

# Eco-HyPack: Smart, Strong, and Sustainable

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**Abstract:** *Industrial packaging remains encumbered by composite heterogeneity, elevated embodied energy, and end of life intransigence that impede circularity and regulatory conformity. This study reports a low-specific gravity bio hybrid composed of alkali pretreated lignocellulosic fibers from Eichhornia crassipes (water hyacinth) co integrated with post-consumer corrugated cellulose. Alkaline pulping de-lignifies and unveils hydroxyl functionalities, intensifying interfacial adhesion, fiber-matrix compatibilization, and hygro-dimensional stability across variable moisture activities. The resultant laminate exhibits an increased tensile modulus to density ratio, enabling volumetric utilization gains and attenuated transportation energy intensity. By concurrently valorizing invasive aquatic biomass and recovering secondary fibers, the platform mitigates landfill flux, displaces virgin carton board, and reduces scope 3 burdens while obviating VOC laden polymeric laminates. Process intensification emphasizes aqueous chemistries, low temperature refining, and disassembly legible bonding, thereby enhancing recyclability, compostability, and benign depolymerization pathways. Life cycle-relevant indicators evidence substantive decrements in carbon intensity relative to conventional carton board baselines, aligning with emergent eco conformity thresholds targeting recyclability, Volatile Organic Compound (VOC) minimization, and embodied carbon ceilings. Collectively, the composite operationalizes techno ecological symbiosis- transmuting nuisance biomass into a high throughput, structurally robust packaging medium- while instituting a scalable, compliance forward route to fiber dominant, end of life legible architectures. Mechanical robustness and process compatibility are retained without sacrificing dimensional stability, establishing a manufacturable pathway for circular industrial logistics.*

**Keywords:** Lignocellulosic bio hybrid, Water hyacinth fibers, Corrugated cellulose, Alkali pretreatment, Fiber-matrix adhesion, Tensile modulus to density ratio, Biomass valorization, Recyclability and compostability, Low embodied carbon materials, Circular packaging systems, Hygro-dimensional stability, VOC free packaging

## 1. Introduction

Water hyacinth (*Eichhornia crassipes*) is a free-floating aquatic plant widely recognized for its rapid growth and invasive nature in freshwater ecosystems. Native to the Amazon basin, it has now spread across tropical and subtropical regions, forming dense mats that obstruct waterways, reduce biodiversity, and hinder human activities such as fishing, irrigation, and transportation<sup>0</sup>. Its extraordinary growth rate doubling every 5–15 days has led to severe ecological impacts, including waterway blockage, reduced oxygen levels, and disruption of aquatic ecosystems. Despite its ecological challenges, water hyacinth has gained considerable attention as a renewable biomass resource due to its high cellulose content, low cost, and year-round availability [2].

Structurally, the plant possesses thick, buoyant petioles and long fibrous roots that grow densely beneath the water surface. These parts contain significant amounts of cellulose and hemicellulose, allowing the extraction of natural fibers suitable for various applications. The fibers are lightweight, flexible, porous, and biodegradable, making them attractive for sustainable material development. Water Hyacinth Fiber has been increasingly explored in the textile and handicraft sector. Extracted fibers are woven into products such as baskets, mats, ropes, furniture elements, and decorative items. Their aesthetic appeal and eco-friendly nature make them popular in artisanal industries. Beyond traditional crafts, the fiber shows potential in composite manufacturing. When combined with natural or synthetic resins, water hyacinth fibers improve thermal insulation and reduce material density, enabling use in low-load structural boards, packaging materials, and eco-friendly construction components [3].

Environmental applications also form a significant area of interest. Due to its porous structure, Water Hyacinth Fiber acts as an effective biosorbent for removing dyes, heavy metals, and pollutants from wastewater. Additionally, the plant's biomass serves as a feedstock for biofuel production, including biogas and bioethanol. In papermaking, its cellulose-rich fibers provide a sustainable alternative for handmade paper and small-scale pulp industries[4].

## 2. Abbreviations

VOC	Volatile Organic Compound
AKA	Alkyl Ketene Dimmer
ASA	Alkenyl Succinic Anhydride

## 3. Botanical Characteristics of Eichhornia Crassipes (Water Hyacinth)

Water hyacinth is a free floating, perennial hydrophyte native to the Amazon basin that has naturalized across tropical and subtropical regions and is widely listed as an invasive aquatic macrophyte. Morphologically, plants form compact rosettes of thick, glossy leaves that range from ovate to rounded; blades are typically held above the water by inflated, spongy petioles whose aerenchymatous tissue confers buoyancy and stabilizes the lamina at the air-water interface[5]. The petiole inflation varies with crowding and light, becoming more bulbous in open conditions and more elongated under dense canopies, reflecting phenotypic plasticity typical of aquatic invaders.



Figure 1



Figure 3



Figure 2



Figure 4

The root system comprises pendent, highly fibrous/feathery roots (often dark purple black) with extensive lateral branching. These fine roots substantially increase surface area for nutrient uptake and entrapment of suspended particulates, contributing to rapid growth and the plant's efficacy in nutrient rich or eutrophic waters. Vegetative propagation is prolific via stolons producing daughter ramets, enabling the formation of dense surface mats that impede light penetration and gas exchange in underlying waters; under favorable conditions, mat area can be double within ~6–18 days. **Error! Reference source not found..**

#### 4. Biomass, Composition, Properties and Applications

##### 4.1 Carton Board: Biomass, Composition, Properties and Applications

Carton Board is a fiber-dominant cellulosic material manufactured from renewable lignocellulosic biomass, recognized for its favorable strength-to-weight characteristics, printability, and compatibility with circular packaging systems. Its production relies on a combination of virgin wood fibers, recovered paper streams, and increasingly, non-wood biomass sources, enabling a versatile and resource-efficient platform for structural packaging applications[6]. Modern Carton Board grades are engineered to balance mechanical performance, surface quality, and functional barrier properties while conforming to emerging sustainability regulations targeting recyclability, carbon reduction, and chemical safety.

Biomass used in Carton Board manufacturing is dominated by softwood and hardwood fibers obtained from sustainably managed forests. Softwood fibers (from pine, spruce, and fir) are long, slender, and rich in cellulose microfibrils, contributing to tensile strength and bulk. Hardwood fibers (eucalyptus, birch, poplar) are shorter and more flexible, improving smoothness, opacity, and surface uniformity. Recovered fibers including old-corrugated containers, mixed office waste, and post-consumer Carton Board form a major feedstock in recycled grades[7]. Their integration reduces energy consumption, diverts waste from landfills, and lowers the overall carbon footprint. Emerging alternative biomasses such as bagasse, wheat straw, bamboo, and aquatic plants offer additional pathways to diversify fiber supply while reducing dependence on virgin forestry resources.

