



Original Research Paper

An Integrated Industrial Management Framework for Sustainable Wood–Plastic Composite Manufacturing and Waste Valorization

Shivam^{1*}, Dr. Simranpreet Singh Gill²

¹Department of Mechanical Engineering, Sardar Beant Singh State University,
Email: shivamsharma110755@gmail.com.

²Associate Professor, Department of Mechanical Engineering, Sardar Beant Singh State University.
Email: Ritchie_223@yahoo.com

Abstract

Wood–plastic composites (WPCs) fall in between of those main three branches of polymer engineering, wood-residue valorization and circular manufacturing. However, typically and for centuries these various elements of the industrial practice have been handled as individual technical interventions (e.g., finding raw materials, drying, compounding the materials, putting them to use and handling the resulting scrap), rather than as part of a coherent and integrated socio-technical system. This paper proposes an Integrated Industrial Management Framework for WPC manufacturing (IIMF-WPC) to integrate the latest knowledge on recycled polymers, lignocellulosic raw materials, industrial extrusion, molding, repeated mechanical recycling, life-cycle assessment (LCA), environmental management and energy management and digital-twin for circular manufacturing. It structures the industrial decision-making process into 8 mutually dependent pillars: feedstock qualification, formulation and interphase design, process control, quality and compliance, closed-loop waste valorization, LCA and techno-economic control, digital traceability and predictive analytics, governance with continuous improvement. There is evidence showing that industrial circularity is technically possible and dependent. The moisture and contamination tolerances of wood flour are generally tightly controlled, thermal stability of lignocellulosic is a limiting constraint in the processing, the compatibilization is formulation-specific, and often clean post-industrial WPC can be reprocessed without significant deterioration of major mechanical properties. Conversely, if polymer families are not controlled for mixing, and/or the post-consumer material older than the target re-use time, weathers, additives and contaminants can compromise the re-use value and process stability. A multi-level KPI Hierarchy is then proposed to establish linkage between yield, energy intensity, recycled content, and scrap recirculation with mechanical-property retention, carbon intensity, cost, and customer quality and end-of-life recoverability. The paper also proposes research propositions and a validation protocol for plant scale studies. The main one is to change the WPC sustainability problem (whether it is a problem of material choice or not), into an integrated industrial-management problem, where the optimal combination of different factors of product quality, product circularity, resource effectiveness, and profitability are optimized simultaneously.

Keywords: wood–plastic composite; industrial management; circular manufacturing; recycling; waste valorization; extrusion; life-cycle assessment; digital twin; sustainable manufacturing; recycled polymer

Highlights

- Changes the perception of sustainability as a material only problem to an eight-pillar industrial-management approach for circular WPC production.
- Avoids mixing recovery with the exercise of qualification gates for recovery to qualify as closed-loop recyclability and helps differentiate the pathways of the clean post-industrial closed-loop recyclability to the pathway for the higher-risk post-consumer recycling.
- Combines and brings together all the KPIs related to quality, energy, environment, circularity and cost onto a single decision architecture.
- Exhibits current re-cycling facts to demonstrate the importance of the digital traceability of polymer identity, moisture, contamination and thermal history.
- Presenting the plant validation propositions, a maturity model and a practical implementation scorecard suitable for future empirical testing.

1. INTRODUCTION

All the while, the manufacturing industry is being called on to limit the consumption of virgin resources, control energy and emissions, exhibit end-of-life responsibility and ensure product predictability. The requirements are especially severe in the case of wood–plastic composites

(WPCs), since the composite material is quite heterogeneous and thus atypical for conventional timber as well as for homogeneous thermoplastics. Multiphase materials composed of dried hydrophilic particles or fibers of lignocellulosic origin, dispersed in a thermoplastic matrix and with various dimensions and

*Corresponding Author:

Received: 13th July, 2026; Revised: 27th July, 2026; Accepted: 20th August, 2026; Available Online: 27th August, 2026
(DOI): 10.70102/AEJ.2026.18.4s.31

weight.¹ They may also be dispersed using compatibilizers, lubricants, pigments, stabilizers, flame retardants or other additives. The environmental potential is thus real but restricted: A WPC has the potential to valorize the use of wood residues, but add recycled polymer; however, it can also make end-of-life planning, traceability, formulation and quality poor management concerns if not given adequate attention. It is an economic and environmental problem from a broader perspective of the material context. The OECD estimates that there were 353 million tons of plastic waste in the world in 2019; 19% of which was incinerated, 22% was mismanaged,

with 50% being landfilled and 9% recycled (after losses).² If the business-as-usual global waste scenario continues, this is estimated to escalate to approximately 1,014 million tons of plastics by 2060 (where recycling will account for only around 17% of the waste volume). WPC production can't be the only solution for the plastics crisis on its own, but adding WPC to the bag segment of the system can be a practical solution to extend the service life of polymers and to convert otherwise low value lignocellulosic residue to a durable product if the system is designed for repeated movement of material.³

Global plastic-waste management distribution in 2019

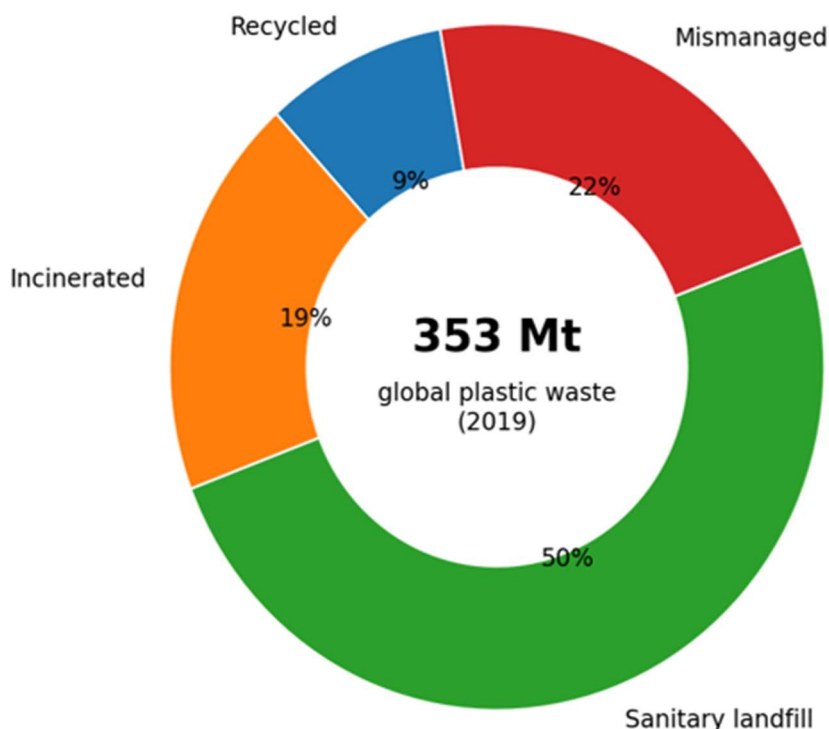


Figure 1. Global plastic-waste management distribution in 2019. Values reproduced from OECD Global Plastics Outlook (2022); percentages are after accounting for recycling losses.

