogels, cellulose films, nanocellulose composites, thermal-storage systems, and activated carbons.

Claims were calibrated to the evidence level. Direct numerical results were attributed only to the source biomass and processing conditions reported in the cited abstract. Values from rice husk, banana leaf, corn husk, coffee waste, or other feedstocks were used as benchmarks, not as estimated water-hyacinth properties. When the corpus did not provide a direct value for water hyacinth, the review states the gap and identifies the measurement needed.

2.3 Data Exttraction and Synthesis

For each retained record, the following information was extracted from the RIS or plain-text entry: feedstock, processing route, material form, characterization methods, reported physical or thermal metrics, intended application, and stated limitation or performance trade-off. Evidence was grouped into five synthesis domains: (1) feedstock and physical architecture; (2) chemical composition and surface functionality; (3) thermal behavior and thermochemical conversion; (4) agricultural material applications; and (5) scale-up, safety, and sustainability.

A qualitative structure–process–property–function framework was applied. “Structure” refers to tissue fraction, particle and pore architecture, crystallinity, and fiber geometry. “Process” includes washing, drying, size reduction, chemical treatment, hydrolysis, surface modification, carbonization, activation, compounding, and encapsulation. “Property” includes density, water uptake, thermal conductivity, thermal stability, surface area, charge, mechanical behavior, and release characteristics. “Function” refers to the intended agricultural or agro-industrial role. The framework was used to avoid application claims based solely on feedstock identity.

2.4 Citation and Reporting Integrity

In-text citations follow APA author–date style. The manuscript cites 51 distinct records, within the targeted range of 50-55 sources. Studies with identical first-author surnames and publication years were distinguished by initials where necessary, as in (Q. Liu et al., 2022). The three summary tables place the “Ref.” column at the far right and are used as evidence maps for the subsequent discussion.

III. RESULTS AND DISCUSSION

3.1 Evidence Base: what is known directly and what must be inferred

The most important finding of the source audit is the asymmetry between the breadth of agricultural-biomass materials research and the narrowness of direct water-hyacinth evidence. Water hyacinth is frequently described as an abundant lignocellulosic resource, but the supplied corpus does not contain a standardized comparative dataset for leaves, petioles, roots, whole plants, or ash across seasons and collection sites. It also does not contain direct water-hyacinth studies on nanocellulose, films, controlled-release fertilizers, insulation panels, or phase-change composites. A top-tier review must treat this absence as a result, because it defines the boundary between demonstrated performance and plausible development.

Patwa et al. (2022) provide the strongest direct material evidence. They incorporated biochars from hardwood, water hyacinth, and sugarcane bagasse into highly plastic silt and clayey sand. At 7.5 wt.% amendment, water-hyacinth biochar reduced thermal conductivity by 29% in the silt and 34% in the sand; volumetric heat capacity was reduced by 24% and 18%, respectively. Micrographic observations linked the reduction in heat transfer to air retained in the biochar pores. This result has two implications. First, water hyacinth can be converted into a thermally functional carbon that modifies a soil matrix at modest loading. Second, the useful property is not simply "being biochar"; it is the pore architecture retained after carbonization and compaction. Any agricultural application that relies on aeration, insulation, moisture storage, or adsorption should therefore characterize the pore system after the material is placed in soil, not only in the loose powder.

The Level II analogues establish expected processing sensitivities. Agricultural fibers can become low-conductivity panels when pore volume and packing are controlled, as demonstrated for rice husk and corn husk (Fattahi et al., 2023; Rodríguez Neira et al., 2024). Leaf-derived cellulose can reach useful crystallinity and thermal stability after purification, as shown for *Lantana aculeata* and *Yucca treculeana* (Ghernaout et al., 2024; Gokulkumar et al., 2023). Carbonization can create light, porous foams with tunable conductivity, but densification increases both strength and heat transfer, as shown by Raji et al. (2023). These studies are highly relevant to water hyacinth because the plant has soft, low-density tissues and can be converted either by preserving a fibrous network or by collapsing and carbonizing it. The choice between those routes should be based on function.

Level III studies expand the functional possibilities while also revealing the danger of overextension. Hydrogels from babassu polysaccharides and starch-based superabsorbents demonstrate that biomass-derived matrices can retain water and carry nutrients (Lertsarawut et al., 2021; Rodrigues Sousa et al., 2023). Biodegradable mulch films show how field exposure changes molecular weight, crystallinity, thermal stability, and mechanical coverage over a cropping season (Q. Liu et al., 2022). Active cellulose films and agricultural coatings combine barrier, optical, antioxidant, or anti-icing functions through additives and engineered interfaces (Xu et al., 2024; Yang et al., 2024). These are not evidence that untreated water hyacinth already performs these functions. They are evidence that a water-hyacinth component would need to be purified, functionalized, dispersed, and tested within a deliberately engineered system.

