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[1.]Imre KISS, [2.] Valentin VLĂDUȚ

AGRO–WASTE FIBRE COMPOSITES MANUFACTURING: COMPARATIVE KEY METHODS AND CHALLENGES IN THEIR PROCESSING

[1.] University Politehnica Timisoara, Faculty Engineering Hunedoara, Department Engineering & Management, Hunedoara, ROMANIA
[2.] National Institute of Research – Development for Machines and Installations Designed for Agriculture and Food Industry – INMA Bucharest, ROMANIA

Abstract: Lignocellulosic fibres derived from agricultural residues (e.g., wheat straw, rice husks, bagasse, corn cobs) are rapidly emerging as viable, low—cost, sustainable reinforcements in polymer composites, offering an environmentally responsible alternative to synthetic glass or carbon fibres. This report synthesizes current knowledge on their composition, properties, processing methods, performance metrics, and industrial adoption. Key findings indicate that treated lignocellulosic fibres can achieve tensile strengths of 20–40 MPa in polymer matrices, with density reductions of 30–50% compared to glass—fibre composites. However, challenges persist in interfacial adhesion, moisture sensitivity, and feedstock variability. With optimized surface treatments (alkali, silane, coupling agents) and advanced processing (compression moulding, extrusion, injection), these bio—composites are gaining traction in automotive, construction, and packaging sectors. Romania shows limited commercial—scale manufacturing of agro—waste composites, with activity centred on research and pilot projects rather than widespread industry. Romanian research on agro—waste composites is primarily academic, led by universities and institutes focusing on lignocellulosic wastes like wheat straw and sunflower husks for sustainable materials. These efforts emphasize prototypes for construction panels and bioplastics, aligning with national circular economy goals, developing prototypes using local lignocellulosic wastes (e.g., wheat straw, sunflower husks) with recycled polypropylene, achieving viable mechanical properties via treatments. The paper concludes with strategic recommendations for scaling production, standardizing feedstocks, and integrating circular economy principles to accelerate market penetration, using right processing method for agro—waste composites.

Keywords: agro–waste composites, key processing methods, comparison, challenges

1. ABOUT AGRO—WASTE COMPOSITES

Lignocellulosic fibres—composed primarily of cellulose (40-70%), hemicellulose (20-40%), and lignin (10-25%)—offer mechanical properties comparable to low—grade glass fibres at a fraction of the cost and environmental impact. Agricultural residues, often burned or landfilled, provide a locally abundant, renewable feedstock. These residues are underutilized, representing untapped economic potential.[1-5] These residues are abundant, low—cost, and underutilized (>60—70% wasted), offering a sustainable alternative to synthetic fibres.

One efficient method of utilization of agro-wastes and by—products is their incorporation into composite materials. Composite materials are made up of two constituents' reinforcement and matrix. Collectively, the materials in composites are constituted in such a manner that the weaknesses of one material can be covered by the strengths of the other material. Reinforcement is usually responsible for load bearing whereas matrix provides load distribution and environment protective properties to the composite. Their combination can provides properties better than their counterparts individually. [1-5] In recent years, several academics have examined the use of by—products and waste materials for composite fabrication.

Agricultural residues represent ~2.5 billion tons/year globally, with the top lignocellulosic sources offering massive feedstock potential for composite reinforcement. Agro—waste composites transform agricultural by—products like husks, straws, and fibres into sustainable materials by combining them with matrices such as polymers or resins, yielding lightweight, biodegradable alternatives to traditional composites. [1-5] These materials promote circular economy principles through waste valorisation, reducing environmental impact while enhancing mechanical and thermal properties. Agro—waste sources for composites primarily include lignocellulosic by—products from agriculture, such as husks, straws, cobs, shells, and fibres, which are abundant, renewable, and rich in cellulose for reinforcement. [1-5] These materials are sourced globally, with high availability in regions like Asia, Europe, and the Americas, supporting circular economy goals by valorising residues that would otherwise be discarded. [6-8]

Agro—waste composites consist of lignocellulosic reinforcements from residues like rice husks, corn stalks, sugarcane bagasse, and wheat straw integrated into a matrix (e.g., thermoplastics like PP, PE, or biopolymers like PLA). [1-5] Agro—waste composites are classified by waste type and matrix, according to Table 1. Processing classes include thermoplastic (e.g., extrusion for profiles), thermoset (e.g., compression for rigid parts), and bio—composites (e.g., mycelium for biodegradable items).