Compositionally, Carton Board is a multilayered composite comprising cellulose, hemicellulose, and lignin in varying proportions depending on pulping method and fiber type. Cellulose typically dominates at 50–85%, forming the structural backbone that imparts strength, stiffness, and dimensional stability. Hemicelluloses support fiber swelling and bonding, while residual lignin contributes to rigidity and hydrophobicity, especially in unbleached kraft pulps. Mineral fillers, such as kaolin clay and calcium carbonate, are incorporated to enhance opacity, print quality, and surface smoothness. Starch-based binders and sizing agents improve inter-fiber bonding, moisture resistance, and sheet integrity[8]. Functional coatings including biopolymer dispersions, water-based barriers, or thin polymer laminates are applied to deliver grease, moisture, or oxygen resistance for food-contact applications. Mechanically, Carton Board exhibits a favorable stiffness-to-density ratio, enabling lightweight packaging designs that maintain structural reliability. Its creaseability and foldability allow efficient converting into cartons, sleeves, trays, and displays[9]. Surface properties smoothness, brightness, and controlled porosity support high-resolution printing essential for

branding and regulatory labeling. Although inherently hydrophilic, functional coatings can elevate its moisture and vapor barrier performance, extending its applicability into frozen foods, dairy, and refrigerated products. Thermal stability during converting operations, combined with low odor and migration characteristics, further supports its acceptance in sensitive sectors such as pharmaceuticals and cosmetics [10].

Applications of Carton Board span both commodity and specialized packaging markets. In fast-moving consumer goods, it forms the structural backbone of cereal cartons, beverage multipacks, detergent boxes, and retail display units. In food packaging, coated grades are used for trays, takeaway containers, and chilled-food applications. The pharmaceutical industry relies on its purity, printability, and tamper-evident converting characteristics for medicine cartons and blister packaging backings. Premium sectors including cosmetics, electronics, and luxury goods utilize high-brightness, smooth-surface grades for visually appealing and structurally robust packaging. Beyond packaging, Carton Board is used in stationery, display boards, craft materials, and as a substrate for laminated composites.

#### 4.2 Water Hyacinth Fiber: Biomass, Composition, Properties and Applications

Water hyacinth (*Eichhornia crassipes*) is a highly productive aquatic macrophyte known for its rapid biomass accumulation and cellulose-rich tissues, making it an increasingly attractive resource for fiber, composites, and environmental applications. Its productivity ranks among the highest recorded for aquatic plants, with growth rates of 29–73% per week in nutrient-rich waters and annual dry biomass yields exceeding  $100 \text{ t}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$  in certain tropical regions. Field studies in Mexico report peak yields of  $\sim 144 \text{ t}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ , following a characteristic sigmoidal growth pattern and short duplication times under warm, nutrient-rich condition [11]. Anatomically, water hyacinth is adapted to floating environments through extensive aerenchyma within its petioles and stems. These air-filled tissues reduce density, improve buoyancy, and allow gas exchange in hypoxic water bodies. Additional adaptations include waxy, water-repellent leaves and erect inflorescences that aid pollination [12]. While the plant is capable of sexual reproduction, most population expansion in invaded ecosystems occurs through rapid clonal growth.

Biochemically, water hyacinth is a lignocellulosic biomass rich in cellulose (typically 35–55%, reported up to >60% in some petiole fibers), with hemicellulose (15–30%) and lignin (5–15%) comprising the remaining structural polymers. Variations arise from organ type, growth stage, and analytical methods, but studies consistently highlight its high cellulose content an important attribute for fiber extraction, pulp production, and composite reinforcement. Fiber extraction generally targets petioles and stems. Mechanical extraction methods, including decortication and crushing, provide quick fiber recovery while limiting microbial degradation. Chemical retting most commonly alkaline NaOH treatments removes pectins and lignin, increasing fiber separation and surface roughness, which improves bonding in bio-composites. Microbial retting offers an environmentally

gentle alternative, producing softer fibers despite slower processing times. Water hyacinth fibers are lightweight, soft, and porous due to their aerenchymatous tissue structure. Although mechanically weaker than bast fibers such as jute or coir, their properties can be significantly improved through chemical treatments that enhance fiber–matrix adhesion. The high absorbency of the fibers makes them suitable for mats, insulation products, and sorbent materials, though hydrophobic modifications are often applied to mitigate moisture sensitivity. Their biodegradability further supports applications in sustainable material development. The combination of low density, biodegradability, and cellulose richness positions water hyacinth fibers for diverse technical and non-technical uses. In the textile and handicraft sector, dried fibers are woven into baskets, mats, ropes, and furniture components, supporting artisanal industries [15]. In engineering applications, the fibers reinforce polymer matrices (epoxy, polyester, and biopolymers) for lightweight panels, insulation boards, and eco-friendly packaging. Environmental uses include biosorption of heavy metals, phytoremediation, composting, and oil spill cleanup using modified fiber mats. In the pulp and paper industry, the plant provides an alternative cellulose source for handmade paper and packaging sheets [16]. Emerging research explores biomedical potentials such as biobased dressings, hydrogels, and nanocellulose production for composite reinforcement and scaffold materials.

### 5. Combining of Water Hyacinth Fiber and Recycled Carton Board Material (Material Composition Rationale)

#### 5.1. Recycled Carton Board Base (70%)

##### 5.1.1 Overview

Recycled carton board serves as the dominant component of the EcoHyPack composite, making up 70% of the overall material matrix. Its production begins with the repulping of post-consumer wastepaper, which is mechanically disintegrated in water to separate fibers. This slurry is then passed through a series of screening and cleaning stages to remove contaminants such as inks, plastics, and adhesives. Once purified, the pulp undergoes sheet formation and pressing, restoring fiber cohesion and enabling reuse in composite manufacturing.

Depending on the mechanical performance required, the recycled carton board component may be layered, corrugated, or densified to enhance rigidity and load bearing strength. The repulped fibers retain a high proportion of their original cellulosic structure, which is crucial for forming strong hydrogen bonds during recombination with water hyacinth fibers. This inherent structural integrity allows recycled carton board to function effectively as the primary reinforcing phase in composite sheet formulations, ensuring stability, durability, and reliable performance in packaging applications [17].

##### 5.1.2 Structural and Mechanical Role

Recycled carton board serves as the primary structural backbone within the composite, functioning as the main load-bearing phase responsible for transmitting and distributing mechanical forces. During the repulping process, its cellulose

fibers rehydrate, disperse, and re-establish a network that reconnects through extensive hydrogen bonding once the sheet is dried. These inter-fiber bonds generate the tensile strength, compressive resistance, and bending stiffness necessary for applications such as protective packaging, rigid panels, and molded fiber components [18]. Even though the fibers inevitably shorten and lose some flexibility with repeated recycling cycles, they retain enough fibrillation and surface area to maintain meaningful inter-fiber contact. This preserved bonding capacity allows recycled carton board to deliver dependable stiffness, durability, and dimensional stability. Its continued resilience makes it an effective reinforcement phase that complements functional additives or secondary fibers without compromising overall integrity. By relying on recycled carton board as the dominant structural constituent, composite products can achieve mechanical performance requirements while simultaneously advancing sustainability goals. This approach supports resource efficiency, reduces dependence on virgin pulp, and reinforces the principles of closed-loop circular material systems [19]. This further strengthens its overall industrial applicability significantly.