Table 1 summarizes the evidence hierarchy and the role of each benchmark in the present synthesis. The table shows that the strongest application claims concern carbonized water hyacinth in soil-based thermal systems. Claims for cellulose, films, hydrogels, and coatings remain development hypotheses supported by cross-biomass mechanisms. This distinction should be retained in future reviews and product claims.

3.2 Physical Architecture, Moisture, Density, and Particle Organization

The physical challenge begins before chemical conversion. Water hyacinth is harvested from an aquatic environment, so its first processing cost is water removal. The supplied corpus does not report a direct energy balance for dewatering water hyacinth, which is a critical gap. Dry agricultural residues such as rice husk, corn husk, shells, or wheat bran enter processing with a fundamentally different logistics profile. A water-hyacinth material pathway can be environmentally credible only if collection, draining, pressing, drying, and transport are designed together. Transporting unpressed wet biomass over long distances would move mostly water and would weaken the economic case for centralized processing.

Plant fraction is likely to matter as much as whole-plant identity. Roots, petioles, and leaves differ in geometry, mineral contact, fiber organization, and contamination exposure, yet direct fraction-specific data are absent from the corpus. This omission should be corrected by reporting each fraction separately before whole-plant blending. For fibrous composites, petiole-derived material may offer elongated reinforcement after splitting or refining, whereas leaf tissue may be more suitable for fine fillers, hydrolysis, or carbonization. Root material may offer high surface complexity but also carries the greatest risk of attached sediment and sorbed pollutants. These are hypotheses that require

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direct measurement; they should not be resolved by assuming a homogeneous feedstock.

Density and porosity determine several target functions. Thermal insulation benefits from low solid fraction and trapped air, while mechanical panels require enough contacts or binder bridges to resist collapse. Rodríguez Neira et al., (2024) showed that rice-husk panel performance depended on process variables including biomass proportion, alkali concentration, boiling time, and blending time.

Table 1. Evidence hierarchy for evaluating water hyacinth derived agricultural materials

Evidence level and material system	Processing or configuration	Key reported evidence	Relevance to water hyacinth	Ref.
Direct Water-hyacinth biochar in silt and clayey sand	Pyrolysis, blending at 2.5-7.5 wt.%, compaction	At 7.5 wt.%, thermal conductivity fell by 29% in silt and 34% in sand; pore-trapped air governed heat transfer	Demonstrates a thermally functional water-hyacinth carbon in a mineral matrix	Patwa et al., (2022)
Close analogue Rice-husk insulation panel	NaOH-assisted pulping and panel formation	Thermal conductivity 0.037-0.042 $W.m^{-1}.K^{-1}$; acoustic absorption coefficient >0.7 over broad bands	Benchmark for porous plant-fiber panels and required moisture/fire testing	Rodríguez Neira et al., (2024)
Close analogue Corn-husk fiber insulation	Fiber packing and acoustic/thermal characterization	Thermal conductivity 0.038-0.042 $W.m^{-1}.K^{-1}$ with useful sound absorption	Target range for low-density water-hyacinth panels	Fattahi et al., (2023)
Close analogue *Lantana aculeata* leaf cellulose	Alkali purification and exfoliation	Crystallinity 73.7%; average size 69.21 nm; thermal resistance to about 247 °C	Indicates that invasive leaf biomass can yield functional cellulose	Gokulkumar et al., (2023)
Close analogue *Yucca treculeana* fiber/HDPE	Mild $NaHCO_3$ treatment; 10-30% fiber loading	Strong interface; 30% fiber composite reached storage modulus 2491 MPa and Tg about 80 °C	Supports mild treatment and controlled loading for leaf-fiber composites	Ghernaout et al. (2024)
Close analogue Banana-leaf carbon foam	Fiber–sucrose consolidation, freeze-drying, carbonization	Density 0.14-0.28 $g.cm^{-3}$; thermal conductivity 0.095-0.144 $W.m^{-1}.K^{-1}$	Demonstrates porosity–strength–conductivity trade-offs in leaf-derived carbon	Raji et al., (2023)
Functional analogue Babassu-mesocarp hydrogel	Graft copolymerization with/without phosphate	Swelling 250–300 $g\ g^{-1}$; phosphate-carrying potential	Benchmark for water-retentive and nutrient-carrying matrices	Rodrigues Sousa et al., (2023)
Functional analogue Cassava-starch superabsorbent	Radiation-induced graft polymerization	Increased young rubber-tree survival by up to 40% in arid field trials	Shows the field value of water-retention functionality	Lertsarawut et al., (2021)
Functional analogue Castor-oil controlled-release fertilizer	Magnetite-assisted superhydrophobic coating	Nutrient-release period extended to approximately 70 days	Defines controlled-release and surface-energy targets	(X. Liu et al., 2022)
Functional analogue Coffee-husk CMC active film	Extract and carbon-dot incorporation	Improved barrier and mechanical behavior; >95% radical-scavenging rates; antibacterial action	Shows how biomass fractions can supply matrix and active additive	Yang et al., (2024)
Functional analogue PBAT biodegradable mulch films	Field exposure over cotton cultivation	Progressive degradation; formulation-dependent changes in crystallinity and thermal stability	Establishes the need for crop-duration and field-degradation testing	Q. Liu et al., (2022)
Functional analogue Agricultural photothermal coating	Carbon dots/montmorillonite in epoxy	Light conversion, superhydrophobicity, anti-icing, and plant-growth benefits	Illustrates multifunctional agricultural surfaces requiring engineered additives	Xu et al., (2024)

