



Agro-Industrial Waste Derived Biocomposites for Structural Applications: Materials, Processing, Mechanical Properties and Recent Advances

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How to Cite this Article:

M., M. L. (2026). Agro-Industrial Waste Derived Biocomposites for Structural Applications: Materials, Processing, Mechanical Properties and Recent Advances. International Journal of Creative and Open Research in Engineering and Management, 2(9), 1-9.
<https://doi.org/10.55041/ijcope.v2i9.250>

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<https://doi.org/10.55041/ijcope.v2i9.250>

Abstract - Agro-industrial residues can be used as fibers, particles, ash, biochar or cellulose-rich reinforcements in polymer composites. Their local availability and low density motivate lightweight products, but a residue-based formulation is not necessarily structural, biodegradable or inherently environmentally preferable. This critical narrative review is extended to consider representative feedstock families, matrix choices, preparation and forming routes, interface engineering, mechanical response, candidate structural applications, durability and recent advances through 2026. The evidence indicates that strength and stiffness are dictated by fiber geometry and orientation, matrix wet out, porosity, formulation and conditioning: treatment can assist load transfer but may also damage fibers or impose processing burdens. Consequently, results from different formulations cannot be collapsed to a universal property range. Illustrative studies highlight both opportunities and limitations: a surface treatment that cleaned kenaf did not necessarily strengthen its epoxy composite, whereas one FDM study observed smaller mean strength losses at 10wt% filler and greater losses at 20wt%, with trade-offs in impact strength. Moisture, creep, fatigue, fire performance, feedstock variation and end of life pose critical design constraints. Hybridization, bio-based matrices, multiscale reinforcement and additive manufacturing expand the design space. This review concludes that near term deployment is best in noncritical and semi structural products; primary load bearing requires statistically sound properties, service life data, structural validation and performance based life cycle comparison.

Keywords - agro-industrial waste, biocomposites, natural fibers, structural materials, mechanical properties, interface engineering, durability, life-cycle assessment, additive manufacturing.

1. INTRODUCTION

Agriculture, food processing, and other industries produce large amounts of stalks, husks, shells, bagasse, straw, and other residues as by-products. These wastes can often be converted into composite reinforcements, partially replacing virgin fillers or fibers and contributing to local material economies. However, the engineering case for their use in composites is rarely straightforward: a composite material system is defined by the interactions of its reinforcement, matrix, and interface, as well as the fabrication, geometry, operating conditions, and end-of-life scenarios of its components [1], [2].

The definition of biocomposite is similarly broad, encompassing materials with natural fiber reinforcement, biobased polymer matrices, biodegradable matrices, or a combination of the three. A composite made of rice husks and polypropylene, for example, contains a biological reinforcement but has a petroleum-based and non-degradable matrix, which considerably limits its sustainability credentials. Different agro-industrial residues also exhibit an extensive variation in their properties, depending on the crop, the region, and the storage and processing conditions. This variability complicates any generalization about the mechanical performance and quality of agro-industrial residue composites [1], [3].

The purpose of this paper is to review the state of the art in materials and processing, identify the main performance drivers, and evaluate the prospects of agro-industrial residue composites in terms of mechanical properties and service performance. It summarizes and evaluates the published literature on the topic, identifying trends and drawing conclusions about the materials' properties. The paper does not present any original experimental results or a systematic analysis of the data published in the peer-reviewed literature base. The paper's central message is that agro-industrial residue composites are best suited for current and near-term applications as light structural or semi-structural materials, with the need for further research before they can be used in major load-bearing components.

This study pulls together published reviews, original research, and case studies published up to 2026 to identify trends in fiber preparation and processing, their effects on mechanical performance, and the key factors influencing the quality and consistency of composite materials. It focuses on the relationships between the properties of the starting materials, the composition and fabrication methods of the composite, and its mechanical performance. It is not a systematic review or a meta-analysis of the



published data, as it concentrates on the trends within one area of materials science and does not attempt to combine the results of different studies using fundamentally different approaches or report varying outcomes in a standardized manner [1], [4], [13], [15].

Finally, the term structural composite also requires clarification, as most reviews of agricultural fiber composites acknowledge that the term encompasses a wide range of materials. At the most basic level, any composite structure that can maintain its shape or support a load can be considered structural. However, its structural role can range from being a lightweight non-critical element to a load-bearing member that requires design calculations. This paper therefore makes a distinction between noncritical product structures, semi-structural elements that distribute or resist limited loads, and structural components that must withstand substantial mechanical stresses and have been tested and documented to perform under these loads without failure.



Fig. 1. Review-derived pathway from residue sourcing to component qualification; life-cycle inventory spans the full value chain [13], [14], [17].

II. MATERIALS AND MATRIX SELECTION

Agro-industrial reinforcements can be made of continuous or discontinuous fibers, short fibers, coarse particles, powders, ash, biochar, or purified cellulose. Bagasse and cereal straws are potential sources of fibrous fractions, rice husk is a good source of silica bearing outer tissues that can be utilized in the form of flour, particles, ash, or biochar, coconut shell and other nutshells are potential sources of hard lignocellulosic particles, while crop leaves, stalks, and fruit processing residues can potentially be processed into fibers or cellulose. Therefore, the selection of materials should be based on the morphology and chemistry of the residue and not only on the plant source [1], [3], [4].