Table 1. Agro—waste composites

CATEGORY	EXAMPLES OF AGRO—WASTE	COMMON MATRICES	APPLICATIONS
LIGNOCELLULOSIC FIBRE—REINFORCED	Rice husk, wheat straw, corn cob, sugarcane bagasse	PP, PE, epoxy, PLA	Construction panels, automotive parts
PARTICLE/FILLER—BASED	Coconut shell, walnut shell, hazelnut shell	Epoxy, PU	Insulation, wear—resistant components
HYBRID/BIO—BASED	Mycelium—grown on agro—substrates, fruit peels	Natural polymers	Packaging, furniture

The process involves collecting, cleaning, grinding, and mixing waste with binders, followed by processing methods to form durable products. [9-21] Key benefits include renewability, low cost, reduced carbon footprint, and properties like improved tensile strength, thermal insulation, and biodegradability.

Poor fibre—matrix compatibility due to hydrophilic agro—waste and hydrophobic polymers leads to weak bonding and reduced mechanical performance. Processing issues include uneven dispersion, high moisture absorption, and variability in waste quality. Scaling production faces financial constraints, limited expertise, inadequate data systems, and regulatory hurdles for commercialization. Solutions involve surface treatments and optimization techniques. [9-21]

2. SHORT HISTORY

Agro—waste composites first appeared in the early 1990s through pioneering studies on coir fibre—reinforced waste polyethylene composites treated chemically for improved surface properties. Early efforts focused on lignocellulosic agro—wastes (e.g., husks, straws) blended with thermoplastics like PP or PE to address incompatibility via coupling agents. Processing methods for agro—waste composites have evolved from basic mechanical blending and manual forming in the early 1990s to advanced, optimized techniques emphasizing sustainability and scalability by 2026. Initial focus was on adapting conventional polymer processing to low—cost fillers like rice husks, with compression moulding dominating due to its simplicity for thermosets.

Early developments on agro—waste composites accelerated in the early 2010s, highlighting plastic—reinforced versions using extrusion and moulding for building/automotive uses. Pioneering work used hand lay—up and simple compression (100—150°C, 10—20 bar) for coir or bagasse/epoxy panels, limited by poor adhesion and manual labour. By late 2000s, extrusion emerged for continuous thermoplastic profiles (e.g., husk/PP pipes), alongside injection moulding for small parts, though fibre breakage was common without pre—treatments. Thermoforming added sheet—based packaging, while hybrid methods like extrusion—compression improved uniformity for automotive interiors.

By 2020-present, focus shifted to sustainability, incorporating treatments like alkali for better adhesion and new agro—waste reinforcements. Optimization via parameters like temperature, pressure, and coupling agents improves properties such as adhesion and moisture resistance. 2020s introduced bio—based innovations: mycelium growth on waste substrates (no heat/pressure), microwave—assisted compression (2—5 min cycles), and thermo—compression at 180—220°C. Hand lay—up and compression moulding differ significantly in performance for agro—waste composites, with compression yielding superior mechanical properties and consistency due to uniform pressure and heat, while hand lay—up offers flexibility but suffers from higher voids and variability. Hand lay—up suits prototypes or complex moulds with agro—fibres like bagasse, as it requires low tooling costs and no press, but operator skill impacts quality. Compression excels for production of rice straw or coir panels, delivering higher density ($>1.2\ g/cm^3$) and moisture resistance, ideal for construction applications in waste valorisation projects. For optimal results, pre—treat fibres in both to enhance adhesion.

Trends point to circular economy integration, with recyclable/disassemblable structures and chemical recycling for full material recovery. High—performance bio—resins, nanocomposites, and mycelium tech will enable smart, lightweight materials for construction, EVs, and packaging.

3. PROCESSING METHODS

Choosing the right processing method for agro—waste composites requires balancing product geometry & design, production volume, mechanical requirements, cost constraints, feedstock characteristics and availability.[9-21] The most common processing methods for agro—waste composites are compression moulding, injection moulding, and extrusion, with compression moulding being the most widely used due to its simplicity, cost—effectiveness, and suitability for particle—filled or short—fibre agro—wastes like rice husks, wheat straw, and bagasse. Common processing methods for agro—waste composites include extrusion, injection moulding, and compression moulding, which adapt thermoplastic or thermoset techniques to incorporate fibres or particles from agricultural residues. These methods typically follow pre—treatment steps like grinding, drying, and chemical treatments (e.g., alkali) to enhance fibre—matrix bonding. [9-21]

Common processing methods for agro—waste fibre composites transform agricultural residues into reinforced panels using established techniques tailored to fibre variability. Large structural composite panels are manufactured using several key methods, each suited to different performance, scale, and production requirements. Common processing methods for agro—waste composites adapt thermoplastic or thermoset techniques to incorporate fibres or particles from agricultural residues. These methods typically follow pre—treatment steps like grinding, drying, and chemical treatments (e.g., alkali) to enhance fibre—matrix bonding. [9-21]

- **COMPRESSION MOULDING** — creates agro-waste fibre composite panels by hot-pressing a mixture of chopped agro-waste fibres (e.g., rice husk, bagasse, or pineapple rind) with thermoplastic or thermoset resins in a heated mould to form dense, uniform panels.