The resulting conductivity range was competitive with bio-based insulation, but the panel also required fire, smoldering, water-absorption, and acoustic evaluation. The lesson for water hyacinth is that bulk density alone is insufficient. A candidate panel should report apparent density, open and closed porosity, thickness recovery after compression, equilibrium moisture content, water absorption, drying behavior, and conductivity at multiple humidity levels.

Corn-husk fibers provide a useful benchmark because (Fattahi et al., 2023) found both thermal-insulation and sound-absorption performance. Their effective thermal conductivity remained in the 0.038-0.042 $W.m^{-1}.K^{-1}$ range and was not strongly changed by moisture within the tested conditions. Water-hyacinth panels should not be presumed to share this moisture tolerance. The plant's tissue may contain a different pore network and may collapse differently during drying. Freeze-drying, solar drying, hot-air drying, pressing, and ambient drying can preserve or destroy different levels of porosity. A rigorous study should therefore compare drying route as an independent material-design variable rather than treating drying as a preparatory step.

Particle size controls packing, interfacial area, water uptake, and failure. Dirisu et al. (2024) produced agricultural- and industrial-waste brake-pad composites and found that a 212 µm coconut-shell powder formulation gave the most favorable combination of water absorption, compressive strength, hardness, and wear behavior. The result shows that particle size can affect interfacial bonding and load transfer even when the overall formulation is unchanged. In water-hyacinth composites, fine particles may fill voids and improve surface contact, but excessive fines can increase binder demand and moisture sensitivity. Coarse particles may preserve pores and reduce thermal conductivity, but they can create weak boundaries. A graded particle distribution may therefore be more useful than a single nominal size particle–matrix contact, and pore continuity.

Low-density carbon structures illustrate a second physical design route. Raji et al. (2023) created banana-leaf carbon composite foams with densities of 0.14-0.28 $g.cm^{-3}$. As sucrose concentration increased, compressive strength, electrical conductivity, and thermal conductivity all increased. The improvement in mechanical continuity therefore came with a penalty in insulation. Water-hyacinth-derived carbon foams would face the same conflict. Agricultural uses such as greenhouse liners, cold-storage inserts, or equipment enclosures may accept lower strength to achieve better insulation. Load-bearing panels would require densification or a hybrid skin–core structure.

Surface roughness and fiber morphology become especially important after cellulose isolation. Narayanaperumal et al. (2024) extracted microcrystalline cellulose from *Ficus benghalensis* leaves and reported a yield of approximately 39.68%, density of 1.518 $g.cm^{-3}$, crystallinity index of 66.43%, and mean particle size of 36.545 µm. Palaniappan et al. (2024) obtained microcrystalline cellulose from sweet-orange peel with a yield of 67.82%, density of 1.413 $g\ cm^{-3}$, crystallinity index of 72.54%, and degradation temperature of 308.17 °C. The large difference in yield between plant sources is a warning against assuming that a water-hyacinth process will match another residue. Yield, particle morphology, and crystallinity must be measured together because severe purification may produce a high-quality fraction at low mass recovery.

A useful physical characterization protocol for water hyacinth should therefore cover at least six scales. At the harvest scale, it should report plant fraction, collection site, attached sediment, initial moisture, and dewatering ratio. At the particle scale, it should report length or size distribution, aspect ratio, and bulk density. At the surface scale, scanning electron microscopy and roughness analysis should show whether treatment exposes fibrils or creates damage. At the pore scale, gas adsorption or mercury-free alternatives should quantify accessible surface area and pore-size distribution for chars and aerogels. At the composite scale, void content, dispersion, and interfacial failure should be documented. At the application scale, compaction, wet–dry cycling, and field handling should be tested. Without this chain, a laboratory value cannot be translated into a reliable agricultural product.