Technologies are well developed to manufacture WPCs on a commercial scale. Extrusion and injection molding are the most applicable molding methods, and compression molding, co-extrusion and additive manufacturing methods expand the product space achievable. WPC applications have recently been reviewed in building products, infrastructure, automotive products, household products, packaging and other engineered products. In the

same literature, however, recurring industrial problems are mentioned: wood morphology variations, the presence of moisture, hygric compatibility at the interface, complex rheological properties, sensitivity to additives, thermal degradation of the lignocellulosic phase, non-standardized recycling pathway for recycled polymer feedstock and variable polymer feedstock.⁴

¹ Mitařová, Z., Mitař, D., & Berladir, K. (2024). Research on Wood–Plastic Composites: A Review of Experimental and Numerical Studies. *Polymers*, 16(11), 1556. <https://doi.org/10.3390/polym16111556>; see also Ayana et al. (2024), *Sustainable Materials and Technologies*, 40, e00983.

² OECD (2022), *Global Plastics Outlook: Policy Scenarios to 2060*. Under the baseline projection, global plastic waste rises from 353 Mt in 2019 to about 1,014 Mt in 2060, while the recycled share reaches about 17%.

³ OECD (2022), *Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options*. Global plastic waste reached 353 Mt in 2019; after recycling losses, 9% was ultimately recycled, 19% incinerated, almost 50% landfilled and 22% mismanaged. <https://doi.org/10.1787/de747aef-en>.

⁴ Ayana, B. et al. (2024). Wood–plastic composites: A comprehensive review of formulation, processing, performance and applications. *Sustainable Materials and*

One of the problems that exists in most of the literature on WPC is its disorganized nature. Optimizing fiber load or coupling agents are covered by materials studies, optimization of screw speed and temperature by processing studies, property retention by recycling studies, comparison of environmental burdens by LCA studies and quality and environmental and energy governance by management-system standards. Buy furniture in a factory, though, these decisions are interdependent. A procurement alternative with wetter wood flour entails a change in dried energy, swiftness and void and scrap. The move up the recycled polymer chain impacts viscosity range, potential for odors, color and contamination hazards, and QC challenges. The forming history and thermal exposure change when deciding to recirculate internal scrap. Optimization of one department could then be transferred as a cost or environmental impact to another department.

This paper addresses that lack by adopting the perspective of integrated industrial-managing problem in sustainable WPC making. The key point being that it is not just the composite formulation itself, but the whole plant system—suppliers, incoming inspection, storage, drying, dosing, compounding, shaping, in-line sensing, laboratory testing, maintenance, energy use, etc., quality release, internal waste and scrap circulation, external waste recovery, environmental accounting, territorial decision rights, etc.—which are relevant. The suggested IIMF-WPC framework integrates these functions with each other using common metrics and data.

Research objective. To create an evidence-informed industrial-management approach that can be implemented to enhance WPC product quality in combination with resource efficiency, circularity, valorization of waste and economic control and deliver measurable metrics and tool to support plant-scale testing.

Research questions.

1. What material and process variables play the largest role in making this an industrial-scale, repeatable and stable process of making recycled-content WPCs?
2. Classifies and routes the best WPC waste to maximize value while maintaining product quality: postindustrial vs. post-consumer waste.
3. What shall be the operational, circularity, environment, quality and financial KPIs to include as a single decision system?
4. How can management-system standards and digital technologies help to be used for traceability, predictive control and continuous improvement?
5. What propositions can be formulated and what steps can be taken in the validation process, in order to be able to create an empirical testable industrial model of the proposed conceptual framework?

The paper would like to contribute the following things: First of all, it correlates the recent material-science evidence and recycling evidence into plant decision rules. Secondly, it establishes a waste-valorization hierarchy applicable to the WPC streams and it separates clean Internal Scrap from "uncertain" Post-consumer Composites. Third, it is presented an integrated KPI and governance framework, ensuring its compatibility with existing quality, environmental and energy principles and LCA principles. Fourth, it formulates a maturity path and an agenda of empirical testing that can be evaluated with plant-oriented data in future research.

2. METHODOLOGICAL APPROACH: CRITICAL EVIDENCE SYNTHESIS AND FRAMEWORK DEVELOPMENT

A critical integrative-review and design-science approach is used in the study. It is not a full systematic review according to PRISMA guidelines and does not report new lab/manufacture measurement data. As a result, the intent is more explanatory and prescriptive; the goal is to find solid technical limitations and apply them as part of industrial-management approaches, synthesizing them into an understandable whole that can be put to a test later in empirical experiments. Priority was placed on peer-reviewed studies and reviews published between 2020 and 2026; earlier LCA and WPC papers and publications that are technically relevant were included; current standards and authoritative statistics were included as well.

Evidence has been organized into six areas: (i) global plastic-waste and circularity context; (ii) WPC feedstocks, formulation and processing; (iii) mechanical recycling and property retention; (iv) WPC life-cycle and end-of-life performance; (v) quality, environmental and energy management standards; and (vi) digital twins and circular manufacturing. Recent systematic evidence found that, in the recycling domain, there are key gaps regarding the form of standardized data and the availability of data, as well as regarding the need for standardized benchmarking, and that recyclability is strongly dependent on polymer type, on wood content and reprocessing method, respectively.⁵

The construction of the framework was carried out based on a cause-control-metric logic. The paper identifies for each major Industrial risk (a) the physical or organizational cause, (b) the control mechanism that must be implemented at the Plant level and (c) the metric/ KPI required to check this. It is thus made special with the purpose of being cross functional. It is designed to avoid a common mode of failure in circular manufacturing, which is to add higher recycled content or more recirculation of waste — but not considering loss of yield, higher energy costs, off-spec production, short product life or the fact that the created product cannot be recycled downstream.

Technologies, 40, e00983.

<https://doi.org/10.1016/j.susmat.2024.e00983>; Ramli, R. (2024), *Materials Today Sustainability*, 27, 100889.

<https://doi.org/10.1016/j.mtsust.2024.100889>.

⁵ Huang, J., Löschke, S., & Proust, G. (2026).

Recyclability of wood plastic composites: A systematic

review. *Materials & Design*, 266, 116102.

<https://doi.org/10.1016/j.matdes.2026.116102>. The review screened 2,134 records and retained 38 studies for detailed synthesis.

2.1 Evidence-to-management translation

Table 1. Evidence-to-management translation used in framework construction.

Evidence domain	Technical finding	Industrial-management implication	Representative source
Wood flour moisture	Recent review guidance recommends keeping wood flour humidity below ~1% for stable WPC processing and storage protection.	Incoming moisture specification; sealed storage; drying control; moisture alarm.	Mitařová et al. (2024)
Thermal processing window	Conventional WPC processing is commonly constrained to about 200 °C because lignocellulosic degradation can cause odor, darkening, porosity and mechanical loss.	Recipe-specific temperature ceiling; residence-time monitoring; melt-temperature alarms.	Mitařová et al. (2024); Hejna & Barczewski (2025)
Interfacial compatibility	Maleated polyolefin compatibilizers are widely used; literature reports typical low-percentage additions, but optimum dosage is formulation-specific.	Supplier-approved additive windows; DOE before scale-up; incoming MFI/MAH checks.	Mazzanti & Mollica (2020); Khan et al. (2025)
Manufacturing route	Extrusion and injection molding are among the most widely used WPC processes; rheology strongly influences processing stability.	Match product geometry to process; monitor torque, pressure, melt temperature and throughput.	Yadav et al. (2021); Mazzanti & Mollica (2020)
Internal-loop recycling	Repeated reprocessing of clean PP-based WPC has shown limited deterioration in many mechanical properties, though color and particle morphology can change.	Separate clean internal scrap; control recycle ratio and thermal history; periodic requalification.	Burgstaller & Renner (2023)
Closed-loop potential	Recent PP/WF work reported >94% tensile-strength retention and >90% stiffness retention after three industrially relevant recycling cycles.	Use property-retention gates rather than arbitrary maximum recycled content.	Valencia et al. (2026)
Environmental preference	LCA evidence indicates secondary raw materials and recycling can outperform virgin-material and disposal-dominant pathways, subject to system boundaries and quality assumptions.	Require LCA/TEA for major material-route changes; avoid burden shifting.	Sommer Huber et al. (2017)
Standards	ASTM D7032 addresses performance rating of WPC/plastic lumber decking and guards; ISO LCA, environmental and energy standards provide management structure.	Integrate product compliance, LCA, EMS and EnMS in one audit architecture.	ASTM D7032-21; ISO 14040/14044; ISO 14001:2026; ISO 50001:2018