### 5.1.3 Recyclability and Environmental Performance

Recycled carton board is widely recognized for its impressive recyclability, with its cellulose fibers capable of undergoing five to seven repulping cycles before experiencing significant structural decline. This extended reuse capacity greatly reduces dependence on virgin wood pulp, helping conserve forest ecosystems while lowering the overall environmental footprint of paper-based industries. By reintroducing post-consumer carton board into successive production loops, the amount of material destined for landfills is substantially reduced, supporting a far more circular and resource-efficient materials economy [20].

In addition to minimizing waste, the environmental advantages of recycled carton board are strongly tied to its reduced processing requirements. Manufacturing recycled fiber typically consumes far less energy, water, and chemical input than producing carton board from freshly harvested pulp. These reductions lead directly to lower greenhouse gas emissions, improved resource conservation, and decreased pressure on industrial water systems [21]. Furthermore, the reduced need for intensive bleaching, pulping, and transportation contributes to a significantly lower carbon footprint across the material's life cycle. As a result, recycled carton boards stand out as an environmentally responsible and highly efficient choice for composite, packaging, and molded fiber applications. Its blend of mechanical reliability, resource circularity, and reduced environmental impact makes it a critical material for advancing modern sustainability goals.

### 5.1.4. Economic and Practical Advantages

Recycled carton board, as a widely available post-consumer waste resource, offers a combination of accessibility, affordability, and performance that makes it highly suitable for sustainable material innovation. Because it is generated in large volumes through everyday packaging disposal streams, its supply is both consistent and economically stable, which supports reliable sourcing for industrial-scale operations. The relatively low processing cost associated with converting reclaimed carton board back into usable pulp especially when

compared to the intensive energy and chemical demands of virgin fiber production significantly enhances its feasibility for large-scale, budget-conscious manufacturing environments. Beyond cost advantages, recycled carton boards retain favorable mechanical characteristics that make it a strong and dependable structural component within composite sheet systems. Its inherent stiffness, compressive strength, and resistance to dimensional deformation enable it to form a robust load-bearing matrix when combined with secondary bio-fibers or functional additives. These mechanical attributes ensure that the resulting composite maintains sufficient rigidity and stability during both forming and end-use conditions.

Together, these benefits position recycled carton board as a cost-efficient, performance-driven foundation for eco-friendly composite materials such as EcoHyPack. Its mechanical reliability, abundant availability, and reduced environmental impact collectively support the development of sustainable, scalable, and commercially competitive bio-composite solutions, making such materials widely adopted.

## 5.2 Water Hyacinth Fiber Reinforcement (30%)

### 5.2.1 Overview

Water hyacinth (*Eichhornia crassipes*) fibers, which make up 30% of the composite formulation, function as the key reinforcement phase within the material. Sourced primarily from the plant's buoyant petioles and hollow stems, these fibers are naturally lightweight, porous, and rich in cellulose, giving them advantageous bonding and absorption properties. Their incorporation improves the composite's flexibility, biodegradability, and microstructural stability while reducing overall density. In addition to enhancing environmental performance, water hyacinth fibers contribute to better moisture regulation and thermal behavior, making the resulting composite more sustainable and versatile for packaging, paneling, and other eco-friendly material applications [15].

### 5.2.2 Chemical and Microstructural Contributions

Water hyacinth fibers contain approximately 55–62% cellulose, which significantly enhances their compatibility with recycled carton board pulp in composite manufacturing. This high cellulose content enables the formation of strong hydrogen bonded networks, improving interfiber adhesion and overall bonding strength within the composite matrix. Additionally, the fibers possess a naturally porous aerenchyma microstructure, characterized by interconnected air chambers that increase surface area and promote better interaction with surrounding pulp or biodegradable binding agents [15]. This porous morphology not only facilitates efficient fiber–matrix integration but also contributes to improved lightweight characteristics, making water hyacinth an effective reinforcement component in sustainable composite sheet and packaging material formulations.

### 5.2.3 Functional Enhancements

The inherent porosity of water hyacinth fibers plays a significant functional role within the composite, offering multiple performance advantages that extend beyond simple weight reduction. Their naturally occurring aerenchyma

channels introduce numerous air-filled voids, which improve thermal insulation by reducing heat transfer through the sheet. This same porous architecture also enhances acoustic absorption, allowing the composite to dampen sound vibrations more effectively than dense, conventional fiber materials [22]. Additionally, the fibers support improved moisture management by regulating humidity within the sheet structure, helping to moderate condensation and maintain dimensional stability under variable environmental conditions.

These combined functional properties make the material well suited for lightweight packaging, insulation panels, molded products, and eco-design applications where energy efficiency, comfort, or environmental responsibility is prioritized. The inclusion of water hyacinth fibers also contributes to a more natural, organic surface texture, giving the composite a distinctive tactile and visual appeal. This aesthetic quality is particularly valuable in consumer-facing products where material character, sustainability messaging, and sensory experience influence user perception [23]. Overall, the integration of porous water hyacinth fibers strengthens both the functional performance and design versatility of the final composite sheet.

#### 5.2.4 Sustainability and Ecological Benefits

Utilizing water hyacinth fibers directly supports ecological remediation because the plant is a globally recognized invasive species that clogs waterways, depletes oxygen levels, and disrupts aquatic biodiversity. Transforming this rapidly spreading biomass into value-added composite materials converts an environmental burden into a productive resource while simultaneously reducing reliance on virgin wood pulp and the associated pressures on forest ecosystems [24]. This redirection of waste biomass not only alleviates ecological damage but also contributes to more responsible raw material sourcing within fiber-based industries.

The natural, cellulose-rich fibers found in water hyacinth are fully biodegradable, compostable, and compatible with existing paper and fiber recycling streams, enabling their seamless integration into circular material systems. Their incorporation supports lower-impact product development by substituting renewable, non-wood fibers for more resource-intensive alternatives. This approach strengthens overall sustainability credentials by merging invasive species management with environmentally conscious design principles. By valorizing water hyacinth in this way, manufacturers can create composites that embody both functional performance and ecological responsibility [25]. The strategy demonstrates how problematic biomass can be transformed into a beneficial input, reinforcing broader goals of waste reduction, regenerative resource use, and nature-positive material innovation. This integration further highlights the potential of bio-based composites to advance sustainable industrial transformation worldwide efforts.