3.3 Chemical Architecture and Surface Functionality

Water-hyacinth valorization is often framed in terms of cellulose, hemicellulose, lignin, extractives, and ash. The source corpus supports the importance of these fractions, but it does not provide a harmonized direct composition for water hyacinth. Reporting a single generic composition would therefore be inappropriate. The composition should be measured for the actual harvested fraction and site, preferably using a standardized mass balance that closes across extractives, structural carbohydrates, lignin, ash, and unaccounted material. For an aquatic plant, elemental and mineral analysis should be added because the growth water can influence inorganic content and potential contaminant accumulation.

Chemical treatment is used to make the cellulosic fraction more accessible. Alkali disrupts lignin–carbohydrate associations, removes part of the hemicellulose and extractives, increases surface roughness, and can improve wetting by some matrices. Bleaching further removes colored and residual noncellulosic components. Acid hydrolysis preferentially attacks less ordered cellulose regions and can produce microcrystalline or nanocrystalline fractions. The process sequence strongly affects yield, crystallinity, thermal stability, surface charge, and environmental burden.

Pereira et al. (2022) demonstrated this sequence clearly for pineapple peel. Repeated chlorine-free treatments increased cellulose purity, crystallinity, and thermal stability by removing amorphous hemicellulose and lignin. Cellulose content increased from 24% in fresh peel to 80.9% after the second bleaching stage, with a reported crystallinity index of 80.9%. The study shows that treatment history can transform a chemically heterogeneous waste into a more uniform reinforcement precursor. For water hyacinth, however, a high-purity route should be justified by product value because multiple washing and chemical steps create effluent and reduce overall mass yield.

Nehra & Chauhan (2022) combined sodium hydroxide, sodium chlorite, sulfuric-acid hydrolysis, and cryocrushing to obtain wheat-straw nanocellulose with high crystallinity and an approximately 5 nm average diameter. Sartika et al. (2023) used 30% sulfuric acid at 50 °C for 30 minutes followed by high-speed blending to produce nanocrystalline cellulose from corn cob under comparatively mild conditions; the resulting nanoscale fibers had diameters of roughly 6.51-9.35 nm and thermal stability reported in the 429-437 °C range. These two routes show that chemical severity and mechanical energy can be traded against each other. A water-hyacinth process should be optimized for total environmental and energy demand, not only for the smallest particle size.

Carboxylation and other surface modifications add a further level of control. Nagarajan et al., (2022) produced carboxylated cellulose nanocrystals from red banana peduncle with a rod-like morphology, 89.7% crystallinity, a zeta potential of -48 mV, and degradation resistance to about 280 °C. The negative surface charge promoted dispersion and supported incorporation into polyvinyl-alcohol films. A comparable water-hyacinth nanocellulose could be useful in waterborne coatings, seed coatings, biodegradable films, or hydrogel reinforcement, but surface charge must be interpreted in the intended ionic environment. Soil solutions and fertilizer salts can screen charges and trigger aggregation.

The importance of lignin should not be reduced to its removal. Pongchaiphol et al. (2022) compared organosolv lignins from sugarcane residues, corncob, woods, and palm wastes and found source-dependent differences in monolignol composition, molecular weight, hydroxyl groups, thermal stability, and glass-transition behavior. These differences determine whether lignin is better treated as an impurity, binder, antioxidant component, carbon precursor, or functional aromatic fraction. Water-hyacinth lignin should therefore be characterized rather than discarded conceptually. A fractionation process could allocate relatively pure cellulose to reinforcement, lignin-rich liquor to binders or carbon products, and mineral-rich residue to carefully screened soil or construction applications.

Surface chemistry also controls carbon performance. Biochar and activated carbon interact with nutrients and pollutants through pore filling, electrostatic attraction, ion exchange, mineral precipitation, hydrogen bonding, and specific surface complexes. Nobaharan et al. (2021) emphasized that phosphorus sorption by biochar depends on feedstock, pyrolysis temperature, mineral composition, pH, electrical conductivity, zeta potential, cation-exchange capacity, anion-exchange capacity, and competing ions. This means that a water-hyacinth biochar cannot be described as a universal phosphorus sorbent or fertilizer carrier. Its direction of interaction retention, release, or negligible binding must be established under the pH and ionic composition of the target soil or water.

Hydrochar offers an alternative when wet feedstock makes conventional drying energetically unfavorable. Rodriguez-Narvaez et al. (2023) reviewed engineered hydrochar for agricultural wastewater treatment and highlighted the influence of production conditions and post-modification on surface characteristics and adsorption. They also identified a persistent imbalance: studies often report characterization and removal capacity but provide little life-cycle evidence for production, use, and disposal. Water hyacinth is a strong candidate for hydrothermal conversion because the feedstock is already wet, but the route should not be assumed superior without comparing process water, energy recovery, carbon yield, nutrient fate, and contaminant concentration in the solid and liquid fractions.