3. TECHNICAL BASIS OF SUSTAINABLE WPC MANUFACTURING

3.1 Feedstock architecture and formulation control

The polymer portion is responsible for the processability of the melt, the resistance to moisture and many of the ductile properties, while the wood or lignocellulosic portion represents the stiffness, the lower density to other mineral filler contents, the surface texture, and partial replacement of fossil derived polymers. Interphases between the two phases are frequently the weakest structural areas owing to the differences in chemical and physical natures of wood (polar, hydrophilic) and common polyolefins (non-polar, hydrophobic). Compatibilizers are actually not just additives, but elements that actually make processes possible, as they promote stress transfer and even can minimize water uptake by stress transfer from one phase to another phase,

which is enhanced by the improved adhesion of the two interfaces. The formulation control of an industry product requires differentiations between nominal composition and effective composition.⁶

Instead of a mass fraction of wood and polymer, a recipe might call for, for instance, particle-size distribution for a particular species of wood, aspect ratio of the wood, moisture content, bulk density, ash content, quantity of extractives, degree of contamination, type of polymer family, the behavior of the polymer in the melt, degree of oxidation, additive package and thermal history of the material. This variability is increased by the use of recycled feedstocks since two bales of 'recycled PP' can be very different in molecular weight distribution, pigment content, fillers, odor and incompatible polymer content and contamination. A strong factory thus considers feedstock in terms of a series of critical-to-

⁶ Mazzanti, V., & Mollica, F. (2020). A Review of Wood Polymer Composites Rheology and Its Implications for Processing. *Polymers*, 12(10), 2304. <https://doi.org/10.3390/polym12102304>. Maleated

coupling/computerizing agents are widely used in WPC formulations, commonly in low single-digit weight percentages; optimum dosage remains formulation-specific.

quality attributes, not simply as a description of commodities. Specifically, moisture, moisture, moisture. Wood flour moisture contents are recommended to be maintained below about 1% for processing, and dried wood flour kept in sealed containers to minimize re-absorption. Too much water can evaporate off the melt, generate porosity, cause shear instability, decrease bonding and lead to rejections.

The management implication is that moisture needs to be managed at three stages: at the delivery, when dryers are unloading discharge and at point of use feeding. With hygroscopic material that can absorb water in storage, only one received measurement is not enough. The fiber load is not just a one-dimensional sustainability goal – it's a system variable. An increase in the wood content could

decrease the amount of polymer required and improve stiffness, but could cause an increase in viscosity, decrease in ductility and increase in moisture pathways, and make it more difficult to achieve complete wetting of particles. Some experimental based studies have indicated that the optimum mechanical properties are found at not more than around 50 wt.% wood for certain formulations, while, recent work related to industrial applications, has indicated their successful composites at around 20–50 wt.% wood fiber based on appropriate control of feedstock and compatibilization. The framework therefore does not establish a single universal loading, but rather a qualification on the basis of product functions, of processing capabilities and end-of-life-strategies.⁷

Table 2. Feedstock qualification architecture for industrial WPC production.

Feedstock	Critical incoming attributes	Primary failure modes	Recommended controls
Wood/lignocellulosic fraction	Moisture; particle-size distribution; aspect ratio; bulk density; ash/soil; species/residue source; odor; extractives	Voids, torque/pressure variability, poor wetting, color variation, inconsistent stiffness	Drying, sieving, densification/palletization, supplier COA, periodic TGA/ash and microscopy
Recycled polyolefin	Polymer identity; MFI/MFR; density; ash; pigments; oxidation; incompatible polymers; moisture	Melt instability, phase separation, odor, brittle behavior, color drift	NIR/FTIR identification, density separation, MFI testing, ash test, contamination limit, lot segregation
Virgin polymer	Grade identity; MFI/MFR; additive package; thermal stability	Inconsistent flow or strength if wrong grade is mixed	Barcode/lot control, supplier certification, silo interlock
Compatibilizer	Graft level, carrier polymer, dosage accuracy, shelf life	Weak interface at under-dose; rheology/cost penalty at over-dose	Gravimetric dosing, recipe lock, periodic mechanical validation
Lubricants/stabilizers/pigments	Dosage, compatibility, migration, thermal/UV stability	Surface defects, slip, color mismatch, long-term degradation	Controlled masterbatch system, additive traceability, accelerated-weathering qualification
Recovered WPC scrap	Polymer family, prior cycles, contamination, weathering, additive history	Unknown thermal history and property drift	Closed-loop material passport; source-coded bins; maximum cycle/risk classification

3.2 Manufacturing routes and process-window management

Extrusion can be especially utilized for continuous profiles such as decking, cladding and structural and semi-structural profiles. Injection molding can be used for higher geometric complexity and discrete parts, while compression molding can be used for products like sheet like parts and depending on the product formulation, a higher fraction of fillers can be used. Additive

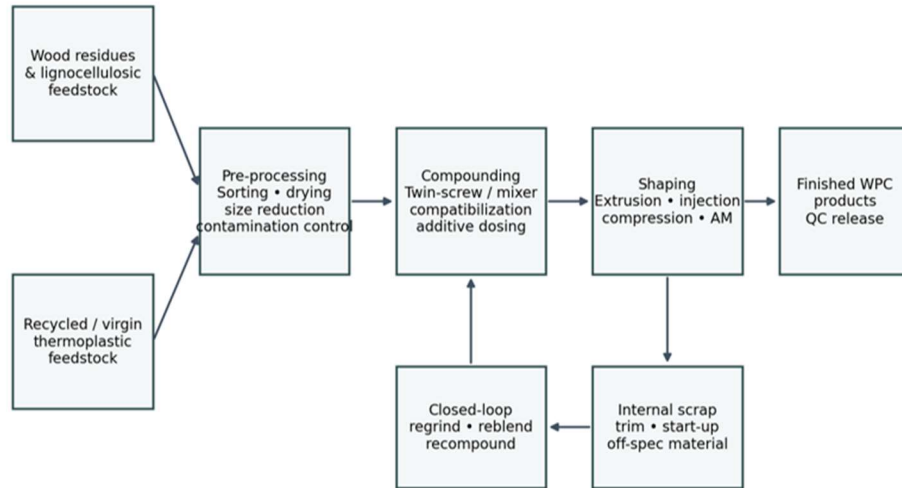
manufacturing is evolving for large format and customized parts, which also add in further specifications and considerations regarding the uniformity of the pellet/filament, the control and management of the anisotropy, and the thermal history. The process selection should therefore be coordinated with formulation, quality requirements, forecast production capacity and the number of scraps which are generated and can be recycled annually.⁸

⁷ Milova et al. (2024) summarize industrial practice in which wood flour is dried to very low moisture levels—often below 1%—to reduce voiding, hydrolytic effects and processing instability.