#### 5.3 Justification for the 70:30 Material Ratio

The 70:30 blend of recycled carton board and Water Hyacinth Fiber (WHF) represent a carefully optimized performance–sustainability tradeoff for composite sheet formation. Maintaining at least 70% recycled carton board ensures that

the composite retains a strong, continuous cellulose fiber network essential for mechanical integrity and dimensional stability. This carton board rich matrix supports effective hydrogen bonding, uniform fiber dispersion, and predictable behavior during key papermaking operations such as wet end formation, drainage, pressing, and calendaring [26]. As a result, the sheet maintains sufficient stiffness, tear strength, and runnability, minimizing disruptions during large scale processing.

Incorporating Water Hyacinth Fiber up to 30% provides meaningful functional benefits without compromising manufacturability. At this proportion, Water Hyacinth Fiber contributes enhanced thermal and acoustic insulation, improved biodegradability, and a distinctive natural surface texture that can be desirable for eco product applications. The fibers also introduce circularity value by utilizing an invasive aquatic species in a productive manner. However, limiting Water Hyacinth Fiber to 30% is crucial, as higher loadings often lead to excessive porosity, elevated moisture retention, and drainage delays due to Water Hyacinth Fiber's high water holding capacity [27]. These issues may cause fiber flocculation, uneven sheet formation, and weakened mechanical strength. Thus, the 70:30 ratio offers a balanced synergy between performance requirements and sustainability goals.

#### 5.4 Mechanical Rationale– Rule- of- Mixtures Perspective

From a first-order rule-of-mixtures perspective for in-plane modulus of a randomly oriented fiber sheet:

$$E_c \approx V_{cb} \cdot E_{cb} + V_{whf} \cdot E_{whf}$$

where:

- $E_c$  is the composite sheet modulus,
- $V_{cb}$  and  $V_{whf}$  are volume fractions of recycled carton board pulp and water hyacinth fibers respectively,
- $E_{cb}$  and  $E_{whf}$  are their effective moduli in the paper network.

Because carton board pulp fibers (secondary fibers) are shorter and partially hornified, they form a dense hydrogen bonded network that delivers reliable stiffness and compressive strength. Water Hyacinth Fiber, while cellulose rich ( $\approx 55$ – $62\%$ ), introduces higher porosity and non-uniform lumen structures that can reduce sheet density if over loaded[28]. Empirically, maintaining Water Hyacinth Fiber  $\leq 30\%$  preserves a percolated carton board network (for bending stiffness, ring crush, and edgewise compression), while Water Hyacinth Fiber contributes surface roughness and micro voids for insulation without excessive penalties to modulus and burst.

#### 5.5 Thermal and Acoustic Performance

Water Hyacinth Fiber's aerenchyma rich structure introduces numerous microscopic air pockets throughout the composite, creating a dispersed porous network that lowers the material's effective thermal conductivity and enhances its ability to attenuate sound. At an inclusion level of roughly 30%, these pores meaningfully increase void fraction while maintaining a structurally coherent carton board matrix. Thermally, the reduced bulk density and higher entrapped air content lead to lower apparent conductivity compared with sheets made from

100% recycled carton board. This makes the composite advantageous for applications requiring moderate thermal buffering, such as protective packaging, eco insulation liners, or lightweight interior panels. Acoustically, the open, tortuous fiber pathways increase internal friction and sound wave scattering, improving energy dissipation particularly in the mid frequency range where porous absorbers are most effective. However, Water Hyacinth Fiber levels above ~30–40% tend to connect these voids excessively, resulting in decreased mechanical strength, increased moisture uptake, and reduced pressing efficiency [29]. Thus, 30% of Water Hyacinth Fiber serves as a practical upper limit that maximizes functional gains while retaining manufacturability.

### 5.6 Moisture Management and Dimensional Stability

Water Hyacinth Fiber is inherently hygroscopic due to its high hemicellulose content and aerenchyma driven porosity, which promotes rapid moisture uptake. At a moderate loading of about 30%, this elevated hygroscopicity remains manageable through targeted process controls. Densification and calendering help collapse excess open porosity, lowering water accessible surface area and improving sheet compactness. Complementing this, surface or internal sizing using AKD, ASA, or suitable bio based hydrophobes creates a barrier that limits liquid penetration and reduces thickness swell. Additionally, a mild alkaline pretreatment for Water Hyacinth Fiber can partially remove hemicellulose and extractives, thereby improving fiber bonding, decreasing free hydroxyl groups, and enhancing dimensional stability[25].

However, increasing Water Hyacinth Fiber content beyond the 30–40% range significantly intensifies moisture sensitivity. Excess porosity and poor matrix consolidation lead to higher thickness swelling, greater water absorption, and a higher tendency for curl or warpage. These effects compromise packaging performance, panel flatness, and long-term structural reliability, reinforcing the need to cap Water Hyacinth Fiber levels at practical thresholds.

### 6. Processability and Yield of the Material

Maintaining a 70% recycled carton board fraction establishes a consistent and reliable processing foundation because these fibers possess well documented drainage, retention, and formation characteristics that align closely with the requirements of conventional papermaking systems. This majority fiber component stabilizes the wet end by providing a predictable fines profile, enabling operators to rely on standard chemical programs for strength, retention, and drainage control. As a result, the sheet consolidates uniformly during pressing and drying, supporting efficient water removal and reducing variability in machine performance. Introducing Water Hyacinth Fiber at a controlled 30% level adds its functional advantages without disrupting the established equilibrium of the carton board matrix[30]. At this proportion, Water Hyacinth Fiber does not produce an excessive fines load—an important factor in preventing slow drainage, wire section flooding, or white-water system overloads. Additionally, Water Hyacinth Fiber at 30% avoids promoting fiber flocculation, helping maintain even fiber dispersion and consistent basis weight profiles across the

sheet. This stability reduces the likelihood of formation related defects such as streaks, thin spots, or localized weaknesses. Dewatering behavior through both the forming and press sections remains within normal operating parameters, ensuring that press solids remain adequate and drying energy demands do not increase. This balance preserves throughput, machine efficiency, and sheet quality.

Water Hyacinth Fiber is plentiful, inexpensive, and often classified as waste biomass generated during routine aquatic weed removal operations. This widespread availability makes it an appealing supplementary fiber source for papermaking, particularly in regions looking to valorize local biomass streams. Maintaining Water Hyacinth Fiber at around 30% within the furnish mix allows mills to benefit from this resource without triggering excessive processing demands. At this moderate inclusion level, Water Hyacinth Fiber can be used with minimal pretreatment, helping avoid energy heavy or chemically intensive methods such as prolonged alkaline retting that are sometimes applied to break down lignocellulosic material more aggressively. By reducing reliance on such steps, mills significantly lower overall environmental impact through decreased chemical consumption, reduced wastewater generation, and lower thermal and electrical energy inputs. This approach also enhances economic feasibility, as it minimizes capital modifications and maintains compatibility with existing equipment and wet end practices. Ultimately, keeping Water Hyacinth Fiber at 30% strikes an effective balance between sustainability, cost efficiency, and operational practicality, enabling scalable integration without undermining process stability or end product quality.