Agro-waste fibres are alkali-treated, chopped (typically 5—10 mm), and blended with resin (20—60 wt% fibre loading). Pre—mixed composite material or prepregs are loaded into heated moulds, which then close and apply pressure. Simultaneous heat and pressure cure the composite, producing parts with high fibre volume and strength. The mixture is preheated into a preform, placed in a matched mould, and compressed under heat and pressure until cured; the panel is then cooled and demoulded. Effective for parts with multiple thicknesses and complex contours, including sandwich panel components.

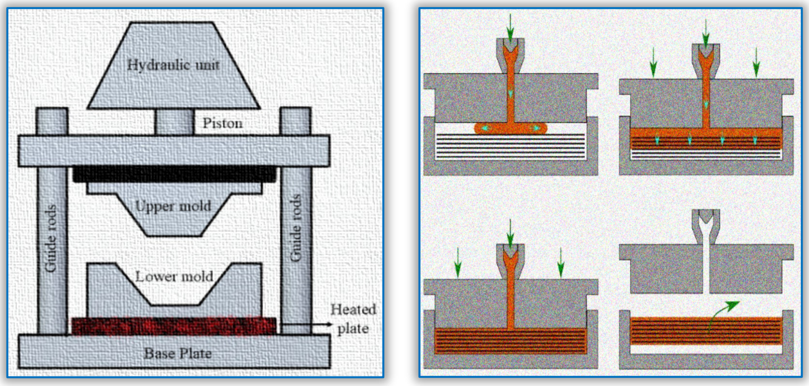

Figure 1. Compression moulding process

Compression moulding parameters must balance matrix flow, fibre integrity preservation, void elimination, and circular economy efficiency. The three pillars—temperature, pressure, time—control 85% of final composite quality. Main parameters are:

- moulding temperature: 150—220°C, balancing resin flow and fibre degradation prevention. Temperature (most critical in this processing method) is adopted for a sufficient to allow heating flow, but avoiding to cause burning (balance flow without degradation).
- pressure: 1—4 MPa for compaction without fibre damage, the progressive compaction preventing fibre breakage.
- curing/holding time: 20—35 minutes, optimizing matrix consolidation, in minimum time for maximum density.
- fibre content: 20—50 wt%, influencing mechanical properties and density.
- pre—heating: 240—270 s at 200—220°C for uniform flow in plant fibre mats.

Each parameter compensates for the others—low temp needs higher pressure/time, high temp allows lower pressure: 175°C ensures resin flows while preserving agro—fibre integrity, 30 bar compacts without breakage, 10 minutes total optimizes throughput vs. quality.

Compression moulding dominates agro—waste processing, but natural fibre properties create 5x more defects than synthetic composites: strength loss due to poor fibre—matrix adhesion, voids & warping at high moisture content (>8%), weak spots due to uneven fibre dispersion, local voids (and therefore, inconsistent properties) or thermal degradation (at >200°C). Key challenges of compression moulding include:

- Heterogeneous agro-waste fibres cause uneven flow and poor wetting, leading to voids or delamination.
- Thermal degradation above 200°C degrades lignocellulosic components, while high fibre content reduces matrix adhesion without compatibilizers.
- Achieving consistent thickness and scalability requires precise parameter control and mould design.

Compression's challenges are easier to solve than other methods.

- **RESIN TRANSFER MOULDING (RTM)** — produces agro—waste fibre composite panels by injecting liquid resin under pressure into a closed mould containing dry natural fibre preforms like bagasse, rice straw, or hemp.

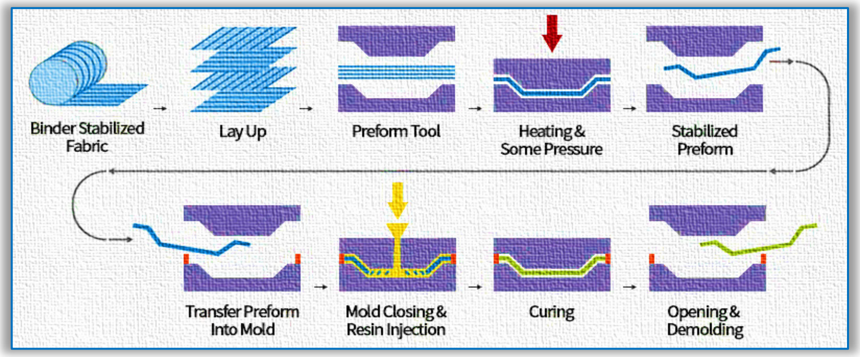

Figure 2. Resin transfer moulding process

Agro-waste fibres are preformed and placed into a matched two—part mould, which is closed and clamped. Resin is then injected at controlled pressure through ports until the preform is fully impregnated, followed by curing and demoulding to form dense panels. This method enables good control over thickness and resin content, with faster cycle times than vacuum infusion. It is suitable for moderately large parts with precise shapes and complex details, controlling low—pressure flow through pre—treated preforms. Therefore, unlike compression's high pressure, RTM prioritizes resin flow dynamics over mechanical compaction.