TABLE I. REPRESENTATIVE AGRO-INDUSTRIAL STREAMS, COMPOSITE FORMS, AND DESIGN CONCERNS

Residue stream	Common composite form or opportunity	Key design concern
Sugarcane bagasse; cereal straw	Short fibers, mats, or particles in thermoplastic, thermoset, or bio-based matrices	Moisture, variable fiber length, surface contamination, and seasonal supply
Rice husk	Milled filler, fiber-rich fraction, ash, or biochar in polymer compounds	Silica/ash content and particle size affect interface, abrasion, and dispersion
Coconut shell and other nutshells	Hard particles or powders for boards, molded parts, and hybrid compounds	Brittleness, particle wet-out, and property dependence on size and loading
Maize, oil-palm, and fruit-processing residues	Leaf/stalk fibers, husk particles, or extracted cellulose	Feedstock separation, preprocessing energy, and batch-to-batch variability

The matrix might be a common thermoplastic material like polypropylene or polyethylene, a thermoset like epoxy or polyester, or a bio-based/biodegradable polymer material like polylactic acid, starch based blends, or bio-epoxy. The matrix governs processing temperature, stiffness, toughness, moisture transport, and end-of-life options. Simply having a high renewable content does not guarantee biodegradability, and a biodegradable matrix does not ensure that a thick or fiber rich finished component will degrade in an unmanaged environment [1], [2].

For structural selection, the relevant comparison is not only strength per unit mass. The designer must take into account stiffness, failure strain, variability, creep, connection behavior, environmental conditioning, and manufacturable part geometry. A material of low density can be desirable if the anticipated loads are low or if the replacement of a heavier panel results in a reduction in system mass, but a high specific property does not necessarily mean adequate absolute strength or stability.

A. Fibrous Residues and Their Variability

Fibrous residues are attractive when their aspect ratio and architecture allows for stress transfer across the matrix. Sugarcane bagasse is generated during juice extraction and can be used as short fiber fraction, mat, or a processed cellulose stream.

Wheat and rice straw contain usable stem fibers but require separation from leaves, nodes, husk, pith, or soil contamination. Coconut coir and palm derived fibers can provide more persistent, coarse reinforcement, while maize and other stalk residues are more variable in bundle size and composition. These broad categories describe opportunities rather than interchangeable reinforcements [1], [3], [4], [13].

The fiber properties measured in a laboratory depend on extraction method as well as crop identity. Retting, decortication, pulping, chemical extraction, and mechanical milling leave different proportions of lignin, hemicellulose, pectin, wax, and residual fines. Aggressive extraction may increase cellulose exposure but shorten or weaken fibers. Mild processing may preserve length but leave surface components that obstruct wetting. For this reason, reporting only “rice straw fiber” or



“bagasse fiber” is not a reproducible material specification; a study should report source, harvest or processing stage, extraction, particle-size or length distribution, drying, and storage [3], [4], [18].

Natural variation is also spatial and seasonal. Soil, cultivar, maturity, weather, fertilizer practices, and post harvest storage can change fiber morphology and moisture. A procurement specification that includes moisture limits, ash and contamination limits, particle size distribution, and accepted batch variability can reduce downstream surprises. These controls may be more important for industrial consistency than the nominal difference between two crop types.

B. Particulate Residues, Ashes, and Biochar

Particulate fillers play a different design role than long fibers. Milled husk, shell, nutshell, bran, fruit peel, and seed residues can be compounded into a matrix using established powder processing equipment. They may raise stiffness or hardness, change friction and thermal response, or reduce resin consumption. In return, they can increase viscosity, form agglomerates, reduce elongation, and initiate cracks if particle shape, size, or interface is poorly controlled. The useful loading is formulation specific; an increase in filler percentage cannot be presumed to increase strength [1], [3], [13].

Rice husk is distinctive because silica is present in its outer structure. It can be used as a natural filler, or it can be converted into ash or biochar. The latter are not equivalent to untreated fibers: thermal conversion changes chemistry, surface area, porosity, and the mechanism of interaction with the polymer. Finely dispersed ash may function as a mineral filler, whereas a carbonized fraction may contribute to stiffness or other functional properties. However, biochar production adds a thermal process and its environmental burden and particle structure must be included in any comparison [3], [13].

Cellulose microfibrils and nanocellulose represent higher value fractions that can act as reinforcing or barrier modifiers at relatively small contents. Their large surface area can increase interfacial contact, but the same surface area makes them prone to aggregation and difficult drying. A well dispersed nanoscale fraction may alter modulus, crystallization, or transport properties, yet scale-up must account for extraction chemicals, water use, energy, and the ability to disperse the material reproducibly [1], [18].

C. POLYMER MATRICES AND SUSTAINABILITY LABELS

Thermoplastic matrices such as polypropylene and polyethylene offer melt processing and potential remelting, but mixed fiber-plastic streams can complicate sorting and recycling. Thermosets such as epoxy and polyester cure into networks that often have good shape retention, but cannot generally be remelted into the original resin. A bio-based matrix may have the same chemical composition as fossil derived polymers, while biodegradable matrices such as some PLA grades need particular temperature, humidity, and microbial conditions to degrade. Bio-based content, biodegradability, and recyclability are different attributes and should be reported separately [2], [13], [14].