### 7. Cost and Circularity of the Material

Recycled carton board serves as an extremely cost-effective primary fiber source because it is supported by mature recovery systems, well-regulated supply chains, and predictable market behavior. Large scale collection networks ensure steady availability, while established grading standards make its fiber quality and composition relatively consistent. This stability translates into reliable pricing and optimized transportation and processing logistics, enabling mills to plan production with minimal fluctuations in raw material cost. The familiarity of recycled carton board with existing pulping and papermaking infrastructure also reduces operational complexity, since mills already understand how these fibers behave in refining, drainage, and retention systems. In contrast, Water Hyacinth Fiber though inexpensive at the point of removal from aquatic environments may require additional handling steps that introduce incremental costs. Collection from lakes or reservoirs often involves specialized equipment, followed by dewatering to reduce bulk, removal of sand, silt, and biological contaminants, and preliminary cleaning to prepare the material for pulping. These steps can add logistical and operational expenses that may offset its initial low cost if used in very high proportions. However, limiting Water Hyacinth Fiber to approximately 30% of the furnish keeps these additional costs manageable. At this level, mills can integrate Water Hyacinth Fiber without needing major process changes or extensive pre-treatment, thereby maintaining low operating expenditures. The Water Hyacinth Fiber fraction still replaces

a meaningful portion of more expensive virgin or wood fibers, yielding a net reduction in overall raw material costs. Meanwhile, the dominant recycled carton board base ensures stable pulping behavior, moderate refining energy requirements, and predictable chemical demand at the wet end. This balance prevents significant increases in OPEX related to drainage aids, retention polymers, or defoamers that might otherwise be required at higher Water Hyacinth Fiber loadings [31].

The 70:30 fiber blend provides a compelling circular materials profile by combining two inherently sustainable and complementary fiber streams. The recycled carton board portion brings with it a high level of post-consumer recycled content, sourced from well-established recovery loops that keep valuable cellulose fibers circulating through multiple product life cycles. Using carton board as the primary fiber fraction reinforces material recirculation, reduces dependence on virgin pulp, and supports waste diversion goals in packaging and paper manufacturing. Integrating Water Hyacinth Fiber at a 30% level further strengthens this circularity narrative. Water hyacinth fiber originates from an invasive aquatic species that is routinely harvested as part of lake and river management programs, where uncontrolled growth can harm biodiversity, block waterways, and degrade water quality. Instead of treating this biomass as waste, repurposing it as papermaking raw material captures additional environmental value. By converting an ecological burden into a functional renewable fiber, Water Hyacinth Fiber contributes to resource efficiency while reducing pressure on forest-based fiber supplies. Both recycled carton board and Water Hyacinth Fiber are biodegradable and compatible with standard paper recycling streams. Their cellulose fibers typically withstand 5-7 reprocessing cycles before significant degradation occurs, enabling repeated reintegration into the production loop. This durability ensures that sheets produced from the 70:30 blend can reenter existing recycling infrastructure without complication. Altogether, the blend exemplifies a circular economic approach: maximizing recycled content, valorizing an underused renewable biomass, extending fiber lifetimes, and reducing reliance on virgin resources while also supporting environmental stewardship in aquatic ecosystems.

## 8. Risk-Mitigation Considerations

### 8.1 Moisture Sensitivity

Water hyacinth fiber (WHF) exhibits inherently high hygroscopicity because its cellular structure contains numerous open lumens and a relatively large fraction of hemicellulose, both of which readily absorb and retain moisture. This elevated water affinity can influence dimensional stability, mechanical strength, and surface smoothness if not properly controlled within the papermaking process. To mitigate these effects, internal sizing is employed early in the wet end. Agents such as AKD, ASA, or newer bio-based hydrophobes react with cellulose during curing, forming hydrophobic ester linkages that reduce water penetration into the fiber wall and limit swelling. Surface sizing provides a complementary outer barrier, forming a continuous film that reduces wicking, enhances surface strength, and improves resistance to humidity-driven

deformation. For applications requiring heightened moisture durability such as packaging, molded fiber products, or fiber-cement alternatives hydrophobizing coatings can be applied to create multilayer moisture shields with predictable performance. Beyond chemical solutions, mechanical and thermal process controls also significantly influence moisture behavior. Optimizing press loading increases sheet consolidation, reducing void volume and open porosity, while tailored dryer section temperature and moisture profiles help achieve a target density and uniform internal structure. Together, these strategies effectively manage Water Hyacinth Fiber's moisture sensitivity, enabling stable end-use performance across varying environmental conditions [32].

### 8.2 Strength Retention

Recycled carton board fibers often arrive with reduced fibrillation and diminished bonding sites due to multiple prior recycling cycles, which shorten fibers and collapse fines. To restore bonding potential, targeted refining is required to re-open fibrils, increase external surface area, and improve hydrogen bond formation. Controlled, low to moderate refining prevents excessive fines generation while reactivating the fiber network for stronger inter fiber adhesion. Water Hyacinth Fiber (WHF), by contrast, benefits from mild alkaline treatment to remove interfering components such as lignin, pectin, waxes, and extractives. This treatment improves fiber flexibility, reduces hydrophobic barriers, and enhances compatibility with recycled carton board fibers in blended furnishes. The cleaner, more reactive Water Hyacinth Fiber surface promotes better bonding and contributes positively to tensile and internal bond strength[33]. To further strengthen the fiber matrix, small additions of starch, hemicellulose rich bio binders, or other biodegradable polymers can be incorporated. These additives enhance dry strength, improve interfiber cohesion, and support uniform stress distribution within the sheet. Importantly, they do so without compromising recyclability or circularity, ensuring the fiber blend remains compatible with existing recovery and repulping systems.

### 8.3 Process Stability

At a 30% Water Hyacinth Fiber inclusion level, wet end stability can be reliably maintained by using well designed retention and drainage systems. Mixed furnishes containing both recycled carton board fibers and Water Hyacinth Fiber can exhibit varied charge profiles and fines behavior, making consistent retention essential for predictable formation and sheet structure. Cationic starch is particularly effective in this context, as it provides both charge stabilization and additional bonding potential, helping to anchor fines and small Water Hyacinth Fiber particles within the fiber network. Polyacrylamide based retention aids either cationic or anionic depending on system chemistry further enhance floc capture while maintaining the necessary micro flocculation balance for uniform formation[34]. Microparticle systems, such as bentonite or colloidal silica paired with a primary polymer, offer an additional layer of control by tightening the fiber fines matrix and improving drainage without inducing excessive floc size. These combinations help reduce fines loss to the white-water loop, sustain consistent sheet solids, and ensure even fiber distribution across the wire. By integrating

such systems, mills can preserve wet end robustness and sheet uniformity, even with the added variability introduced by Water Hyacinth Fiber, supporting stable machine operation and high-quality paper production.