⁸ Mitařová et al. (2024) and Hejna, A., & Barczewski, M. (2025), Journal of Bioresources and Bioproducts,

10(2), 123–127, note that conventional WPC melt processing is generally constrained around 200 °C because lignocellulosic fillers begin to thermally degrade at elevated temperature.

Integrated material and manufacturing flow for circular WPC production



Closed-loop route is prioritized for clean post-industrial scrap; post-consumer material requires polymer identification, contamination screening and performance qualification.

Figure 2. Integrated material and manufacturing flow for circular WPC production. Diagram developed by the authors from the synthesized literature.

One of the major limitations of the WPC processing is the conventional thermal ceiling. It is generally accepted that about 200 ° C is a practical limit on reviewing because cellulose etc. can begin to degradation; above this temperature breathability and mechanical breakdown may be starting to become a problem along with darkening and release of odor and volatiles. The safe window for the process will vary based on species, balance, oxygen exposure, moisture, additives and polymer matrix, and is not suitable for use of a universal temperature – based process, but rather requires a validated recipe specific operating envelope. The other link between formulation and plant stability is the rheology. Adding fiber, usually increases apparent viscosity and can change shear

thinning properties, adding lubricants can decrease or increase viscosity depending on chemistry and formulation, and adding compatibilizers can decrease or increase viscosity, depending on chemistry and formulation. Industrial control: laboratory rheometric is useful at the formulation stage, and the production line provides on-line "rheometric proxies", such as the torque required by the extruder, motor load, melt pressure, die pressure, melt temperature and specific energy consumption. The batch trend for these variables will alert for moisture excursions, feed inconsistency, contamination, or contaminant-dosing errors prior to finished-product testing.

Table 3. Process-window and control architecture.

Process stage	Critical variables	Failure mechanism	Recommended control/KPI
Drying / preconditioning	Wood moisture; dryer temperature; residence time; dew point	High moisture → porosity, unstable pressure, weak interface; overdrying/overheating → discoloration or degradation	Moisture at dryer outlet; kWh/kg water removed; dryer yield
Gravimetric feeding	Mass flow of polymer, wood, compatibilizer and additives	Recipe drift, segregation, starvation or overfeeding	Feeder deviation %; lot genealogy; alarm count
Compounding	Barrel profile; screw speed; torque; residence time; melt temperature	Poor dispersion, fiber damage, degradation, excessive energy use	Specific energy; torque CV; pressure CV; melt-temperature excursion time
Shaping/extrusion	Die pressure; cooling rate; haul-off speed; dimensions	Warping, voids, surface defects, dimensional drift	OEE; dimensional Cp/Cpk; scrap kg/t
Injection molding	Melt/mold temperature; injection speed/pressure; hold time	Short shots, burn marks, fiber orientation variability, warpage	Cycle time; reject rate; cavity pressure trend
Regrinding/recycling	Particle size; metal removal; recycle ratio; cycle count	Dust, contamination, excessive thermal history, inconsistent flow	Recycled fraction; cycle count; property retention; fines %

4. WASTE VALORIZATION AND CIRCULARITY STRATEGY

4.1 A hierarchy for WPC waste streams

The Waste valorization should start with the segregation and not with the technology of recycling. An immediate profile trim after the extrusion is not the same as a deck board with fasteners and biological growth in it, and there

may be unknown/weighted pigments as well. The universal treatment of all WPC waste as a single waste stream eradicates information and can lower the value of a WPC's internal waste stream to one that is mixed waste. The proposed hierarchy thus puts WPC material in order of information quality and contamination risk.

Table 4. Proposed WPC waste classification and valorization hierarchy.

Waste class	Typical source	Risk profile	Preferred route	Value-retention potential
Class A: clean post-industrial WPC	Start-up scrap, edge trim, off-cuts, dimensional rejects from a known formulation	Same polymer family and additive history; low contamination	Closed-loop regrind/reblend/recompound into same or compatible product	Very high
Class B: controlled downstream scrap	Fabrication/installation off-cuts with documented grade	Known grade but possible external dirt/fasteners	Cleaning + size reduction + controlled blend	High
Class C: returned post-consumer mono-grade WPC	Known manufacturer/product family; service-aged	Weathering, oxidation, moisture, biological/foreign material	Identification, cleaning, requalification, possibly core layer or downgraded product	Medium
Class D: mixed WPC/plastic/wood stream	Unknown product families and polymers	Incompatible matrices, fillers, contamination	Advanced sorting; selective use; alternative composite products	Low–medium
Class E: contaminated or non-recyclable residue	Hazardous contamination or technically infeasible mechanical recycling	Safety, emissions, severe quality risk	Specialized recovery, energy recovery or disposal according to regulation	Low

Compared to the destructive conversion routes, mechanical recycling recovery route is the more preferred route for clean streams of thermoplastic WPCs as it conserves more of the embodied material value of thermoplastic wastes. Burgstaller and Renner reprocessed WPCs made from PP and wood up to five times and noted a reduction in wood-particles and gradual darkening of color, but noted minimal other impacts on most mechanical properties.⁹ This finding has industrial relevance in it, since it allows the possibility of recycling clean in-house WPCs, however, it cannot be assumed to be true for all post-consumer WPCs or polymer families. An experimental study done in 2026 gives a more quantitative help. It is concluded that 3 reprocessing

cycles were carried out on PP/wood-fiber composite made by 20 wt.% wood fiber and MAPP 2%. The tensile strength retention was around 94.5%, tensile-modulus retention was approximately 90.0% and flexural-modulus retention was approximately 92.9% in the 3rd cycle as per the reported table value. Using this data, in the same study, the tensile strength (Tensile strength in the articles) of neat PP was estimated to be about 93.9%, and tensile modulus (Tensile modulus in the articles) to be around 85.1%, while flexural modulus was estimated to be around 78.8%. The important managerial takeaway is that 'three cycles are always safe' is not the case and that recycling decisions need to be made based on property profiles and materials trees not on some hard-wired recycled-content number.¹⁰

⁹ Burgstaller, C., & Renner, K. (2023). Reprocessing of Polypropylene-Based Wood–Plastic Composites: Effects on Properties and Morphology. *Macromol*, 3(4), 754–765. <https://doi.org/10.3390/macromol3040043>. PP/WPC material containing 40 wt% wood was reprocessed through five cycles with limited deterioration in major mechanical properties, although

colour darkening and particle-size changes were observed.

¹⁰ Valencia, L. et al. (2026). *RSC Applied Polymers*, 4, 363–378. <https://doi.org/10.1039/D5LP00332F>. Property-retention values presented in this paper were calculated from the authors' tabulated cycle-0 and cycle-3 data for PP and PP/20 wt% wood-flour composites.