The matrix is chosen based on the service envelope. It should wet the reinforcement at a feasible viscosity and process temperature, retain properties at the intended temperature and humidity, resist creep under sustained stress, and bond to fasteners or coatings. A matrix that performs well in a dry lab test can soften or age rapidly in a hot, humid environment. Whereas, a rugged fossil based matrix can outperform a biodegradable resin in a long-life part. The correct comparison considers the whole product, not only the source of a single constituent [14], [18].

D. FEEDSTOCK SELECTION AS AN ENGINEERING DECISION

Residues have competing uses. Some are returned to fields to protect soil, maintain organic matter, and recycle nutrients; others are already used for animal bedding, energy, or process heat. A composite manufacturer must consider the fraction that can be sustainably and reliably diverted rather than treating all harvest residue as free feedstock. The residue's market value also changes the appropriate allocation in a life cycle assessment. Once a waste stream becomes a saleable co-product, the assumption that it carries no upstream burden becomes less defensible [1], [16], [17].

A practical screening sequence begins with a local supply map and then tests the stream's variability, contamination, and conversion yield. The intended product determines whether long fibers, short fibers, particles, ash, or cellulose are needed. The matrix and process define the allowable moisture and temperature window. Finally, the intended service environment determines whether the composite requires coating, hybridization, or a sheltered use. This sequence avoids selecting a residue solely because it is abundant in aggregate statistics.

III. PROCESSING AND INTERFACE ENGINEERING

A. Feedstock Preparation and Forming

A typical process chain includes cleaning and sorting, drying, size reduction or fiber extraction, classification, optional surface modification, compounding with polymer, forming, and conditioning. Moisture control is essential because wet biomass can generate vapor and voids during melt processing or curing. Grinding and sieving produce reproducible particle fractions but can shorten fibers and increase dust; mechanical, chemical, or enzymatic fiber extraction can preserve useful aspect ratio but adds cost, water, and energy demands [1], [3], [4].

Hand lay up and vacuum assisted infusion are accessible for low-volume thermoset laminates and mats, although labor and resin distribution limit throughput. Compression or hot pressing is widely suited to boards, sheets, and molded parts. Extrusion and injection molding support scalable thermoplastic compounding, but shear and heat can shorten or degrade fibers. Resin



transfer molding can produce more controlled laminates when permeability and resin flow are well managed. Process choice is therefore a trade off among fiber architecture, production scale, dimensional tolerance, cycle time, and quality control [2].

B. Surface Modification and Load Transfer

Plant fibers contain cellulose, hemicellulose, lignin, waxes, and other constituents. Their polar, moisture-attracting surfaces are often poorly compatible with nonpolar thermoplastics. Alkali treatment can remove surface impurities and part of the hemicellulose or lignin, increasing roughness and exposing cellulose; silane and other coupling treatments can promote bonding between fiber and matrix; and maleated polymer compatibilizers are used in some polyolefin systems. These strategies may improve wet out and interfacial shear transfer, but treatment severity, residual chemicals, fiber source, and matrix chemistry control the outcome [5], [6].

Treatment is not a guaranteed strength increase. In one compression-molded kenaf/epoxy study, 50 wt% fiber composites were prepared with untreated fiber and fiber treated in 6 wt% sodium hydroxide for 24 h. Although the treatment cleaned the fiber surface, it damaged fiber strength and the treated composite showed reduced tensile performance relative to the untreated-fiber composite [5]. The example illustrates why optimization must evaluate both single-fiber damage and composite behavior, while accounting for wastewater, chemical recovery, and treatment energy.

Other controls are equally important: fiber length and aspect ratio, orientation, volume fraction, dispersion, matrix viscosity, mold pressure, cure or melt history, and void content. As reinforcement content rises, stiffness may initially improve, but poorly wetted bundles, agglomeration, and porosity can reduce strength and impact resistance. Process monitoring and incoming-feedstock specifications are therefore essential to reproducibility.

C. PRE-TREATMENT, COUPLING, AND COMPOUNDING

Pretreatment is best understood as a means of controlling the fiber surface and moisture response, not as a universal recipe. Washing and sieving remove dust and soluble impurities. Drying limits vapor generation and void formation during melt processing or cure. Alkali treatment can remove some non-cellulosic surface material and increase roughness. Silanes, maleated compatibilizers, and selected coatings can bridge chemical differences between a polar fiber and a less polar matrix. Enzymatic or physical treatments may lower chemical consumption in some applications, but process water, enzyme recovery, reaction time, and residual organics need to be measured [5], [6], [18].

Treatment severity creates a design trade off. A stronger solution or longer exposure may increase fiber roughness while also degrading cellulose, reducing fiber strength, or causing fibrillation that makes handling difficult. The kenaf/epoxy study in [5] is useful because it evaluated both the fibers and molded composites: the selected alkali treatment cleaned the surface but did not produce the expected composite tensile improvement. This result should not be generalized as evidence against alkali treatment. It shows that treatment concentration, time, temperature, rinsing, drying, and matrix type must be optimized as a complete process.