## 9. Sensitivity to Alternative Ratios

### 9.1 80:20 Ratio

An 80% recycled carton board fraction provides a more conventional performance profile due to the dominance of well processed secondary fibers with predictable morphology and bonding behavior. Compared to a 70:30 blend, this higher recycled fiber proportion generally yields improved mechanical attributes, including higher ring crush strength, better bending stiffness, and more uniform caliper control. The sheet also exhibits more consistent drainage and water removal because recycled carton board fibers have well characterized fines content and lower variability than Water Hyacinth Fiber. As a result, paper machine runnability tends to be smoother, with fewer formation disturbances and more stable vacuum, pressing, and drying performance [17]. This is particularly advantageous on high speed or older machines that are more sensitive to non-wood fiber variability.

However, increasing recycled carton board content to this level reduces the sustainability and functional enhancements contributed by Water Hyacinth Fiber. With only 20% Water Hyacinth Fiber, the displacement of forest derived fibers is smaller, and the valorization of invasive biomass becomes less significant. Functionally, the composite retains a denser and less porous microstructure, which diminishes the thermal insulation and acoustic damping benefits typically associated with Water Hyacinth Fiber's intrinsic porosity. As a result, the material profile becomes more aligned with conventional recycled fiber performance, offering reliable mechanical strength but only modest gains in multifunctionality or ecological impact.

### 9.2 60:40 Ratio

Increasing the Water Hyacinth Fiber content to 60:40 pulp-to-Water Hyacinth Fiber ratio significantly enhances the composite's thermal insulation capacity and contributes to a more textured, visibly natural bio-composite surface. The higher proportion of Water Hyacinth Fiber introduces additional voids and micro-porosity within the matrix, which improve heat-retention characteristics and impart a desirable organic aesthetic. These benefits, however, come with pronounced trade-offs that impact both material performance and process efficiency [35].

As Water Hyacinth Fiber is inherently hygroscopic and contains a highly porous internal structure, water uptake increases sharply at elevated fiber loadings. This heightened moisture sensitivity not only affects dimensional stability during manufacturing but also raises concerns about long-term durability in humid environments. Mechanical properties such as ring crush strength and bending stiffness also decline, primarily because the increasing Water Hyacinth Fiber fraction disrupts fiber bonding and leads to a less consolidated structural network. Reduced interfiber contact limits hydrogen bonding, resulting in a weaker and more

compliant sheet. From a production standpoint, the drainage and formation behavior becomes notably more difficult to control at 40% Water Hyacinth Fiber. The slower dewatering caused by Water Hyacinth Fiber's high-water retention prolongs machine run times and introduces variability in sheet uniformity. Additionally, the increased tendency for Water Hyacinth Fiber particles to form flocs raises the risk of inconsistent basis weight and localized defects. These processing complications not only strain overall manufacturability but also heighten the challenge of maintaining dimensional accuracy, further emphasizing the careful balance required when optimizing Water Hyacinth Fiber content in bio-composite formulations.

### 9.3 70:30 Ratio (Selected)

The 70:30 pulp-to-Water Hyacinth Fiber ratio is selected because it represents the most effective balance of mechanical performance, functional enhancement, process stability, and sustainability within the evaluated formulation range. At a 70% recycled carton board content, the composite maintains a dominant, continuous fiber network that is sufficiently dense and well-bonded to deliver dependable structural properties. This proportion ensures that hydrogen bonding remains strong across the sheet, preserving essential attributes such as ring crush resistance, bending stiffness, and overall dimensional stability. The recycled carton board fibers already refined and fibrillated from previous life cycles create a cohesive matrix that supports predictable behavior during both wet-end operations and final product use[36]. From a manufacturing standpoint, the 70% carton board base plays a critical role in maintaining process robustness. It enables smooth drainage through the wire by preventing excessive water retention, which is a common issue when Water Hyacinth Fiber levels exceed the optimal threshold. This predictable drainage also contributes to consistent press section solids and steady moisture profiles entering the drying section. Such stability directly translates to efficient runnability on existing papermaking equipment without requiring major modifications, additional chemical aids, or slower machine speeds. The 70:30 ratio therefore supports scalable production and aligns with the goal of achieving low-disruption integration into traditional fiber-based manufacturing lines. The inclusion of 30% Water Hyacinth Fiber introduces targeted functional enhancements that elevate the composite beyond the capabilities of pure recycled carton board. Water Hyacinth Fiber's naturally occurring aerenchyma structures and porous vascular channels introduce microcavities into the sheet, contributing to improved thermal insulation and beneficial acoustic dampening. These features help create a more functional and versatile bio-composite suitable for applications where energy efficiency, comfort, or sensory performance are valued. Additionally, the controlled porosity supports a subtle increase in bulk, which enhances tactile properties and perceived material naturalness a desirable feature in sustainable consumer packaging applications.

Equally important are the environmental advantages offered at this Water Hyacinth Fiber loading. Incorporating 30% Water Hyacinth Fiber contributes meaningfully to biomass valorization by transforming an invasive or under-utilized plant residue into a functional filler fiber. This reduces

dependence on virgin forest-based fibers, reinforcing a circular economy narrative that strengthens the sustainability profile of the final product. Because Water Hyacinth Fiber is biodegradable and non-toxic, its integration further aligns with eco-design principles and can contribute to improved end-of-life biodegradation or compostability. Crucially, the 30% Water Hyacinth Fiber level remains below the thresholds where detrimental effects begin to outweigh benefits. At this proportion, moisture uptake is elevated but still manageable, sheet formation remains uniform, and drainage instability is minimized. Unlike higher Water Hyacinth Fiber ratios, the fiber network does not become overly open or prone to de-bonding, and the risk of flocculation is controlled. This ensures that the material maintains acceptable dimensional stability, consistent basis weight, and appropriate mechanical strength.

## 10. Manufacturing Process of Ecohypack

The extraction of pulp from water hyacinth begins by harvesting the plants and reducing them into a workable fibrous mass through chopping, shredding, and mechanical crushing. This size reduction exposes the internal tissues, making them more responsive to subsequent chemical treatment. The resulting biomass is then subjected to alkaline cooking in a solution typically containing sodium hydroxide (NaOH) or potassium hydroxide (KOH) which helps break down lignin, hemicellulose, pectins, and other non-cellulosic substances that bind and stiffen the plant structure[37]. During this cooking stage, the alkaline environment loosens the matrix surrounding the cellulose fibers, facilitating their separation and improving pulping efficiency.

Once adequate delignification is achieved, the mixture is thoroughly washed with clean water to remove residual chemicals, solubilized impurities, and degraded organic

matter. Repeated washing ensures that the remaining fiber fraction is chemically neutralized and safe for further processing[38]. The cleaned material is then refined through beating or mechanical fibrillation to enhance fiber flexibility, bonding potential, and sheet-forming capability. At this stage, the prepared pulp can be molded, blended with other fibers, or formed into paper sheets, making it a raw material suitable for a wide range of eco-friendly products.