Main parameters of the RESIN TRANSFER MOULDING (RTM) are:

- injection pressure (most critical in this processing method): 5—120 bar, balancing flow speed and fibre washout prevention, assuring minimum pressure for complete fill and maximum fibre retention.
- resin viscosity: 100—500 cPs for effective penetration into porous agro-waste structures.
- fibre volume fraction: 35—50%, achieved via preform compaction, having in view that the high fibre volume fraction assure a high performance, but flow—limited.
- mould temperature: 30—60°C to control cure rate and minimize defects (warm for flow, cool for dimensional stability)
- filling time: 1—10 minutes, influenced by port design and preform permeability.

RTM excels for complex geometries and high fibre volume fractions (40—60%) using long agro—fibres like bagasse, wheat straw, or coir, delivering superior surface finish and 35—60 MPa tensile strength vs. compression moulding's 25—40 MPa. However, hydrophilic agro—fibres demand precise flow control to avoid fibre wash and dry spots.

Resin Transfer Moulding offers superior performance for complex agro—waste composites (45—60% fibre volume, 35—60 MPa tensile), but hydrophilic natural fibres create unique flow and bonding issues absent in synthetic fibre RTM. Key challenges include:

- uneven resin flow through heterogeneous agro-waste fibres causes voids (up to 5%) and dry spots, requiring flow simulation and optimized injection strategies. Agro—fibres absorb 8—15% moisture, therefore swells preform and blocks resin flow
- high pressure risks fibre displacement ("washout") in low-density preforms, while achieving uniform wetting demands surface treatments.
- scalability is hindered by mould costs and precise control for thick panels.

RTM challenges are double compression moulding's complexity, but double the performance (50—60 MPa vs 25—40 MPa) justifies premium applications like automotive exteriors. For construction panels, compression wins on simplicity.

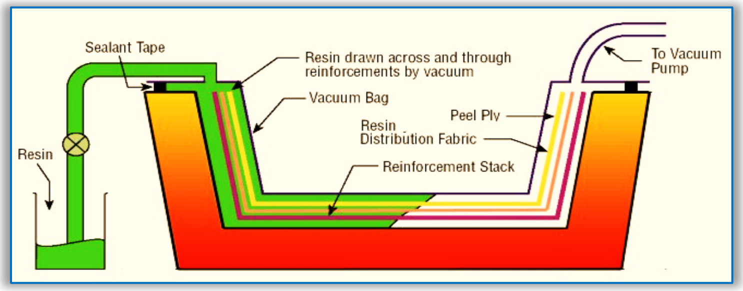

Figure 3. Vacuum infusion process

- **VACUUM INFUSION** (also known as RESIN INFUSION) — is a manufacturing process for creating high-quality composite panels from agro-waste fibres like rice husk, bagasse, or hemp by pulling low-viscosity resin through a dry fibre preform under vacuum pressure.

Dry agro—waste fibre mats or preforms are placed in a mould, covered with a vacuum bag, and sealed. A vacuum pump evacuates air (typically to 0.8—1 bar), compacting the fibres and drawing resin from inlet lines through the preform until fully saturated. Therefore, the laminate then cures under vacuum. The method produces high–quality laminates with excellent fibre/resin ratio and minimized voids. It is suitable for large, complex parts and medium volume production with good mechanical properties. Main parameters of the process are:

- vacuum level: 80–95% vacuum (0.8–0.95 bar) to ensure compaction and void minimization (maximum vacuum without preform collapse).
- resin viscosity: below 500 cPs for optimal flow through porous agro-waste fibres, assuring fast wetting, and controlled flow.
- fibre volume fraction: targets 40–50% for balanced strength; agro-waste often achieves 35–45% due to natural variability.
- infusion time: 10–60 minutes, controlled by inlet port design and resin flow paths.
- temperature: 20–40°C to manage resin gel time and prevent premature curing.

Vacuum Infusion uses atmospheric pressure (approx. 1 bar) to drive low–viscosity resin through dry agro–fibre preforms, achieving 40–55% fibre volume fraction and <2% voids with excellent surface finish on one side. Ideal for large, thin panels (boat hulls, wind blades, truck panels) using long fibres like wheat straw, bagasse, or coir. In fact, the core principle: no injection pressure, just vacuum and flow media control resin front propagation.

Vacuum Infusion promises large–area panels with <2% voids and Class A surface finish, but agro–waste fibres (wheat straw, bagasse, husks) amplify flow control and preform stability issues. Key challenges include:

- agro–waste fibres' high porosity and inconsistency lead to race–tracking (uneven resin flow), requiring precise preform compaction and flow simulation.
- voids (>2%) arise from poor wetting of lignocellulosic surfaces, often mitigated by compatibilizers or hybrid fibres.
- process scalability for panels is limited by vacuum bag leaks and long infusion times for thick sections.