Compounding must preserve a useful balance between dispersion and fiber integrity. High shear helps break up particle clusters, but can shorten fibers and reduce their aspect ratio. Low shear may preserve length but leave bundles, entrapped air, and poor matrix penetration. For compression molding, mat architecture, preform moisture, pressure, and temperature govern resin distribution and consolidation. For extrusion or injection molding, screw design, residence time, melt temperature, and injection flow determine fiber attrition and orientation. For every route, void fraction and fiber distribution should be measured rather than inferred from the nominal recipe [2], [13], [14].

D. THERMOPLASTIC AND THERMOSET MANUFACTURING ROUTES

Thermoplastic compounding often begins with drying and premixing, followed by twin-screw extrusion or another melt-compounding operation. The resulting pellets may be injection molded, compression molded, or extruded into profiles. This sequence lends itself to process integration and higher throughput, but repeated thermal histories can degrade both polymer molecular weight and biomass. A low processing temperature may protect the fiber yet leave the matrix too viscous for complete impregnation. The process window is therefore bounded by the matrix melt behavior on one side and the biomass thermal stability on the other.

Thermoset processing begins with a liquid resin or low-viscosity precursor, which can infiltrate mats or aligned architectures before curing. Hand lay-up and vacuum assisted infusion are flexible but require controls on resin content, air removal, and operator technique. Resin transfer molding can produce more repeatable shapes if preform permeability and flow paths are understood. Cure kinetics and exotherm matter because thick sections may heat unevenly. Thermoset composites can be relevant where dimensional stability is important, but their crosslinked matrix presents more difficult mechanical recycling than thermoplastics [2], [13].



TABLE II. PROCESSING ROUTES AND THEIR MAIN ENGINEERING TRADE-OFFS

Route	Typical fit	Main control or limitation
Compression / hot pressing	Boards, sheets, mats, molded shells	Preform moisture, pressure uniformity, voids, cure or cooling
Extrusion / injection	Compounded thermoplastics and repeatable parts	Fiber attrition, dispersion, melt temperature, flow orientation
Hand lay-up / infusion / RTM	Thermoset laminates and shaped preforms	Labor, resin distribution, permeability, cure consistency
FDM / direct ink writing	Complex shapes, prototypes, localized production	Rheology, nozzle limits, layer bonding, anisotropy

Table II summarizes common routes in terms of the architecture they enable and the principal risks. The same process name can produce very different composite quality when fiber moisture, aspect ratio, matrix viscosity, pressure, or thermal history changes. Consequently, process selection should be treated as part of material design, not as a downstream manufacturing detail [2], [13], [14].

IV. MECHANICAL PROPERTIES AND STRUCTURAL POTENTIAL

A. Tensile, Flexural, Impact, and Stiffness Response

Tensile strength measures resistance to axial failure, while tensile modulus reflects initial stiffness; flexural tests combine tension and compression across a bending section and are sensitive to surface defects, span to depth ratio, and specimen architecture. Agro-waste composites often show their most useful performance when reinforcement orientation and wet out are controlled. Short random fibers and particles are easier to compound but generally provide less directional load transfer than aligned fibers or woven mats. A rise in modulus may coexist with lower strain to failure or impact toughness, so “better mechanical properties” should never be used without naming the test and metric [2]-[4].

Published property values should be compared only when matrix chemistry, reinforcement fraction, fiber geometry, conditioning, and test standard are sufficiently similar. Reviews cover systems ranging from flour filled commodity plastics to aligned fiber bio-epoxies, and the reported values cannot be treated as a single design envelope [1]-[4]. A defensible comparison reports the full formulation, processing history, density, test geometry, sample count, variability, and moisture conditioning. For engineering selection, specific strength and stiffness are useful, but absolute capacity, buckling resistance, joints, and long-term allowable values remain decisive.

B. Candidate Product Classes

Near-term opportunities include interior automotive panels, furniture and decking components, noncritical housings, partitions, boards, acoustic panels, and lightweight building products. These applications value low mass, surface finish, thermal or acoustic function, and the ability to mold complex shapes. Structural roles may also be possible in hybrid components where a conventional load bearing frame carries primary loads while an agro-waste composite provides a panel, skin, or secondary reinforcement. Such use should be described as application-specific rather than as a general substitution for glass or carbon fiber composites [2], [8], [9].

Construction evidence requires careful classification. Agro-waste used as aggregate, ash, or fiber in cementitious concrete is not the same material system as a polymer matrix biocomposite. Reviews of agricultural waste concrete report promising structural results in selected beams and mixes, but also identify variability and gaps in long term durability and standards; those findings indicate the importance of qualification, not proof that a polymer composite is already code-ready [11].

C. FAILURE MECHANISMS AND TEST INTERPRETATION

Failure in a short fiber or particle composite is usually progressive rather than a single clean break. Matrix cracks can initiate around a cluster or void; a crack may then deflect along an interface, pull fibers out, or rupture them. In a laminate, damage may include matrix cracking, delamination, local buckling, or edge splitting. Fiber pull out can dissipate energy in some configurations, but extensive pull out also signals inefficient load transfer. Microscopy and fracture surface analysis therefore help explain why two specimens with similar average tensile strength may fail differently [2], [18].