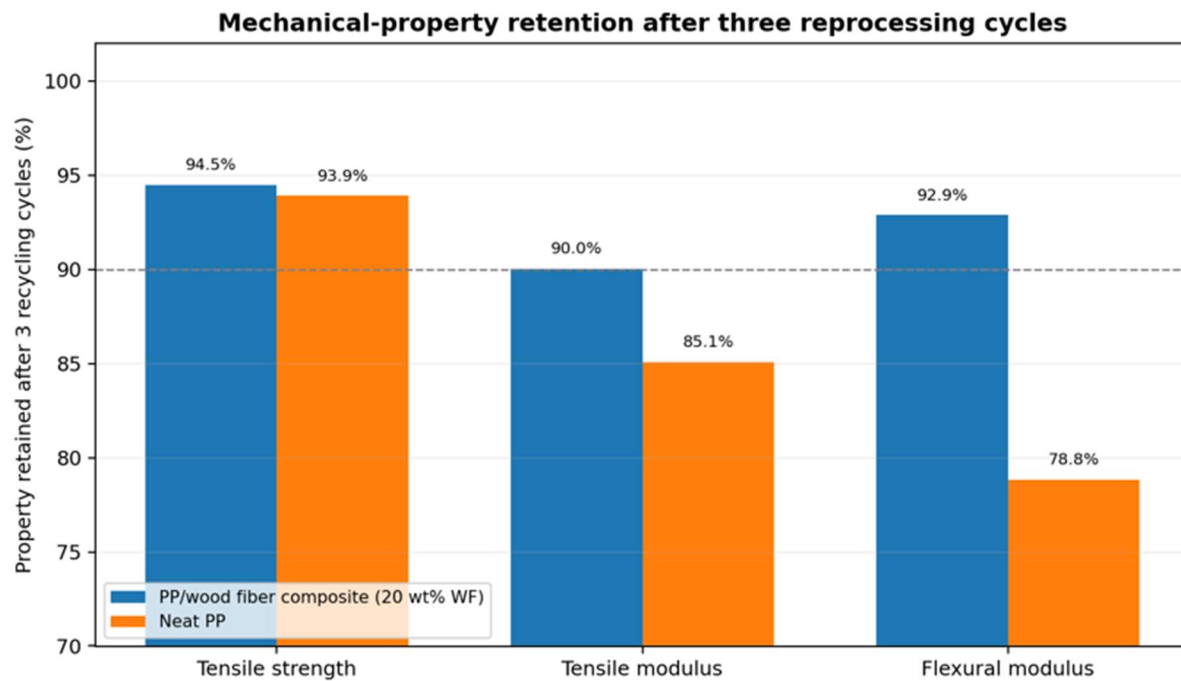


Figure 3. Property retention after three reprocessing cycles, calculated from the values reported by Valencia et al. (2026).

In addition, and another consequence of the increasing literature being published is towards a higher level of circularity. Hou et al. published a WPC made from wood-waste flour and poly(p-dioxanone) that was chemically repolymerized to yield products near to those in its original feed with an LCA carbon footprint of 1.06kg CO₂-eq / kg material. Though scientifically viable, industrial managers need to differentiate between laboratory prototype and potential commercialization. Technological-economic assessment must be performed in addition to the LCA to consider the closed-loop recovery of chemicals, including cheaper market concerns, safety questions, technical characteristics and chemical reactions involved in this closed loop.¹¹

4.2 Life-cycle and techno-economic decision rules

Circularity has nothing to do with superiority for the environment. It may use too much electricity, involve long transports, yield high reject fractions or low-quality material that does not last long enough to be re-used.¹² In order to do this, major formulation and waste-routes decisions would be considered based on life-cycle thinking as informed by ISO 14040 and ISO 14044, which outline the principles, framework, requirements and guidelines for LCA. Durability should differ according to the product service that it provides; in this case, the functional unit should be one square metro of decking for a promised service life, not just one kilogram of material.

The LCA evidence in this domain has been created for WPCs which helps substantiate this systems perspective. Sommer Huber et al. concluded that the use of secondary materials in WPCs was environmentally and technically better than using simply virgin materials in their assessed system and that recycling was the best option compared to the disposal-oriented alternatives, while the recycled WPC quality and quantity entering new products was still a sensitive parameter. In a separate study on PVC/wood-floor boards, various measures for enhanced material and energy efficiency, coupled with increased use of secondary materials and better end-of-life recycling were shown to have a significant impact on the modeled climate change effects, and the reported combined overall improvement was estimated to be approximately 55% over the initial situation. Techno Economic Analysis (TEA) should always be included alongside LCA as a circular solution that does not provide yield, uptime and market quality is not likely to stay. For the framework, at least the following cost/credit parameters should be assessed in the scenarios: raw-material cost, preprocessing cost, energy cost, additive cost, labor, maintenance, scrap disposal credit/cost, quality-loss cost, capital expenditure, throughput, product selling price and effect of service-life on the product. It's the match up of marginal system cost per conforming functional unit, rather than the purchase price of recycled-resin itself that is the relevant target.¹³

¹¹ Hou, Y. et al. (2024). High wood-content recyclable wood-plastic composite and its closed-loop valorization. *Chemical Engineering Journal*, 499, 156478. <https://doi.org/10.1016/j.cej.2024.156478>. The study reports a composite containing 70 wt% wood-waste flour, material recovery in a closed-loop concept, and a cradle-to-gate climate-change result of about 1.06 kg CO₂-eq per kg of product for the assessed system.

¹² ISO 14040:2006, Environmental management—Life cycle assessment—Principles and framework, and ISO 14044:2006, Environmental management—Life cycle assessment—Requirements and guidelines, provide the internationally recognized methodological foundation for LCA.

¹³ Brunnhuber, N., Windsperger, A., Perdomo Echenique, E. A., & Hesser, F. (2023). Implementing Ecodesign During Product Development: An Ex-Ante Life Cycle

5. INTEGRATED INDUSTRIAL MANAGEMENT FRAMEWORK (IIMF-WPC)

Twin Tickets are allotted for the comprehensive study of the integrated management framework in industry (IIMF-WPC). There are eight pillars to the framework of IIMF-WPC. Individual pillars are not sufficiently powerful in their own right. The key to this is conceived as a closed-loop control system, with the plant being regarded as a

part of it: specifications and targets are planned; materials and processes are carried out; performance is measured; deviations are analyzed and corrected; correcting learning is instrumented into recipes and supplier rules and waste-routing logic. This is in line with the evolution-based thinking of management-system standards together with specific technical restrictions of the WPC.¹⁴