- **PREPREG LAYUP WITH AUTOCLAVE CURING** – adapts high–performance composite techniques to agro-waste fibres (e.g., hemp, rice straw, or bagasse) by using partially pre–impregnated sheets for precise, low–void panels suitable for structural applications.

Agro–waste fibres are impregnated with B-stage resin to form prepregs, cut to shape, and hand- or automated-laid up in precise orientations on a mould. Pre–impregnated fibre layers are stacked and cured under heat and pressure in an autoclave. The stack is vacuum–bagged to remove air, then placed in an autoclave for elevated pressure and temperature curing, followed by cooling and demoulding. The method provides uniform material properties and very high strength, used for aerospace-grade panels. Due to the high cost and complexity, it is suitable for specialized applications requiring exceptional performance. High pressure, low temperature, precise thermal control is the core principle: 5–7 bar achieves 65% fibre volume while 120–140°C protects hemicellulose/lignin from degradation. Main parameters of PREPREG LAYUP WITH AUTOCLAVE CURING are:

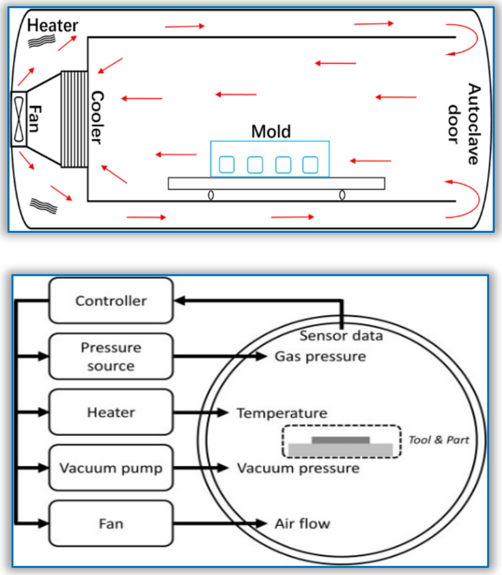

Figure 4. Prepreg layup with autoclave curing process

- autoclave pressure: 5–10 bar to consolidate layers and minimize voids (<1%), assuring maximum consolidation without fibre crush.
- curing temperature: 120–180°C, ramped per resin system to fully crosslink without degradation, in a protective two–stage cure, slow and steady, preventing micro–cracking.
- fibre volume fraction: 50–60%, higher than wet processes due to controlled prepreg resin content.
- layup sequence: specific ply angles (e.g., 0°/90°/±45°) for tailored anisotropy.
- vacuum level: 0.9–1 bar pre-autoclave to debulk layers.

Prepreg autoclave processing targets aerospace–grade performance (55–65% fibre volume, <1% voids, 50–80 MPa tensile) using pre–impregnated agro–fibre sheets. However, thermosensitive natural fibres limit temperatures to 120—150°C (vs. 180°C carbon prepregs), requiring modified cure cycles and specialized resin systems for wheat straw/bagasse viability. Prepreg autoclave promises aerospace—grade quality (60%+ fibre volume, <1% voids, 50—80 MPa tensile), but thermosensitive agro—fibres (wheat straw, bagasse) face major thermal and compatibility barriers that limit commercial viability vs. compression moulding. Key challenges include:

- prepreg production with agro—waste is rare and costly due to poor resin-fibre adhesion on lignocellulosic surfaces, requiring silane treatments or hybrid blends.
- hygroscopic fibres absorb moisture, complicating tack and storage (must remain frozen).
- autoclave scalability limits panel size, while thermal mismatch risks warping or delamination in thick layups.

Fundamental reality is: autoclave's 60% fibre volume advantage becomes irrelevant when agro—fibres lose 45% integrity at required temps, while compression moulding delivers 85% performance at 5% cost.

▦ **SPRAY-UP AND HAND LAYUP** — are open—moulding techniques adapted for agro-waste fibre composite panels, using chopped fibres from sources like rice husk or sugarcane bagasse with liquid resin for cost—effective, large—scale production.

In SPRAY-UP, chopped agro-waste fibres (25—50 mm) are sprayed together with catalyzed resin onto a mould using a chopper gun, building layers progressively, while HAND LAYUP involves manually placing and consolidating fibre mats or chopped strands with brushed—on resin. Fibres and resin are manually applied or sprayed into moulds. Excess resin is rolled out for compaction, and the laminate cures at ambient temperature or with mild heat, followed by demoulding. The method is simple and cost—effective, but less uniform quality and used for less critical large panels where precision is less critical.