Test geometry can amplify these differences. Flexural strength may be strongly affected by surface flaws and specimen thickness. Tensile testing of discontinuous fibers can show high scatter when local orientation varies. Impact tests measure a different combination of damage initiation and energy absorption than quasi static tension. Fatigue results depend on stress ratio, frequency, specimen heating, and failure definition. Unless these conditions are reported, an apparent ranking among residues may reflect the test setup rather than an intrinsic feedstock advantage [7]-[9].

D. WHAT REPRESENTATIVE EXPERIMENTS SHOW AND DO NOT SHOW

The kenaf study discussed earlier highlights one limit of a simple “chemical treatment improves adhesion” narrative: changing the surface can alter the fiber itself, and a cleaner surface does not ensure a stronger finished composite [5]. In a separate fused deposition study, PLA was compounded with lignocellulosic fillers obtained from *Opuntia ficus indica* and *Posidonia oceanica*. The authors found that, for their selected formulations, replacing up to 20% of the PLA with filler did not significantly change processability or measured mechanical performance [15]. That is evidence that some waste fillers can be



integrated into a printable formulation, not evidence that all agro-residue composites retain matrix strength at 20% loading or that the printed parts meet structural design requirements.

The same caution applies to rice husk composites. Rice husk reviews describe polymer systems using husk flour, shell fibers, ash, and biochar across several matrices and processing methods [3]. Because each form has a different morphology and surface, data from one cannot be substituted for another. The important synthesis is a set of relationships: fine particles often disperse more easily but provide less reinforcement length; ash introduces a silica rich mineral phase; and aligned or longer fibers can carry greater directional load if impregnation and bonding are adequate. These relationships guide formulation but do not replace testing of the actual feedstock batch.

Table III and Fig. 2 show a single study trade off: 20 wt% filler lowered strength relative to neat PLA, while Charpy impact increased at 10 wt% and fell at 20 wt%. The largest strength loss occurred for OFI20; these results do not establish cross study rankings or structural qualification [15].

TABLE III. REPORTED MECHANICAL PROPERTIES OF SELECTED FDM-PRINTED PLA BIOCOMPOSITES [15]

Formulation	Filler (wt%)	Tensile strength (MPa)	Flexural strength (MPa)	Charpy impact (kJ/m ²)
PLA	0	60 ± 2	98 ± 6	21.2 ± 0.5
OFI10	10	54 ± 2	58 ± 4	25.4 ± 0.7
OFI20	20	32 ± 5	46 ± 2	11.3 ± 0.4
POL10	10	52 ± 2	76 ± 8	23.9 ± 1.0
POL20	20	38 ± 7	60 ± 4	15.9 ± 0.8

OFI = *Opuntia ficus-indica* flour; POL = *Posidonia oceanica* flour. Values are reported mean ± the source-reported variation; no significance test is inferred here. Filler contents are mass fractions. Tensile testing used at least seven specimens at 25 °C and 50% RH; flexure and impact followed ASTM D790 and D6110, respectively [15].

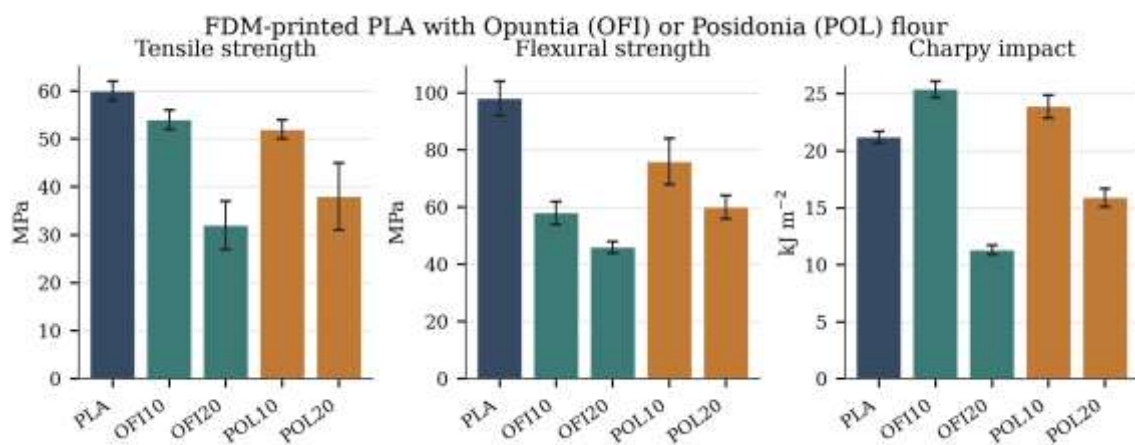


Fig. 2. Within-study tensile, flexural, and Charpy impact results for FDM-printed PLA formulations. Error bars reproduce the article's reported ± values; formulations and test conditions are not representative of all agro-waste composites [15].

E. Structural Design Implications

Structural qualification requires characteristic properties and design values, not only the mean strength of a small sample. The characteristic value must account for scatter and be associated with a specific formulation, process, direction, conditioning state, and material lot. Safety factors then address uncertainties in loading, environment, production, and consequence of failure. Natural fiber composites add uncertainty from biological variability and moisture history, so quality assurance must trace the feedstock and the manufacturing batch [8], [18], [19].