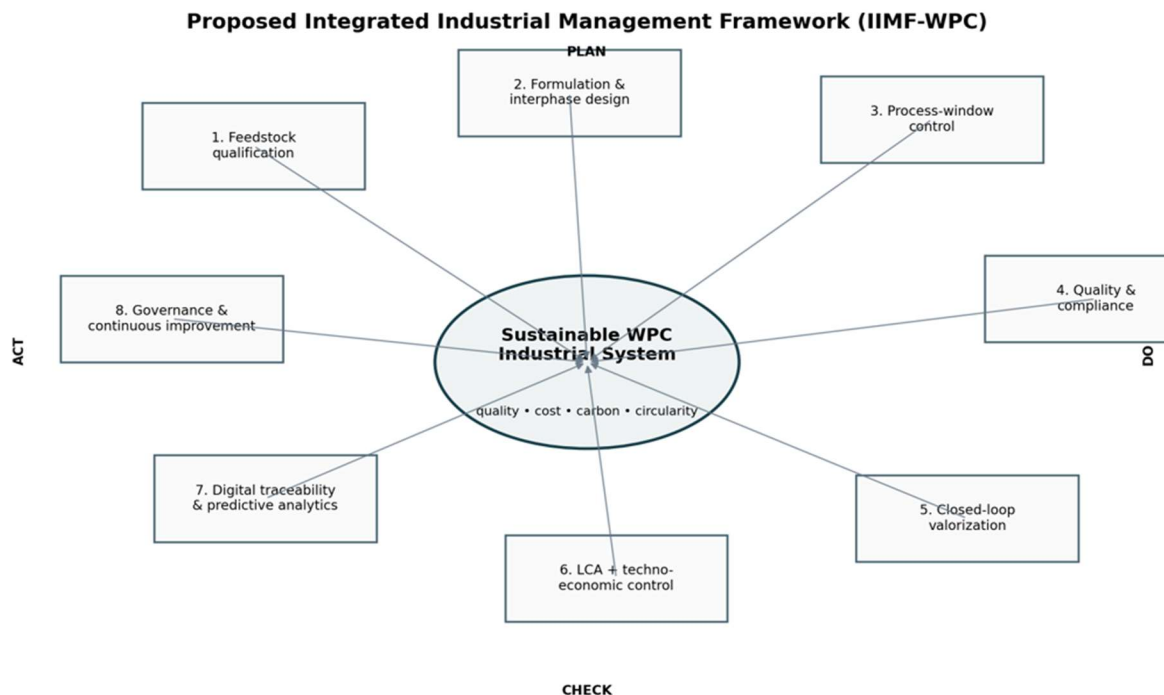


Figure 4. Proposed Integrated Industrial Management Framework for WPC manufacturing (IIMF-WPC).

5.1 Pillar 1 — Feedstock qualification and supplier governance

We call to the attention of decision makers that the first pillar establishes a set of risk-based specifications of wood residues, recycled/virgin polymer and additives. The capability evidence should be used, and not nominal material descriptions, for supplier approval. Incoming screening of high risk recycled feedstocks should be tightened such as identification, MFI / MFR, moisture, ash and contamination screen, and color and odor screen. Supplier scorecards should include documents for rejection of lots, lot variation, supplier documents to prove traceability and documents to prove corrective-action response and use of recycled content. When possible, hitherto in industrial trials, densified wood pellets will also enhance the logistics and the dosing, by increasing

wood pellet bulk density and decreasing dust production, with the aim of introducing standardized wood-fiber pellets with low dust and controlled shape dimensions for the purpose of scaling up compounding.¹⁵

5.2 Pillar 2 — Formulation and interphase engineering

Recipes need to be treated as validated process designs with locked material families, validated & approved rules, revision control. Levels of compatibilizer, lubricant package and recycled content range will need to be established by design of experiments (DOE) during development and require requalification if there is a material change in the source of feedstocks. The formulation database should include a correlation with composition and tensile/flexural properties, water absorption, impact, color, weathering, density, flow and

Assessment of Wood-Plastic Composites. In Progress in Life Cycle Assessment 2021, pp. 23–40.

https://doi.org/10.1007/978-3-031-29294-1_3. The assessed improvement package reduced the initial climate-change result of 145 kg CO₂-eq by 55%.

¹⁴ Sommerhuber, P. F., Wenker, J. L., Rüter, S., & Krause, A. (2017). Life cycle assessment of wood-plastic composites: Analysing alternative materials and identifying an environmental sound end-of-life option. *Resources, Conservation and Recycling*, 117, 235–248.

<https://doi.org/10.1016/j.resconrec.2016.10.012>. The assessed secondary-material pathways showed environmental advantages, and recycling was the preferable end-of-life route in the evaluated system.

¹⁵ ASTM D7032-21, Standard Specification for Establishing Performance Ratings for Wood-Plastic Composite and Plastic Lumber Deck Boards, Stair Treads, Guards, and Handrails, provides performance-based requirements relevant to WPC building products.

recyclability. Such a change is usually the cause of an informal change at the machine while manufacturing recycled material, without proper machine updates in the material model, and this is especially important to avoid.

5.3 Pillar 3 — Process-window control and statistical process management

Validated process window should incorporate all of Wood moisture, feeder ratio, extruder torque, extruder press, extruder temp, barrel/zone temperatures, screw speed, feed, specific energy, vacuum/vent, cooling parameters, and dimensional products. When the measurement system is stable and the targets for capability are meaningful, use of statistical process control (SPC) is suggested. Alarm limits need to be different from what they are to shut down. For instance, a short over-temperature event might be salvageable, but if overheating is occurring for an extended period of time, above the validated thermal window, material quarantine is recommended since dimensions may still appear acceptable, but degradation has occurred.

5.4 Pillar 4 — Quality, durability and compliance assurance

Quality control should be linked to the factory tests with the longer-term potential risks of service. Finished product mechanical testing, in-process testing, moisture/water-uptake, color, and, if applicable, UV, freeze-thaw, biodeterioration, slip, creep and fire-performance testing should be performed on incoming material and in-process to be complemented. One path for ASTM D7032-21 to help develop performance ratings can be found in the environmental conditioning and structural performance requirements for WPC and plastic lumber deck boards, stair treads, guards and handrails. Product characteristics should never be used as a general assurance of quality, but rather as an example of the appropriate standard to use for the specific product application.

5.5 Pillar 5 — Closed-loop scrap management and waste valorization

At generation, all scrap should be given a source code. Internal material should be protected against floor sweepings, metals, adhesives and labels and mixed polymers. On the recycle route, maximum hold time, grinding specification, metal detection, blend ratio, and thermal-cycle count and requalification frequency should be defined. Post-consumer material follows another qualification pathway which involves the identity check, weathering/contamination assessment and application-specific risk review. Value retention is the basis for decisions for the hierarchy for waste: value retention through prevention is preferred, followed by direct reuse, closed-loop mechanical recycling, controlled cascading, advanced recovery, or (at the last resort) energy recovery/disposal if all technologically and environmentally viable value retention options are not pursued.

¹⁶ ¹⁶ ISO 14001:2026, Environmental management systems—Requirements with guidance for use, is the current edition of the ISO environmental-management-system standard (published April 2026).

5.6 Pillar 6 — LCA, energy and techno-economic control

Matching material balance must be used to guarantee environmental and financial control. There should be the same denominator, that is, the conforming product output, driving energy intensity, carbon intensity, water use, waste generation and waste cost. For energy management, ISO 50001:2018 explicitly introduces aspects of energy management life cycle and measurable environmental performance and offers a structured, systematic energy-management framework. For environmental management, ISO 14001:2026 provides the current, proactive environmental-management-system framework, and also explicitly includes aspects of environmental performance and aspect of the life cycle (energy management). These systems combine for less duplication in data collection and to help make sustainability performance auditable and not promotional.