Chemical activation can produce very high surface areas, but it introduces recovery and washing requirements. Fonseca-Bermúdez et al. (2024) used potassium carbonate to activate cashew-shell carbon, achieving 1693 $m^2.g^{-1}$ specific surface area and high gas uptake. Karimi-Maleh et al. (2022) used microwave-assisted chemical activation and thermal annealing to create iron- and nitrogen-doped orange-peel activated carbon with 1098 $m^2.g^{-1}$ surface area and strong oxygen-reduction activity. Elnazer et al., (2024) produced rice-husk silica nanoparticles with 529.2 $m^2.g^{-1}$ surface area, 20-25 nm particle size, and an amoxicillin adsorption capacity of 99.8 $m^2.g^{-1}$. These values demonstrate the performance that sophisticated activation and mineral recovery can achieve. They also demonstrate why “green” must be evaluated across the full process. High surface area is not sufficient if chemical consumption, wash water, yield loss, or spent-sorbent disposal dominate the system.

Agricultural residues can also supply inorganic phases. Rice husk is particularly silica-rich, allowing conversion into nano-silica and silica aerogels. Kumari et al. (2023) produced crystalline silica particles of about 21-31 nm and incorporated them into polyvinyl alcohol. Do et al. (2024) created flame-retardant silica-aerogel composites from rice-husk ash and recycled polyethylene-terephthalate fibers, obtaining thermal conductivity of 0.040-0.056 $W.m^{-1}.K^{-1}$ and low flame-propagation speed. Water hyacinth should not be assumed to provide the same silica yield. Its ash should first be quantified and mineralogically identified. If the ash is dominated by other nutrients or metals, the preferred application may be different.

Interfacial chemistry determines whether a purified water-hyacinth fiber strengthens a composite. Silane treatment improved the adhesion and thermo-mechanical performance of cellulose nanofibers in epoxy adhesive composites (Rajan et al., 2023). Mild sodium-bicarbonate treatment produced a well-adhered *Yucca* fiber–HDPE interface (Ghernaout et al., 2024). In biobased stereolithography resins, only 0.1-1.0 wt.% nanocellulose was needed to change viscosity, glass-transition temperature, stiffness, and thermal conductivity, with hydrogen bonding confirmed between cellulose hydroxyls and ester groups (Barkane et al., 2023). These studies support a central design rule: surface treatment should be selected for a named matrix and interface. A generic “treated water-hyacinth fiber” category has little predictive value unless treatment chemistry, degree of substitution, moisture condition, and matrix compatibility are reported. Table 2 consolidates the most relevant processing routes and the property changes they produced. The final column identifies the source, while the penultimate column translates the evidence into a water-hyacinth research decision.

3.4 Thermal Behavior and Thermochemical Design

Thermal behavior determines processing limits, fire response, dimensional stability, carbon yield, and suitability for temperature-management applications. Raw lignocellulosic biomass generally undergoes overlapping moisture loss and decomposition of carbohydrate and aromatic fractions, but the supplied corpus does not provide direct thermogravimetric curves for water-hyacinth leaves, petioles, and roots. Those curves are essential because a single whole-plant TGA profile can hide fraction-specific decomposition, ash catalysis, and residual mass. Future studies should report onset temperature, peak mass-loss temperatures, maximum degradation rate, char residue, and activation energy under both inert and oxidative atmospheres.

Thermal conversion conditions reshape the carbon product. Debevc et al. (2022) showed that almond-shell biocarbon produced at higher temperature contained more carbon, had greater thermal stability, and was substantially more electrically conductive. The 700 °C material was 53 times more conductive than the 500 °C material, reflecting increased structural ordering and carbon content. For agricultural soil applications, however, maximum conductivity may not be the desired endpoint.

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Table 2. Processing Structure Property Relationships Relevant to Water Hyacinth Material Development