Connections are a particularly important weak point. Bolted holes, adhesive joints, inserts, and bonded seams introduce stress concentrations and can expose cut fibers or end grain like pathways to moisture. Bearing, pull through, delamination, and fastener relaxation may govern before the unnotched coupon strength is reached. A practical structure may therefore require local reinforcement, edge sealing, hybrid skins, or mechanically designed inserts. Such details are rarely captured in coupon level tensile and flexural data.

For components with directional loads, architecture can be more efficient than simply increasing fiber content. Continuous or aligned fibers can be placed along principal load paths; woven or stitched forms can improve transverse integrity; random short fibers offer more isotropic behavior and easier mass production but generally lower directional efficiency. Hybrid architecture can place a higher performance outer layer around an agro-waste core or combine fibers with a conventional reinforcement where the safety case requires it. This provides a route to substitute material selectively rather than requiring full replacement of a conventional composite [8], [9], [18].



F. Candidate Applications by Exposure and Consequence

Automotive interiors and transport panels are promising because low mass and acoustic damping can be valuable while the part may be protected from direct weather. Yet interior parts still face temperature cycling, humidity, odor and volatile emission requirements, fire regulations, abrasion, and long term vibration. A natural fiber panel that passes a room temperature bending test may not pass a hot humid aging requirement. Candidate selection should therefore be tied to the actual component category, not to a general statement that plant fibers are used in automobiles [2], [14].

For buildings, sheltered wall panels, door cores, ceiling elements, interior partitions, and furniture components are closer-term opportunities than exposed primary beams. Outdoor decking or cladding introduces ultraviolet radiation, rain, freeze-thaw, fungal growth, and wet dry cycling, so coatings, edge protection, and drainage details may be essential. Cementitious applications containing agro-waste, such as shell aggregate or ash modified concrete, belong to a separate materials class. Their structural studies may help define testing questions, but their design rules cannot simply be transferred to a polymer matrix composite [11], [18].

Agricultural equipment and rural infrastructure offer another possibility when local feedstocks and local repair networks coincide. A locally manufactured enclosure, tool housing, pallet, or noncritical panel may gain from reduced transport and a familiar supply stream. At the same time, agricultural equipment can encounter water, fertilizer, soil abrasion, and cleaning chemicals. The use case is attractive only when maintenance and replacement intervals are accounted for; low feedstock cost is not enough to justify a short-lived part.

V. RECENT ADVANCES

Recent research is broadening the feedstock palette beyond conventional natural fibers. Wheat straw is a well studied, regionally abundant stream in parts of Europe, while fruit peels, nutshells, coffee silverskin, bran, and agricultural ashes are being explored as particulate or functional additions. These feedstocks can enable local circular value chains, but the best material will depend on the availability, competing uses, collection radius, and preprocessing infrastructure of each region [1], [4].

Hybridization combines two fiber types or a natural fiber with a conventional reinforcement to balance stiffness, toughness, cost, and moisture response. Multiscale designs that combine macro-fibers with cellulose micro or nanofillers aim to improve stress transfer and barrier behavior, although dispersion and agglomeration remain difficult. Bio-based matrices and compatibilizers can reduce fossil derived content, but their process windows, moisture resistance, cost, and end of life performance must be assessed together rather than inferred from bio-based labeling [1], [2], [7].

Additive manufacturing is an emerging route for complex geometries, rapid iteration, and localized production. Biomass filled filaments or printable pastes are sensitive to particle size, feedstock moisture, rheology, nozzle dimensions, layer direction, and interlayer adhesion. Printing parameters influence strength, flexibility, and dimensional accuracy, and layer-wise anisotropy means that results from a small coupon cannot be assumed to transfer directly to a full component [10]. For now, additive manufacturing is most compelling for prototypes and low volume parts while structural reliability data mature.

A. Waste-Derived Matrix Building Blocks

A more complete circular-material strategy can use residues both as reinforcement and as feedstock for polymer building blocks. Reviews describe routes from agricultural biomass to starch-based plastics, cellulose materials, polylactic acid precursors, and other biodegradable or bio based polymers [14]. This approach could reduce the fossil origin of both matrix and reinforcement, but it also adds conversion steps. Fermentation, extraction, purification, polymerization, and compounding each have yield, energy, and chemical requirements. An all biomass formulation is not automatically lower impact if those upstream operations are inefficient or the material fails early.

B. Hybrid and Multiscale Design

Hybridization is increasingly used to address the limitations of a single natural fiber. Two plant fibers may provide a balance between tensile stiffness and impact absorption. A natural fiber can also be combined with glass, basalt, or another higher strength reinforcement in a hybrid laminate, placing each material where its properties are most useful. Multiscale reinforcement adds cellulose fibrils, microcrystals, or nanoscale particles to a matrix containing larger fibers. These approaches are promising but make dispersion, interface chemistry, recyclability, and data interpretation more complex [2], [9], [18].

A hybrid design should be evaluated across the full part and its life cycle. Adding a small amount of a synthetic fiber may improve load capacity enough to reduce section thickness or extend service life, but it may complicate separation at end of life. Conversely, an all bio based matrix may simplify a sustainability narrative while lowering moisture resistance. Engineering optimization should therefore specify the target failure mode and service environment before choosing the hybrid architecture.