5.7 Pillar 7 — Digital traceability, material passports and predictive analytics

There needs to be information continuity throughout material cycles in a circular WPC plant. For each production lot, a minimum of polymer family, wood source, additive recipe, recycled fraction and an estimate of the previous cycle count (where known), key process history and finished product quality results should be preserved. Early stages of maturity, MES/ERP integration, inline sensors and digital twins enable anomaly detection, predictive quality and scenario optimization. The digital twin review for circular manufacturing over the past few years focuses somewhat on real-time monitoring, lifecycle data, AI-driven decision-making and a requirement for data to flow continually throughout the lifecycle. Digitalization is thus regarded as an enabler for physical circularity and not as an alternative.¹⁶

5.8 Pillar 8 — Governance, competence and continual improvement

In a circular manufacturing, there exist cross-functional trade-offs and therefore, decision rights have to be explicit. Look beyond the unit price in procurement; don't always accept new tonnage at circular on service-lives without any expected or measurable reduction in CO2 emissions; do not accept circular when there is no evidence of carbon reduction; don't reject circular options without risk testing. Given the fact that there are many variables to consider, a cross-functional review of the WPC Circularity Review Board is proposed to approve major changes to feedstock, recipe, product and waste-route using the standard evidence pack of technical validation, cost, LCA screen, regulatory review, and end-of-life impact.¹⁷

6. QUANTITATIVE KPI ARCHITECTURE

One of the key innovations in the framework is the fact of the absence of local optimizations in the system due to the linking of KPIs. Force recycled content as an added value, but only in the context of yield, property retention,

¹⁷ Saadiah, S. M., & Noh, S. D. (2025). Digital twins in circular manufacturing: A systematic perspective on data-enabled resource loops and lifecycle decision support. *Sustainability*, 17(16), 7316. <https://doi.org/10.3390/su17167316>

energy, cost and service quality. The KPI listed below is set in a formula to allow a plant to enter data in it without

trying to imagine that the words "Generic" could apply to any formulation.

Table 5. Proposed multi-dimensional KPI system for IIMF-WPC.

KPI	Formula / definition	Decision purpose
Material yield (%)	Conforming product mass / total input mass $\times 100$	Overall conversion efficiency; detects hidden scrap and purge losses
Post-industrial scrap rate (kg/t)	Internal scrap mass / conforming tons	Direct waste-generation intensity
Closed-loop recirculation rate (%)	Internal WPC scrap reintroduced / eligible internal WPC scrap $\times 100$	Effectiveness of internal circularity
Qualified recycled polymer content (%)	Mass of qualified recycled polymer / total polymer mass $\times 100$	Circular polymer substitution without ignoring quality gates
Secondary lignocellulosic content (%)	Qualified residue-derived lignocellulosic mass / total lignocellulosic mass $\times 100$	Use of by-product/residue wood resources
Specific energy (kWh/t)	Total line energy / conforming product tons	Links process stability and energy performance
Carbon intensity (kg CO ₂ e/FU)	Life-cycle GHG / functional unit	Captures upstream, manufacturing and Eola effects
Water intensity	Net process water / conforming output	Relevant where cooling or washing is significant
Property retention after recycling (%)	Recycled-cycle property / virgin or cycle-0 property $\times 100$	Technical circularity gate
First-pass yield (%)	Conforming product without rework / total product $\times 100$	Quality + process stability
Customer return/claim rate	Returns or claims / shipped units or tons	Service-performance indicator
Circular value recovery (%)	Economic value retained through reuse/recycling / theoretical material value	Financial quality of waste valorization
Cost per conforming functional unit	Total conversion + quality + waste cost / conforming FU	Prevents misleading raw-material savings
Traceability completeness (%)	Lots with complete material/process genealogy / total lots $\times 100$	Information prerequisite for safe circularity

Management should avoid isolated targets such as 'maximize recycled content.' A more defensible objective is constrained optimization: maximize recycled content and value recovery subject to minimum product-performance, process-capability and service-life requirements, while minimizing cost and environmental burden. A simplified plant decision function can be written as:

Maximize $Z = w_1(\text{Circularity}) + w_2(\text{Yield}) + w_3(\text{Quality}) - w_4(\text{Energy}) - w_5(\text{Carbon}) - w_6(\text{Cost}) - w_7(\text{Risk})$

where the weights ($w_1 \dots w_7$) are strategic priorities set by the organization and the solution is constrained by product specifications, regulatory requirements and validated

process windows. In a real plant, multi-objective optimization could be implemented using Pareto analysis rather than forcing all criteria into one monetized score.

7. RISK-BASED DECISION MODEL

The IIMF-WPC framework recommends a modified failure-mode-and-effects analysis (FMEA) for circularity changes. Conventional severity–occurrence–detection scoring can be extended with a circularity exposure factor that captures uncertainty introduced by feedstock history, contamination and repeated processing. The purpose is not to create an artificial precise risk number, but to ensure that higher recycled content triggers proportionate evidence requirements.

Table 6. Illustrative circular-manufacturing FMEA for WPC operations.

Failure mode	Effect	Severity	Occurrence tendency	Detection/control	Response
Wet wood feedstock	Steam/voids, weak interface, pressure instability	High	Medium–high	Dryer outlet moisture + feeder-area check	Hold lot; redry or reject; investigate storage humidity
Mixed polymer contamination	Phase incompatibility, brittle product, unstable melt	High	Medium	NIR/FTIR, density/MFI screen	Quarantine; sort; downgrade if validated
Excess thermal history	Oxidation, discoloration, molecular degradation	Medium–high	Medium	Cycle-count + melt-temperature history + MFI	Reduce recycle ratio;

					stabilize; requalify
Compatibilizer under-dose	Poor adhesion, low strength, high water uptake	High	Low–medium	Gravimetric feeder verification; mechanical trend	Correct feeder; quarantine affected lots
Uncontrolled recycle ratio	Property variability, color/flow drift	High	Medium	Recipe interlock + material genealogy	Stop line; restore validated blend
Weathered post-consumer WPC	Unknown oxidation/biological contamination	High	Medium	Surface cleaning, spectroscopy, mechanical requalification	Use controlled cascading application or reject
Dust accumulation	Fire/explosion and housekeeping risk	Critical	Process-dependent	Dust monitoring/housekeeping/audits	Engineering controls; dust collection; safe handling procedures
Misleading circularity claim	Reputational/regulatory risk if recycled content raises burden or reduces life	High	Medium	LCA/TEA + quality/service evidence	Correct claim; governance review

8. DISCUSSION

8.1 Why an integrated management framework is necessary

This evidence reviewed here calls for a transformation of the concept of WPC sustainability. WPCs are more frequently marketed as environmentally friendly since they are able to incorporate recycled thermoplastic with renewable lignin content-based material. That's not a complete sentence. Every part of the WPC chain, from raw materials to drying energy, the additives to manufacturing yields, service life, maintenance and logistics and end-of-life route, has an effect on the WPCs environmental performance. Similarly, recycled content is not a stable material property but it is a parameter of supply-chain and process control. Integrated departmental control, in turn, forms the basis of an industrial sustainability. This is the reason for successes with high recycled content in the laboratory but failures during scale-up. Even when the polymer and wood are all recycled of the same kind, and mixing the two materials is controlled, a laboratory can adopt the use of a homogeneous batch of those materials. A commercial line has to deal with a variety of issues such as truck-to-truck variability, humidity in the warehouse, feeding dynamics, start-up scrap, die changes, maintenance events, color requirements, and customer specification limits. The integrated frame is deliberately translated laboratory results practice-based to operating controls like incoming specification, Camp, orpa and release gates for recycle-class segregation, material genealogies.