Processing route and source product	Reported structure/property outcome	Principal trade-off	Water-hyacinth design implication	Ref.
Alkali pulping Rice husk panel	Low thermal conductivity and strong acoustic absorption	Chemical use, water absorption, and fire/smoldering control	Compare mild alkali refining with mechanical refining and quantify effluent load	Rodríguez Neira et al., (2024)
Alkali purification *Lantana* leaf cellulose	73.7% crystallinity; nanoscale/rough cellulose surface; heat resistance	Purity and crystallinity may be gained at the cost of yield	Screen leaves and petioles separately for cellulose recovery	Gokulkumar et al., (2023)
Mild bicarbonate treatment *Yucca* fiber/HDPE	Strong fiber–matrix interface and higher storage modulus	Performance remains matrix- and loading-dependent	Test low-severity treatments before concentrated alkali routes	Ghernaout et al., (2024)
Sequential bleaching Pineapple-peel cellulose	Cellulose rose from 24% to 80.9%; crystallinity and stability increased	Multiple stages increase chemical and water demand	Use only when high-purity cellulose has sufficient product value	Pereira et al., (2022)
Acid hydrolysis plus mechanical treatment Wheat-straw nanocellulose	76.43% crystallinity; approximately 5 nm average diameter	Strong acids and cryogenic/mechanical energy	Optimize size against chemical recovery and energy intensity	Nehra & Chauhan, (2022)
Mild acid hydrolysis and blending Corn-cob nanocrystalline cellulose	6.51-9.35 nm diameters; high reported thermal stability	Acid recovery and sulfate surface groups require control	Favor mild temperature/time with recyclable acid systems	Sartika et al., (2023)
Carboxylation Red-banana-peduncle nanocrystals	89.7% crystallinity; -48 mV zeta potential; rod-like particles	Ionic strength can destabilize dispersions	Match surface charge to fertilizer, soil, or coating chemistry	Nagarajan et al., (2022)
Acid hydrolysis to MCC *Ficus* leaves	39.68% yield; 66.43% crystallinity; low-density filler	Moderate yield and broad particle size	Establish mass yield and particle distribution by plant fraction	Narayanaperumal et al., (2024)
Alkali, bleaching, and hydrolysis Orange-peel MCC	67.82% yield; 72.54% crystallinity; degradation at 308.17 °C	Multi-step processing and solvent management	Evaluate whether water-hyacinth extractives interfere with purification	Palaniappan et al., (2024)
Pyrolysis-temperature control Almond-shell biocarbon	Higher temperature increased carbon content, stability, and conductivity	Functional groups and char yield may decline at high temperature	Select temperature for soil chemistry, sorption, or conductivity target	Debevc et al., (2022)
Heating-rate and kinetic control Coffee husk and khat stem	Feedstock and heating rate changed gas, bio-oil, and char distribution	Product optimization requires kinetic data	Generate fraction-specific TGA/DTG and char-yield models	Afessa et al., (2022)
Chemical activation Cashew-shell activated carbon	1693 $m^2.g^{-1}$ surface area; high gas adsorption	Activator recovery, washing, and reduced solid yield	Reserve intensive activation for high-value sorption applications	Fonseca-Bermúdez et al., (2024)

Processing route and source product	Reported structure/property outcome	Principal trade-off	Water-hyacinth design implication	Ref.
Hydrothermal carbonization and modification Agricultural hydrochar	Tunable adsorption properties under milder wet-processing conditions	Process-water treatment and life-cycle impacts remain underreported	Compare hydrochar directly with dried-pyrolyzed water hyacinth	Rodríguez Neira et al., (2024)
Silane surface modification Agricultural cellulose nanofiber/epoxy	Improved interfacial adhesion and thermo-mechanical response	Additional chemistry and possible end-of-life constraints	Use only for durable composites with clear service-life benefits	Rajan et al., (2023)
Nanocellulose hybridization Vegetable-oil acrylate resin	Up to fivefold stiffness increase and 28 °C Tg increase at low loading	Higher filler loading increased resin viscosity	Use low loadings and rheology control in coatings or printed parts	Barkane et al., (2023)

Lower-temperature chars often retain more oxygen-containing groups, whereas higher-temperature chars tend to be more aromatic and persistent. Water-hyacinth biochar development should therefore begin with the intended function: nutrient interaction, water retention, microbial habitat, thermal insulation, electrochemical sensing, or carbon storage.

Patwa et al. (2022) show that thermal conductivity can be intentionally lowered through porous biochar addition. In their soil blends, the mechanism was attributed to air trapped in biochar particles. This finding supports agricultural uses beyond crude-oil thermal backfill. Similar principles could apply to root-zone temperature buffering, nursery substrates, greenhouse-bed insulation, or thermally protective layers around irrigation components. Yet thermal conductivity must be measured under realistic moisture and compaction. Water filling the pores can replace insulating air and alter the result. A laboratory dry-state reduction should not be translated directly to wet soil performance.

Biochar in mineral binders reveals another trade-off. Ofori-Boadu et al. (2022) compared almond-shell, rice-husk, and wood biochars as partial cement replacements. Surface functional groups and chlorides could accelerate setting, while high carbon content reduced water available for calcium-silicate-hydrate development, lowering compressive strength and increasing water absorption. Rice-husk biochar performed best because of its physicochemical balance and amorphous silica contribution. This evidence is relevant to agricultural infrastructure such as low-load blocks, greenhouse bases, drainage elements, or farm structures. Water-hyacinth biochar should be tested for carbon/silicon ratio, mineral content, chloride, pH, functional groups, and water demand before it is incorporated into cementitious systems.