C. ADDITIVE MANUFACTURING AND DIGITAL PROCESS CONTROL

Additive manufacturing provides fine control over geometry and fiber path, yet the route imposes its own design limits. Fused deposition modeling (FDM) deposits a thermoplastic filament in adjacent roads and layers. A natural filler can lower material cost or valorize a waste stream, but it can also change melt flow and increase nozzle wear or clogging. Direct ink



writing can process a viscous paste but requires a rheology window that supports extrusion and retains shape after deposition. In both cases, the layer interfaces and build direction create anisotropy [10], [15].

One PLA-FDM study produced printable formulations with 10 and 20 wt% *Opuntia* (OFI) or *Posidonia* (POL) flour, but higher loading reduced mean strengths, most strongly for OFI20. Table III and Fig. 2 show the measurements and their formulation-specific scope; printability alone is not structural qualification [15].

Digital manufacturing advances can also improve feedstock traceability. Moisture sensing, inline torque or pressure monitoring, thermal imaging, and computer vision may detect changes in feedstock or dispersion during production. Coupled with batch records, these tools can help identify the process states associated with acceptable quality. Their value depends on calibrated models and representative training data; a sensor dashboard alone cannot correct an inconsistent incoming biomass stream.

VI. DURABILITY, QUALIFICATION, AND SCALE-UP

A. Moisture, Fatigue, Creep, and Fire

Moisture is a coupled chemical and mechanical problem. Hydrophilic fibers absorb water, swell, and create stresses at the interface; repeated wetting and drying can promote microcracking, debonding, and delamination. A 2025 review reports tensile-strength losses up to about 40% and elastic modulus reductions of 20-30% in some reviewed conditions, with results strongly dependent on fiber fraction, fiber type, and treatment. These values describe reported cases, not universal reduction factors [7]. Coatings, surface treatments, hybridization, and matrix selection can reduce exposure or slow water transport, but do not remove the need for service environment testing [7], [8].

Cyclic loading and sustained loading are also critical. Fatigue performance changes with moisture, stress ratio, orientation, architecture, and interface quality; the evidence base is often weighted toward tension-tension tests, while compression fatigue and realistic combined environments are less represented. Plant fiber composites can exhibit substantial creep, so stiffness and strength measured immediately after manufacture are insufficient for long term elements [8], [9]. Fire and biological resistance also depend on the entire formulation: lignocellulosic reinforcement can increase combustibility, while coatings or flame retardants may affect emissions, recyclability, and the claimed environmental advantage [2], [8].

B. Testing, Standards, and Environmental Claims

Coupon testing should be paired with conditioning and structural scale validation. Flexural measurements can follow recognized composite methods such as ISO 14125, while tensile, impact, water uptake, fatigue, creep, weathering, freeze thaw, fire, and biological exposure require protocols appropriate to the matrix and intended service. A standard test provides repeatability; it does not by itself establish design allowables, connection capacity, or acceptance by a building code [8], [11], [12]. Robust qualification therefore requires statistical sampling across batches, documented feedstock controls, manufacturing tolerances, and full scale element testing.

Scale up also depends on residue logistics. Low or negative gate cost at the farm does not necessarily mean low delivered cost after collection, drying, storage, separation, chemical treatment, transport, and rejected-batch management. Life cycle assessment should compare a defined product and functional unit against a realistic incumbent, including changes in service life, maintenance, resin source, land management, transport, and end of life. Residue removal can also compete with soil carbon and nutrient-return functions. Sustainability should therefore be demonstrated by a transparent system boundary rather than presumed from the use of waste biomass [1], [2].

C. STRUCTURAL DESIGN GUIDANCE AND ITS LIMITS

The European technical specification CEN/TS 19101:2022 is an important development for fibre-polymer composite structures because it addresses the design basis, material properties, environmental effects, creep, fatigue, and connections [19]. It demonstrates the level of design evidence needed for structural composites. It should not be read as an automatic approval for any agro-waste formulation: a material must have representative test data and an accepted route for deriving design properties. Existing specifications for established FRP systems may not cover the variability and durability profile of a particular residue reinforced polymer.

A qualification program for a proposed component should proceed from material coupons to subcomponents and then to full scale elements. Coupons establish tensile, flexural, shear, impact, and environmental conditioned properties. Subcomponent tests address holes, bonded seams, inserts, and edge effects. Full scale testing checks load distribution, deflection, instability, manufacturing defects, and failure modes that are absent from small coupons. The sequence should be tailored to consequence: an interior trim panel and a pedestrian bridge member require very different evidence.

D. DURABILITY AND ENVIRONMENTAL CONDITIONING

Moisture enters through exposed surfaces, cut edges, pores, and cracks. Water can plasticize some matrices, swell the fiber, and weaken the interface. The mismatch in dimensional response can lead to residual stress on drying and microcracking after repeated cycles. Ultraviolet radiation can degrade the polymer surface, while heat can accelerate oxidation or hydrolysis depending on the matrix. Freeze thaw exposure adds another mechanism when absorbed water expands. Accelerated aging tests



should be interpreted alongside realistic field exposure, since a single severe laboratory condition may not reproduce the sequence of wetting, drying, heating, and loading seen in service [7], [8], [18].