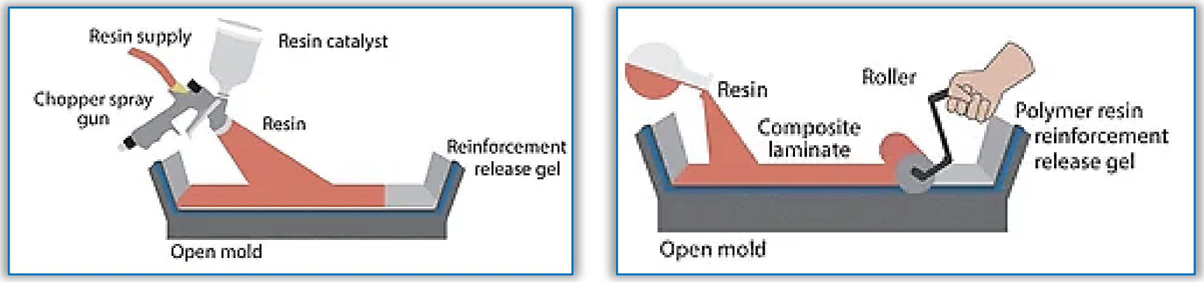

Figure 5. Spray—up and Hand layup processes

Main parameters of SPRAY—UP and HAND LAYUP processes include:

- fibre content: 15—30 wt% to balance reinforcement and processability.
- resin—to—fibre ratio: 1:1 to 2:1 by weight, adjusted via roller consolidation.
- layer thickness: 2—5 mm per pass to avoid sagging in spray—up.
- curing time: 1—24 hours at 20—40°C, accelerated by catalysts (1—2 wt%).

Spray—Up and Hand Layup are lowest—cost entry methods ideal for prototyping and large simple shapes using chopped agro—waste fibres (wheat straw, sunflower husks, bagasse), wet but not drowning. These open—mould wet processes at 60—70% lower cost than closed—mould methods, an fibre / resin ratio at level 1 / 2 ensuring complete saturation while controlling weight/cost. Open—mould wet processes amplify fibre wetting, resin waste, and operator dependency issues multiple worse than closed—mould methods. Key challenges include:

- High resin demand (up to 70 wt%) results in heavy, low-strength panels with voids from poor wetting of agro—waste's waxy surfaces.
- Fibre chopping inconsistency causes uneven distribution and weak interfaces without alkali treatment.
- Labour—intensive hand layup limits scalability, while spray-up generates airborne dust and styrene emissions, complicating worker safety and environmental compliance.

Open—mould challenges are manageable with training and process discipline. 60% resin waste and operator variance limit scale—up.

▦ **CONTINUOUS ROLL FORMING (DOUBLE—BELT LAMINATING or DOUBLE-BELT PRESS)** — enables continuous production of agro—waste fibre composite panels by feeding fibre—resin mats between heated, flexible belts under controlled pressure for uniform, high—throughput panels from materials like rice straw or bagasse.

For sandwich composite panels, layers are bonded under heat and pressure in a continuous process. Therefore, agro-waste fibres are blended with thermoplastic resin (e.g., PP or PVC), formed into a continuous mat via carding or air—laying, and fed between two heated conveyor belts. The belts apply pressure while heating melts the resin, consolidating the mat into a flat panel that cools and is cut to size downstream. It is efficient for producing large, flat composite sandwich panels for structural and building applications.

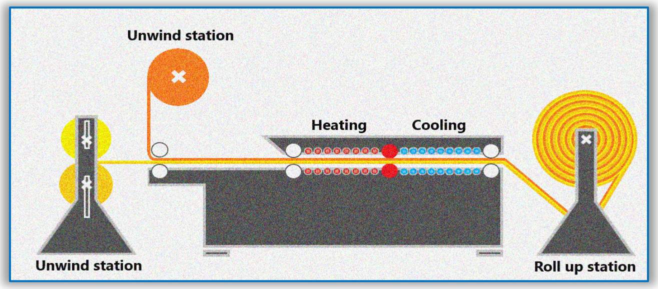

Figure 6. Double—belt laminating (double—belt press) process

Double—belt lamination enables continuous production of flat agro—waste panels (up to 10m/min line speed) using heated belts (140—180°C) and uniform pressure (5—20 bar), perfect for high—volume construction boards from wheat straw/sunflower husks. However, continuous processing amplifies fibre dispersion, resin flow, and heat management issues double worse than batch compression moulding. Main parameters of the DOUBLE—BELT LAMINATING process are:

- belt temperature: 180—220°C for thermoplastic flow without fibre degradation.
- line pressure: 0.5—3 MPa for density control (0.8—1.2 g/cm^3).
- line speed: 1—10 m/min, balancing throughput and consolidation.
- fibre content: 40—70 wt%, optimized for mat permeability.

Key challenges include:

- uneven mat formation from variable agro—waste fibre lengths causes density gradients and weak zones.
- moisture in lignocellulosic fibres leads to steam voids or hydrolysis during heating, requiring pre—drying.
- scaling requires precise tension control to prevent belt wear or mat tearing, while edge trimming generates waste.