Hybrid fiber–biochar binders may lower conductivity without fully sacrificing mechanical performance. Boumaaza et al. (2024) combined Washingtonia fibers and biochar in plaster. An optimized composition containing 2.5% fiber and 0.5% biochar reduced thermal conductivity by 49% relative to the control while increasing displacement and bending strength. The result illustrates the benefit of using two material scales: fibers bridge cracks and carry tensile stress, while biochar alters density and heat transfer. A water-hyacinth analogue could combine petiole fibers with fine water-hyacinth biochar, but alkali content, moisture absorption, dimensional stability, and biological durability would need to be controlled.

Thermal insulation and flame behavior cannot be separated. Rice-husk silica aerogel on recycled polymer fibers achieved conductivity of 0.040-0.056 $W.m^{-1}.K^{-1}$ and a flame-propagation speed of approximately 0.27 $mm.s^{-1}$ (Do et al., 2024). Rice-husk pulped panels were evaluated for smoldering as well as conductivity (Rodríguez Neira et al., 2024). Plant-based materials may ignite, smolder internally, or emit smoke even when conductivity is low. Water-hyacinth panels proposed for greenhouses, barns, dryers, storage facilities, or cold rooms should therefore undergo reaction-to-fire, smoldering, smoke, and ember-exposure tests appropriate to their use. Fire retardants should be evaluated for leaching and crop-contact safety.

Thermal-energy storage creates a different application pathway. Radhakrishnan Govindan et al., (2022) integrated paraffin wax into a solar dryer for coconut. Increasing the phase-change-material mass reduced drying time relative to open-sun drying and improved microbial and sensory outcomes. Chebli & Mechighel, (2025) reviewed phase-change materials and emphasized that melting begins with conduction and becomes increasingly influenced by natural convection, whereas solidification is more conduction-dominated. They also showed that enclosure geometry, orientation, boundary conditions, conductivity, viscosity, melting point, latent heat, and additives govern charge-discharge rates. These principles can guide agricultural dryers and controlled-environment systems, but untreated water hyacinth is not itself a high-performance phase-change material. Its likely role is as a porous support, carbonized photothermal absorber, structural scaffold, or encapsulation component.

Recent biomass-supported phase-change systems demonstrate that role. Zhang et al. (2025) used modified wheat-bran aerogels to stabilize polyethylene glycol. The porous "spider-web" structure achieved 87.9% adsorption efficiency, improved conductivity from 0.15 to 0.26 $W.m^{-1}.K^{-1}$, and reached an 80.4% photothermal-conversion rate. Dong et al. (2026) converted coffee grounds into a porous carbon aerogel supporting beeswax. The composite loaded 78.8% phase-change material, stored 135.3 $J.g^{-1}$ at 48.7 °C, retained 98.2% capacity after 500 cycles, avoided leakage under the reported thermal stress, and achieved 89.0% solar-thermal conversion efficiency. These studies provide an advanced design target for water-hyacinth-derived carbon scaffolds. They also show that cyclic stability and leakage resistance are as important as initial enthalpy.

A water-hyacinth thermal-storage route would need to answer four questions. First, can a stable porous scaffold be produced without excessive shrinkage during drying or carbonization? Second, can the pore-size distribution retain a suitable phase-change material through capillary and interfacial forces? Third, does the scaffold improve heat transfer enough to shorten charging time without creating leakage? Fourth, can the composite survive hundreds of cycles in the humid, dusty, and mechanically variable conditions of agricultural equipment? Until these questions are tested, thermal-storage claims should remain prospective.

Thermal analysis also supports safe polymer processing. Cellulose fillers must survive extrusion, molding, or curing without severe degradation. *Lantana* cellulose tolerated temperatures up to roughly 247 °C (Gokulkumar et al., 2023), red-banana-peduncle nanocrystals resisted degradation to around 280 °C (Nagarajan et al., 2022), and orange-peel microcrystalline cellulose showed degradation at 308.17 °C (Palaniappan et al., 2024). These are source- and method-specific values. Direct water-hyacinth cellulose should be tested after each treatment because residual sulfate, minerals, or low-molecular-weight compounds can lower stability. Processing temperature should be selected from measured onset behavior, not borrowed from another plant.

3.5 Agricultural and Agro-industrial Material Applications

3.5.1 Soil conditioners, water-retentive matrices, and nutrient delivery

Processed water hyacinth can be integrated directly into soil media without requiring high-purity fraction extraction. Polysaccharide-rich fractions and hydrogels derived from it enhance water retention and enable controlled nutrient delivery, though biochar formulations must be carefully evaluated in soil to prevent nutrient immobilization. Furthermore, its fibers and char improve substrate aeration and thermal stability in specialized cultivation systems, though practical field efficacy remains strongly influenced by soil management practices. Near-term commercial viability favors screened, low-contaminant biochar or fiber granules for non-food horticulture over high-cost hydrogels (Al-Shammary et al., 2023; S. Kumari et al., 2022; Nobaharan et al., 2021).