Creep is time dependent deformation under sustained load. It matters for beams, shelves, panels, and connections that may support a constant dead load for years. Fiber-matrix bond, fiber orientation, moisture, temperature, and polymer viscoelasticity influence creep. A short term modulus cannot be used as a long term stiffness without a validated reduction or prediction model. Fatigue has a similar dependence on load history and environment. Testing should report stress ratio, frequency, waveform, temperature, conditioning, and run out definition; otherwise the reported cycle count is difficult to use in design [8], [9], [19].

Fire performance is another application gate. Lignocellulosic fibers are combustible, and polymer matrices contribute heat release and smoke. Flame retardants, intumescent coatings, or mineral additions may improve fire response, but can alter mechanical properties, processability, emissions, and recyclability. Therefore, fire performance should be verified on the final formulation and representative thickness rather than inferred from the reinforcement or matrix in isolation [2], [18].

E. Life-Cycle Assessment and Functional Equivalence

LCA is functional unit dependent, not a green label. Kilogram to kilogram comparisons can mislead when density, thickness, load capacity, or service life differ; compare components delivering equivalent performance over an equivalent service period [16], [17].

Many agro-biocomposite LCAs stop at the factory gate, even when service durability is central; replacement, coating, and repair can change results. The 2026 review notes cradle to grave assessments remain less common and methodological/data gaps materially affect conclusions [16], [17].

Treat a residue as burden free only when it has no competing use and no extra cultivation is induced; collection, transport, or field removal changes the assumption. Report allocation and test sensitivity to service life, transport, drying/treatment energy, matrix content, and end of life [1], [16], [17].

F. Manufacturing Scale-Up and Quality Assurance

Commercial scale up depends on more than equipment capacity. Producers need stable supply contracts, covered storage, moisture management, preprocessing, and a way to segregate grades. A central compounding plant may gain scale economies but incur transport cost for bulky, low density residues. Local preprocessing can lower transport of water and coarse biomass, but may require capital investment and quality systems across multiple sites. These decisions depend on residue concentration, processing yield, and the distance to product manufacturers [1], [13], [14].

Quality assurance should connect incoming feedstock data with part performance. A batch record can include supplier, location, harvest or production window, moisture, ash, particle size distribution, treatment recipe, drying history, compounding settings, and test results. Statistical process control can then identify drift before it becomes a field failure. If a design uses aligned fibers, orientation and lay up records are essential; if it uses injection molded short fibers, fiber length after compounding and gate orientation may be the critical measures.

VII. RESEARCH GAPS AND IMPLEMENTATION PRIORITIES

A. Establish Feedstock and Formulation Specifications

A first priority is to replace vague crop labels with material descriptors. Future papers and supplier specifications should report residue origin, crop or process stream, extraction route, moisture, ash, size or length distribution, density, and storage history. Polymer formulation should state matrix grade, additives, compatibilizer, reinforcement mass and volume fractions, and any surface treatment residues. This minimum record would make cross-study synthesis more reliable and help identify which differences are biological and which are caused by processing [1], [3], [4], [13].

B. Build Durable, Application-Specific Data Sets

A second priority is a coordinated test matrix that combines mechanical loading with environmental conditioning. A useful program would compare dry and conditioned tensile/flexural properties, impact, creep, and fatigue for the same formulation, then examine retained properties after wet dry, thermal, ultraviolet, and freeze thaw exposures relevant to the use case. Compression fatigue and connection tests deserve particular attention because these modes are underrepresented relative to simple tension coupons [7]-[9], [18].

C. CONNECT MATERIAL COUPONS TO DESIGN ALLOWABLES

Data should be collected across independent feedstock batches and production runs so that characteristic rather than best-case values can be estimated. Models of moisture transport, time dependent deformation, and fatigue should be calibrated against those observations and validated on components not used for model fitting. Design rules can then specify limits for environment, geometry, defects, and joints. Such development should build on composite design principles while explicitly testing their assumptions for biologically variable reinforcement [8], [18], [19].

D. VALIDATE MANUFACTURING AND CIRCULARITY TOGETHER

Demonstration parts should be manufactured with realistic equipment and quality controls, not only laboratory methods. Pilot projects can test whether a local residue supply supports consistent production across seasons and whether rejected parts



can be reprocessed. The same pilot should collect inventory data for energy, water, chemicals, yield, scrap, transport, maintenance, and end of life. Joining mechanical validation to LCA prevents a sustainability case from relying on a high performing coupon or a cradle to gate estimate alone [16], [17].

Shared test procedures and open data including unsuccessful formulations would improve comparability and help identify process trade-offs across polymer, agricultural, and structural engineering research [5], [7], [19].

VIII. CONCLUSIONS

Agro-industrial residues can reinforce polymers, but performance depends on feedstock, interface, processing, and conditioning. The FDM data show higher filler loading can reduce strength even when printable [15]. Near term uses are protected, semi structural products. Load bearing adoption requires batch control, durability and connection testing, component validation, and service life LCA. Select each formulation against a defined load and exposure envelope.

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