Industrial double—belt press showing continuous panel output—ideal for agro—waste scale—up.

- **UNCONVENTIONAL METHODS FOR AGRO-WASTE FIBRE COMPOSITE PANELS** include emerging techniques like microwave curing, 3D printing (FDM), and Framed Vacuum—Assisted Resin Transfer Moulding (F—VARTM), which offer rapid processing, customization, or cost reductions beyond traditional moulding.

- **MICROWAVE CURING**: Preforms of agro-waste fibres (e.g., sisal) mixed with thermoplastics like PP or EVA are placed in a microwave oven (fixed-frequency, 900W max) with a ceramic mould for volumetric heating and rapid curing. Optimized exposure (wattage and time) melts the matrix for consolidation.

Challenges include uneven heating causes hotspots or incomplete curing; fibre-matrix dielectric mismatch limits penetration depth. Also, mould materials must be microwave—transparent, and scaling for large panels requires hybrid heating.

- **3D PRINTING (FDM FILAMENTS)**: Corn cob cellulose fibres are extracted via alkaline hydrogen peroxide treatment, modified with rice bran oil, and compounded into PLA filaments (1—5 wt% fibre) for fused deposition modelling to print panels or structures.

Challenges include high fibre loading clogs nozzles and reduces interlayer adhesion and the fibre agglomeration needs chemical modification. It is limited to thin panels; mechanical isotropy is poor without optimized raster angles.

- **FRAMED VARTM (F—VARTM)**: Non-metal framed moulds hold agro-waste particulates (e.g., hazelnut shells, emmer hulls <1% MC), infused with low—viscosity epoxy under vacuum for decorative panels, reducing capital costs vs. metal moulds.

Challenges include moisture sensitivity demands pre—drying and raising costs. Variable particle packing leads to ~8—10% lower flexural strength than rigid moulds. In this method the frame flexibility risks leaks in large formats.

4. COMPARATIVE APPROACH

These methods allow production of large structural composite panels tailored to requirements of construction, aerospace, automotive, and agricultural applications, balancing cost, quality, and performance. Large structural composite panels are typically manufactured by following methods:

- PREPREG LAYUP with AUTOCLAVE CURING: Pre—impregnated fibres are layered and cured under heat and pressure, producing aerospace—grade panels with uniform properties but higher cost.
- SPRAY—UP and HAND LAYUP: Fibres and resin are manually sprayed or laid up, suited for less critical large panels due to lower uniformity and slower speed.
- COMPRESSION MOULDING: Pre-mixed composite material is loaded in heated moulds, then compressed and cured under heat and pressure, used for parts with complex shapes and variable thickness.
- VACUUM INFUSION: Dry fibre reinforcements are laid into a mould and covered with a vacuum bag. Resin is drawn through by vacuum pressure, creating high—quality laminates with good fibre/resin ratios and minimal voids, suitable for complex and large parts.
- RESIN TRANSFER MOULDING (RTM): Fibres are placed in a closed mould and resin is injected under pressure, enabling controlled thickness and fast cycle times for medium—scale production.
- CONTINUOUS ROLL FORMING (DOUBLE—BELT LAMINATING): A continuous process used mainly for sandwich composite panels, bonding layers under heat and pressure efficiently for large flat panels.

These methods vary in complexity, cycle time, quality, and scalability, allowing tailoring to the application demands in construction, aerospace, automotive, or agricultural sectors.

Table 2. Summary Table

METHOD	APPLICATION SCALE	SURFACE QUALITY	STRENGTH & CONSISTENCY	CYCLE TIME	COMPLEXITY
VACUUM INFUSION	Medium to large parts	High	High	Moderate	Medium
RESIN TRANSFER MOULDING	Medium parts	High	High	Faster than infusion	Medium
COMPRESSION MOULDING	Small to medium parts	High	High fibre content	Fast	Medium
PREPREG LAYUP & AUTOCLAVE	Specialized, aerospace	Very high	Very high	Long	High
SPRAY—UP / HAND LAY—UP	Large, less critical	Moderate	Variable	Slow	Low
CONTINUOUS ROLL FORMING	Large sandwich panels	High	Good	Continuous	Medium

Agro-waste fibre composite panels are manufactured via diverse methods, each balancing cost, quality, scalability, and fibre suitability. Main processing methods for agro—waste fibre composites rely on established, scalable techniques like compression moulding and RTM, while unconventional methods introduce rapid or low—cost innovations but remain niche. Main methods excel in uniformity and throughput for structural panels via controlled pressure/heat, but require pre—treatment (alkali/silane) while unconventional cut energy/time (microwave 900W cycles) and tooling (F—VARTM frames), yet struggle with fibre variability and scale. Hybrids favour mains for now, while unconventional grow via automation.