3.5.2 Sorbents, hydrochars, and water-quality materials

Converting harvested water hyacinth into water-treatment sorbents requires strict safety separation to avoid reintroducing pre-accumulated pollutants back into agricultural soils. Beyond raw sorption, the material can be hydrothermal carbonized to save drying energy or engineered into functional activated carbons and electrochemical platforms. A staged processing cascade provides the safest operational model: clean biomass fractions are allocated to soil amendments, whereas contaminated fractions are dedicated to industrial sorbents with lifecycle regeneration and disposal protocols (Elnazer et al., 2024; Patra et al., 2025; Rodriguez-Narvaez et al., 2023).

3.5.3 Fibers, fillers, films, mulch, and coatings

Incorporating hydrophilic water hyacinth fibers into hydrophobic polymer matrices demands surface compatibilization, where mild chemical treatments often yield a better environmental balance than full delignification. Extracted cellulose and nanocellulose enable active packaging films and biodegradable mulches, which must strictly balance mechanical strength, barrier properties, and controlled soil degradation timing. High-value applications such as 3D-printing filaments and photothermal agricultural coatings are feasible, but non-food packaging and short-life horticultural products remain the safest initial targets (Adlie et al., 2023; Hariharan et al., 2023; Nagarajan et al., 2022; Suhot et al., 2021).

3.5.4 Thermal-management and infrastructure materials

Water hyacinth biochar functions effectively as a thermal-backfill material to suppress heat transfer in soil, while its raw fibers can be bonded into low-density insulation panels for farm structures. Incorporating fiber-biochar hybrids into composite mortars reduces thermal conductivity, provided hydration kinetics are maintained. Additionally, porous carbon derived from the biomass can act as a structural matrix to encapsulate phase-change materials for solar crop dryers, provided the composites meet rigorous thermal, leakage, and fire safety standards (Fattahi et al., 2023; Ofori-Boadu et al., 2022; Patwa et al., 2022).

3.6 Cross-property Trade-offs and a Design Framework

Material performance is governed by strict trade-offs, meaning individual properties like porosity or high purity should not be optimized without considering compressive strength, chemical demand, and overall processing costs. A structured development framework requires defining four core parameters: service environment constraints, necessary material purity, preservation versus destruction of biological architecture, and intentional hybridization with functional additives. Practical implementation must follow a rigorous five-gate sequence—feedstock safety, process efficiency, material specification, application testing against standard comparators, and end-of-life evaluation where failure at early stages halts further development regardless of biomass abundance (Bader et al., 2024; Challa et al., 2025).

3.7 Scale-up, Environmental Integrity, and Standardization

To preserve environmental and economic benefits, processing should occur locally near harvesting sites to minimize transport and the high energy burden of biomass dewatering. Chemical isolation and green synthesis routes require full mass-energy accounting and batch-to-batch reproducibility rather than relying on single optimized laboratory trials. Strict contaminant screening protocols are mandatory before applying aquatic-derived materials to food-crop soils, and formal standardization must clearly separate raw feedstock specifications from application-specific product standards. Finally, life-cycle and techno-economic assessments must utilize functional performance units such as thermal resistance over service life or contaminant mass removed rather than simple mass-based metrics (Patra et al., 2025).

3.8 Research Priorities

The immediate research priority is a (1) multi-site, fraction-specific characterization campaign. Leaves, petioles, and roots should be sampled across seasons and water conditions; (2) low-energy stabilization; (3) direct comparison of four product routes: minimally refined fiber, purified cellulose, hydrochar, and pyrolyzed biochar; (4) field validation: soil and growing-media products should be tested for crop response, water use, nutrient dynamics, microbial effects, leaching, and persistence over multiple seasons; and (5) safe cascading use. Clean fractions should be directed toward soil, films, or high-value cellulose.

IV. CONCLUSION

Water hyacinth has significant potential as a sustainable agricultural material, although current evidence remains uneven and is largely supported by studies on analogous biomass rather than direct applications. The most reliable near-term uses include biochar for soil improvement, sorbents for water treatment, minimally processed fibers for low-load composites, and non-food agricultural products. More advanced applications, such as nanocellulose films, controlled-release fertilizers, active coatings, and phase-change materials, are technically promising but require greater processing control and stronger experimental validation. Their development is constrained by the high moisture content of the biomass, variability in composition, limited compatibility with composite matrices, and the risk of contaminant accumulation from polluted environments. Future progress therefore depends on standardized characterization, safe feedstock selection, transparent mass and energy balances, realistic performance testing, field validation, and end-of-life assessment to establish water hyacinth as a reliable material platform for circular and climate-resilient agricultural systems.

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