### 10.1 Preparation

The preparation process for extracting pulp from water hyacinth begins with carefully harvesting the plant from ponds, lakes, or slow-moving waterways where it commonly grows in dense floating mats. Once collected, the roots are removed because they typically contain higher amounts of dirt, sand, and microbial residues, making them less suitable and less efficient for pulping. After trimming away the roots, the remaining stems and leaves are thoroughly washed to eliminate mud, algae, decayed organic matter, and any attached aquatic organisms[39]. Conducting an intensive cleaning step not only improves the purity and brightness of the final pulp but also reduces the amount of chemicals required during subsequent processing stages.

Following the washing process, the water hyacinth material is spread out to dry. Drying may be carried out under direct sunlight or in shaded, well-ventilated areas, depending on climatic conditions and available infrastructure. This drying step usually lasts for about a week and serves to lower the moisture content, prevent microbial growth, and make the fibrous tissues easier to handle and transport. Once the plant material is completely dried, it is cut into smaller pieces to facilitate mechanical breakdown. These cut pieces are then mashed, crushed, or blended into a coarse, thick pulp using mechanical tools, effectively preparing the material for the upcoming cooking stage.

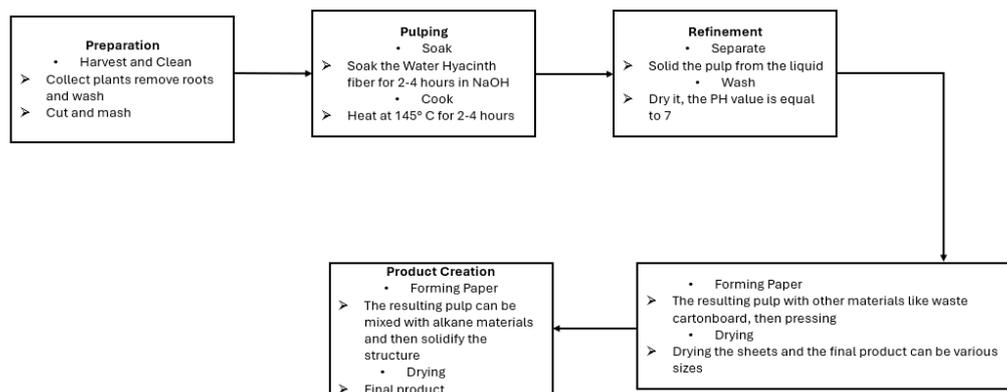


Figure 5

### 10.2 Pulping (Chemical Process)

The pulping stage is a crucial step in converting water hyacinth into usable cellulose fibers[40]. It begins by placing the previously mashed plant material into a container filled with a strong alkaline solution, typically made from sodium hydroxide (NaOH) or potassium hydroxide (KOH). The purpose of this soaking phase is to allow the alkaline chemicals to deeply penetrate the fibrous structure of the plant. This helps initiate the breakdown of lignin,

hemicellulose, waxes, and other binding components that hold the plant cells together. The soaking period ensures that the mixture is uniformly saturated before high temperature treatment begins.

Once adequately soaked, the mixture is transferred to a cooking vessel, often a large steel pot or a pressure digester[41]. It is then heated for about 2 to 4 hours at temperatures reaching approximately 145°C. This combination of heat and alkalinity triggers a chemical

reaction that dissolves noncellulosic materials, effectively freeing the cellulose fibers from their rigid matrix. During cooking, the mixture gradually turns into a dark, softened mass as unwanted components break down and separate.

After cooking, the pulp becomes significantly more pliable and easier to wash, refine, and eventually transform into paper or other biodegradable products.

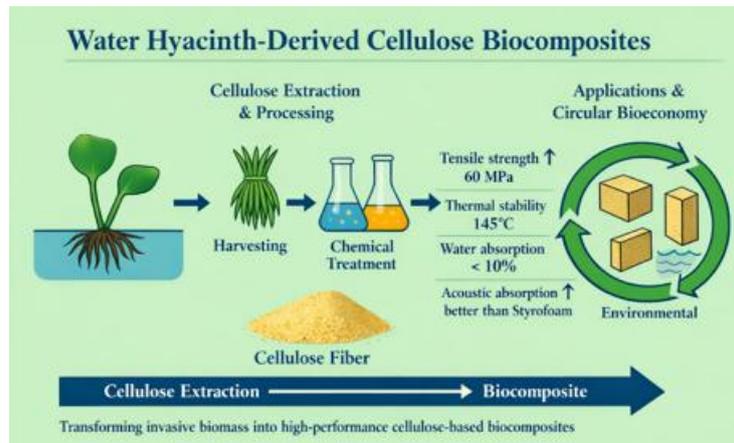


Figure 6

### 10.3 Pulp Refinement

After the chemical cooking process, the next stage focuses on refining the pulp to improve its purity and texture. The first step is to separate the solid pulp from the liquid "black liquor," which contains the used alkaline chemicals and dissolved organic waste such as lignin and hemicellulose[42]. This separation is usually done through filtration or draining, ensuring that the solid fibers are isolated for further cleaning[43].

Once separated, the pulp is washed thoroughly with fresh water multiple times. This repeated washing continues until the mixture reaches a neutral pH (around 7), ensuring that all residual alkaline chemicals are removed[44]. Neutralizing the pulp is essential for preventing degradation of fibers and ensuring safety in later stages. After washing, the pulp is screened to remove impurities, such as unprocessed plant fragments or contaminants. Finally, the screened fibers are fed into a disintegrator, which breaks them down into a smoother, finer, and more uniform pulp suitable for papermaking or other applications.

### 10.4 Product Creation

Once the pulp has been fully refined, it becomes ready for transformation into usable end products. One of the most common applications is papermaking. To create paper, the prepared pulp is first mixed with water to form a slurry and can also be blended with other materials such as recycled paper or wastepaper to enhance strength, texture, and durability[45]. This mixture is then spread evenly over a fine mesh screen, allowing excess water to drain while the fibers interlock on the surface. The wet sheet formed on the screen is gently pressed to remove additional moisture, improving its density and structural integrity. After pressing, the sheets move to the drying stage, where they are laid out in the sun, placed under fans, or passed through heated rollers depending on the production scale. Proper drying ensures the paper becomes firm, smooth, and ready for handling. Once fully dried, the sheets can be cut into various sizes and shapes, depending on

their intended use, such as writing paper, craft sheets, packaging material, or decorative handmade paper.

Beyond paper, water hyacinth pulp is versatile and can be used to develop a range of eco-friendly products. One emerging application is the production of bioplastics, where the pulp is combined with natural binders to create biodegradable alternatives to conventional plastic. Additionally, the pulp can be used in creating molded products, eco bricks, biodegradable trays, and artisanal crafts, making water hyacinth a valuable raw material for sustainable product development.