Table 3. Manufacturing methods comparison

METHOD	FIBRE VOLUME FRACTION	COST LEVEL	SCALABILITY	STRENGTH/VOIDS	BEST FOR
VACUUM INFUSION	35–50%	medium	medium	good/low voids	thin panels
RESIN TRANSFER MOULDING	35–50%	high	high	excellent/low	structural parts
COMPRESSION MOULDING	20–50 wt%	low	high	moderate/med	mass production
PREPREG/AUTOCLAVE	50–60%	very high	low	superior/min	high—performance
SPRAY—UP/HAND LAYUP	15–30 wt%	very low	low	poor/high	prototypes/large
CONTINUOUS ROLL FORMING	40–70 wt%	medium	very high	good/low	flat panels
MICROWAVE CURING	10–30 wt%	low	low	variable/med	rapid prototyping
3D PRINTING (FDM)	1–3 wt%	high	low	low/poor	custom shapes
F—VARTM	40–60%	low—med	medium	good/low	decorative

Manufacturing costs for agro—waste fibre composite panels vary widely by method, influenced by equipment, labour, resin use, and scale, with open—mould processes being cheapest but lowest quality. Open methods excel for low—volume prototypes, while continuous processes suit mass production; unconventional ones like microwave reduce energy costs by 50—70% but lack maturity. Several factors drive down manufacturing costs for agro-waste fibre composite panels by optimizing material use, process efficiency, and scale:

- Scale and throughput: Economies of scale lower unit costs through higher production volumes, as seen in continuous roll forming (1—10 m/min lines) spreading fixed tooling over more panels. Batch processes like compression moulding benefit from multi—cavity moulds.

- Low—cost materials: Using cheap agro-waste and low-resin methods like spray-up (despite high resin wt%) or microwave curing (50—70% energy savings) minimize inputs. Local sourcing cuts transport by 20—30%.
- Process simplification: Open—mould (hand layup) and low—pressure methods (F—VARTM, compression at 1—4 MPa) avoid expensive equipment like autoclaves. Rapid cycles (microwave 1—5 min vs. autoclave hours) boost output.
- Waste and energy reduction: Pre—drying fibres (<1%) prevents defects, cutting rework; lean practices recycle trim (10—15% savings). Automation in roll forming or RTM simulation optimizes resin flow, reducing voids and scrap.
- Labour, location and automation: Labour—intensive spray—up suits low—wage regions. For agro—waste, automated chopping and mat forming ensure uniform fibre distribution, avoiding rework from voids or dry spots. Automated systems like robotic layup or continuous roll forming lines replace manual processes (e.g., hand layup in spray—up), cutting workforce needs by 50—80%.

Best practices for agro-waste supply chain efficiency focus on minimizing losses, ensuring feedstock quality, and integrating digital tools for agro—waste fibre composite panel production. First, partner directly with local farms for seasonal agro-waste (e.g., rice husk, bagasse) via contracts secure steady volumes at low cost. Also, pre—treat fibres (alkali washing, chopping) at decentralized hubs near farms reduce bulk and spoilage. Store in climate—controlled silos with predictive analytics forecasting supply based on harvest cycles, avoid the overstock or shortages. Automation significantly lowers costs in agro—waste fibre composite panel production by reducing labour, waste, and cycle times while improving consistency.

5. CONCLUDING REMARKS

Lignocellulosic fibres from agricultural residues are a transformative, sustainable alternative to synthetic reinforcements, offering compelling economic and environmental benefits. While mechanical properties lag behind glass/carbon fibres, optimized processing and surface treatments enable viable applications in automotive, construction, and packaging. With strategic investments in infrastructure, standardization, and R&D, these bio—composites can support the circular economy goals and reduce reliance on imported synthetics.

Lignocellulosic fibres from agricultural residues are increasingly deployed as sustainable, low—cost reinforcements in polymer composites. These residues—often burned, landfilled, or underutilized—offer cellulose—rich fibres (40-70% cellulose) that can replace 30-50% of synthetic glass/carbon fibres in non—structural applications, reducing weight by 30—50% and cost by 50—70%. With optimized surface treatments (alkali/silane) and strategic processing (compression/ extrusion), these fibres can achieve mechanical performance sufficient for automotive interiors, construction panels, and packaging—accelerating Romania's circular economy transition while reducing landfill dependency. Agro—waste composites processing aligns perfectly with circular economy principles by transforming agricultural residues (wheat straw, sunflower husks) from landfill/burn liabilities into high—value, carbon—negative materials for construction panels and automotive parts. The optimal methods maximize waste valorisation, energy efficiency, and material recyclability.

Compression moulding remains the gold standard (70% of applications). For most agro—waste composites—particularly wheat straw, sunflower husks, rice husks, and bagasse—compression moulding offers the optimal balance of cost, scalability, and performance. It handles high filler loadings (30—60 wt%), produces construction panels/boards, being the perfect match for Romania's abundant residues. Start with compression moulding for immediate market entry (panels, insulation), then expand to injection/extrusion as volume grows.

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