## 11. Pros and Cons of the Material

### 11.1 Pros

#### a) Sustainability and Circularity

The EcoHyPack composite advances circular material design by combining post-consumer recycled carton board with water hyacinth biomass, thereby reducing reliance on virgin forest resources while simultaneously converting an invasive aquatic species into a productive raw material. Both constituents demonstrate biodegradability and compatibility with multiple recycling loops, typically allowing five to seven repulping cycles before fiber shortening becomes limiting. When free of synthetic coatings, the composite is also compostable under controlled aerobic conditions, strengthening its alignment with circular economy and low waste manufacturing frameworks. Substituting virgin pulp with recycled fibers significantly lowers embodied energy, water consumption, and greenhouse gas emissions, while the removal and utilization of water hyacinth contribute directly to aquatic ecosystem restoration efforts.

#### b) Functional Performance Enhancement

The incorporation of water hyacinth fibers introduces aerenchymatous micro voids, which reduces thermal conductivity and improves the material's potential for thermally protective packaging and environmentally conscious interior applications. The inherent porosity of hyacinth fibers also supports mid frequency acoustic

damping, making the composite suitable for panels, craft boards, and sustainable packaging inserts requiring sound absorption capability. The hybrid material exhibits a naturally textured surface with visible bio fiber inclusions, contributing to enhanced aesthetic and tactile qualities valued in premium, eco focused product lines.

#### c) Lightweight Structure and Material Efficiency

Despite the relatively porous reinforcement, the composite maintains adequate stiffness due to the continuous hydrogen bonded network formed by recycled carton board fibers. The resulting low density facilitates material down gauging in light to medium duty applications, reducing raw material usage while preserving performance. This balance between weight and strength enhances the suitability of the composite for environmentally conscious packaging and display applications.

#### d) Cost and Feedstock Availability

Recycled carton boards are consistently available through established municipal and industrial recovery streams, ensuring stable input supply at a low cost. Water hyacinth, prevalent in many tropical and subtropical regions, offers abundant biomass that can be harvested at minimal cost and processed into usable fiber with standardized cleaning and retting procedures. Organized harvesting and preprocessing of water hyacinth additionally create opportunities for localized employment and socio-economic benefit in affected regions.

#### e) Process Compatibility and Manufacturing Feasibility

At a 70:30 ratio of recycled carton board to water hyacinth fiber, the composite generally maintains acceptable drainage characteristics, sheet formation uniformity, and press/dryer runnability on conventional papermaking equipment. Only modest process adjustments such as the use of retention aids, sizing agents, or optimized mixing protocols are typically required to integrate the water hyacinth fibers effectively. This compatibility reduces the need for capital investment or major process redesign, supporting the feasibility of large-scale production within existing fiberboard or recycled paper manufacturing lines.

### 11.2 Cons

#### a) Mechanical Constraints

Water hyacinth fibers possess lower intrinsic tensile and flexural strength compared to more established natural reinforcement fibers such as jute or coir. Their aerenchymatous structure introduces higher porosity within the composite, which can diminish the formation of a dense, load bearing fiber network. As a result, the inclusion of water hyacinth fibers may lead to reductions in bending stiffness, ring crush resistance, and burst strength when compared to conventional recycled carton board boards. Due to these mechanical limitations, the EcoHyPack composite is not inherently suited for high load, high stacking, or wet strength packaging applications unless it undergoes additional reinforcement or densification treatments. Situations requiring long term compressive resistance, such as corrugated boxes for industrial transport, may necessitate structural additives or modified processing approaches.

#### b) Moisture Sensitivity and Dimensional Stability

Water hyacinth fibers are inherently hygroscopic, which contributes to elevated water absorption and higher Cobb values in the composite. Their porous structure makes the material susceptible to thickness swelling, dimensional instability, and curl under humid or fluctuating environmental conditions. Prolonged exposure to water or high humidity can accelerate mechanical degradation and weaken fiber–matrix bonds. This moisture sensitivity restricts the use of the composite in applications requiring wet strength durability, sustained outdoor exposure, or environments with significant humidity variation unless appropriate hydrophobic modifications are implemented.

#### c) Processing Considerations

Water hyacinth fibers require thorough cleaning, retting, and size reduction to achieve adequate dispersion within the pulp matrix. If not properly processed, excessive fines, fiber agglomeration, or flocculation can impair sheet formation uniformity and increase drainage time on the wire section of papermaking equipment. These issues become more pronounced as the proportion of water hyacinth fiber increases beyond approximately 30–40%. Elevated WATER HYACINTH FIBER loadings can also disrupt the balance of freeness and retention, leading to non-uniform fiber distribution, slow dewatering, and increased energy consumption during drying. Such processing challenges impose practical limits on scalable production when operating within conventional paper making infrastructure.

## 12. Conclusion

Blending 70% recycled carton board with 30% water hyacinth fiber results in a highly sustainable, low-cost, and biodegradable composite material that aligns with the growing demand for environmentally responsible packaging solutions. This innovative hybrid composition leverages the abundant cellulose content present in water hyacinth, a fast-growing aquatic plant widely regarded as an ecological challenge due to its rapid spread and disruption of aquatic ecosystems. The plant's naturally porous internal structure, combined with its fibrous composition, enhances bonding interactions within the composite matrix. These features contribute to improved flexibility, reduced overall density, and increased biodegradability, making the resulting material both lightweight and environmentally compatible. Recycled carton board plays an equally crucial role by supplying the composite with essential structural strength, durability, and a reliable recyclability track record. As a well-established packaging material, carton board provides a sturdy and familiar backbone that supports load-bearing applications and ensures mechanical performance. When these two materials are combined in a 70:30 ratio, the resulting hybrid minimizes reliance on virgin wood pulp, reduces material waste, and transforms an invasive plant species into a valuable, functional resource.

The resulting material referred to as EcoHyPack embodies key principles of the circular economy by extending the useful life of carton board fibers while simultaneously converting water hyacinth biomass into a productive material stream. EcoHyPack can be molded, pressed, layered, or thermoformed to create various packaging formats, including

trays, cartons, protective inserts, cushioning elements, and lightweight storage containers. Beyond its environmental strengths, EcoHyPack offers notable economic advantages. By lowering raw material costs and reducing dependence on imported fibers, it becomes especially attractive for manufacturers in developing regions. Furthermore, harvesting and processing water hyacinth creates livelihood opportunities in communities where the plant is abundant, turning an ecological problem into a source of local economic benefit. EcoHyPack thus represents a meaningful advancement toward greener, more responsible, and socially inclusive packaging solutions for the future.

The composite's unique material characteristics open possibilities for innovative product designs that balance performance and sustainability. Its reduced weight lowers transportation emissions, while its biodegradability supports environmentally conscious disposal practices. EcoHyPack can also be adapted for specialty uses such as protective cushioning, horticultural trays, or compostable craft materials, highlighting its versatility across different industries. These expanded applications further strengthen the case for adopting hybrid bio-based materials as viable alternatives to traditional plastic or wood-derived packaging, encouraging broader environmental responsibility in manufacturing sectors worldwide. This further reinforces long-term sustainability.

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