8.2 Implications for recycled polymers and wood residues

Thus, the greatest near term circularity potential exists with clean post-industrial material. It has a known chemistry, known additive history and it has little/no environmental exposure. There's also an economic

argument to be considered, since there's a cost savings from not having to transport the waste into the country or to its destination, as well as not needing to sort it outside. In this stream, though, a considerable amount of literature exists on the aggressive use of closed loop recirculation as long as property retention and process stability are quantified. The post-consumer material has its own risk posture due to unknown product genealogy, contamination and weathering. The 2026 systematic review on loop recycling also clearly states the areas of post-consumer recycling and standardized benchmarking where development is lacking, emphasizing the need for qualification, not making assumptions. The role of wood residues is also described in the framework. The residues from sawdust etc. can be utilized in a cascading manner, as wood flour, via valorization of the wood waste and hence limit the demand for purpose-grown filler materials, but residual usage must not be done at the expense of other applications or pollution. Construction and demolition wood, for instance, may include coatings, preservatives or metals or gypsum and/or mineral soils. However, EPA estimates 40.8 million tons of wood products for construction and demolition waste products in the U.S. in 2018, which illustrates the potential scale but also the diversity of this feedstock class.

8.3 Product quality and standards as circularity enablers

Quality assurance is sometimes seen as impeding circularity due to the fact that it is limiting on feedstock variation. The reverse is more true: credible quality systems provide greater circularity as they represent the evidence needed to be able to take variability seriously. ASTM D7032 does just this by providing mechanical and environmental testing-based ratings for the performance of WPC/plastic lumber, not just by composition. A product may then include an assortment of materials as

long as it does not lose the performance outcomes documented in the standards. The same performance-based mentality should be applied to recycled content qualification as well. Environmental and environmental and energy management systems supplement each other in the field. This is why ISO 14001:2026 further enhances the relationship between environmental goals, control of operations and measurable results, and ISO 50001 offers a framework for energy baseline and performance baselines. If all of these systems communicate where there is waste and quality and production systems, management will have a clear view of whether a recycling effort really helps the plant or simply shifts waste and energy from one department to another.¹⁸

8.4 Digitalization and Circular Material Passport

History is important in creating composite quality, especially in WPCs, and digital twins are relevant in this

application. It is important to note that two identical looking pellets can have many variations in their polymer family, prior cycles, wood source, additives, and thermal exposure. This information can be captured on a material passport to accompany each lot, helping to enable safe blending rules. When mature, a digital twin can be tied into real-time line signals and used to anticipate properties and/or off-spec risk. A recent review of circular publishing sentiment reinforces that visualization is not the only part of the story behind the digital twin value, but data flow, monitoring, prediction, and decision to help with the lifecycle. The sequenced digital architecture is IIMF-WPC's suggestion, then, traceability should be followed by statistical analytics, predictive models and only finally achievable autonomous optimization.¹⁹

8.5 Research propositions derived from the framework

Table 7. Research propositions for empirical validation of IIMF-WPC.

Proposition	Testable statement
P1	Plants with tighter feedstock-qualification capability will achieve higher recycled-content utilization without increasing first-pass reject rate.
P2	The positive effect of internal scrap recirculation on material cost will be mediated by property-retention performance and moderated by thermal-history control.
P3	Traceability completeness will positively influence both circular value recovery and customer-quality stability by reducing uncontrolled material mixing.
P4	Specific energy consumption will exhibit a U-shaped relationship with recycled/wood content beyond a formulation-dependent optimum because excessive viscosity and preprocessing can offset material savings.
P5	Integrated LCA–TEA decision gates will reduce the incidence of burden shifting compared with recycled-content targets used in isolation.
P6	Digital process monitoring will strengthen the relationship between feedstock variability and stable output by enabling earlier detection and recipe intervention.
P7	Segregation of post-industrial and post-consumer WPC streams will produce higher circular value recovery than undifferentiated mixed-stream recycling.
P8	Organizations operating under integrated quality–environment–energy governance will show faster learning rates in circular WPC scale-up than organizations using functionally isolated controls.

9. PLANT-SCALE VALIDATION ROADMAP

Future research is needed to validate IIMF-WPC in one or more industrial lines, following a longitudinal design, to bring the work from the conceptual framework to the Q1, empirical level. The recommended data window is to look at a minimum of 6–12 months of data to account for

changes in the supplier, seasonal humidity, maintenance events and multiple production campaigns. The production lot is the preferred unit of analysis, is connected with the raw-material lots and scrap-recycle batches.

Table 8. Proposed plant-scale validation protocol.

Validation phase	Main activity	Suggested measures / analysis
Phase 1 — Baseline mapping	Map material and data flows; identify current scrap classes, energy meters, tests and data gaps.	Mass balance, OEE, scrap, energy, quality claims, traceability completeness
Phase 2 — Measurement-system validation	Verify moisture, MFI, weighing, pressure/temperature, dimensional and mechanical measurement repeatability.	GR&R where applicable; calibration; missing-data rate
Phase 3 — Controlled recycle trials	Run designed trials at increasing internal recycle ratios within same polymer family.	Torque/pressure CV, energy, output, tensile/flexural, impact, water uptake, color

¹⁸ Huang, Löschke and Proust (2026) identify major evidence gaps in post-consumer WPC recycling, harmonized recyclability testing and standardized reporting across repeated reprocessing cycles.

¹⁹ U.S. Environmental Protection Agency (2020), Advancing Sustainable Materials Management: 2018

Fact Sheet / Construction and Demolition Debris data. The EPA estimated 600.3 million tons of U.S. construction and demolition debris in 2018, including about 40.8 million tons of wood products.

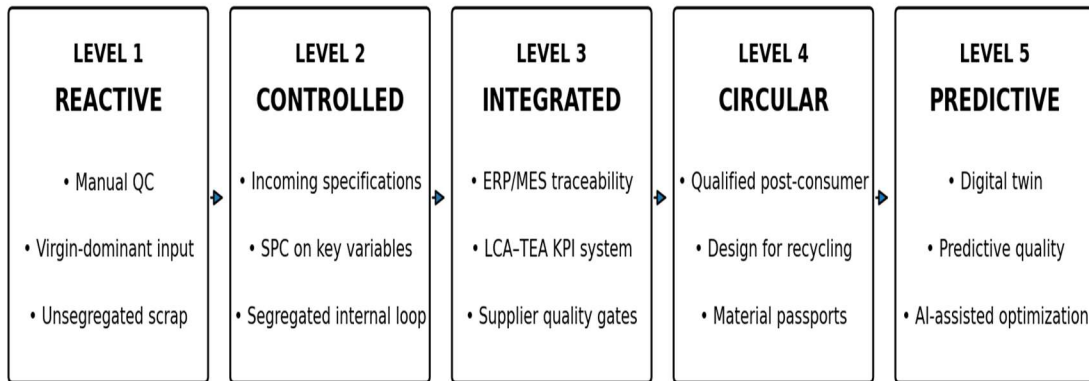
Phase 4 — Feedstock variability trials	Compare supplier lots/recycled grades under controlled recipes.	ANOVA/mixed models; capability; interaction effects
Phase 5 — LCA/TEA scenarios	Compare virgin-dominant, internal-loop, and qualified post-consumer scenarios.	kg CO ₂ e/FU, kWh/FU, cost/FU, value recovery
Phase 6 — Digital model	Train predictive models using material genealogy and line signals.	RMSE/MAE, classification accuracy, false alarms, avoided scrap
Phase 7 — Governance evaluation	Track approval cycle time, corrective actions and cross-functional decisions.	Time-to-close CAPA, repeat deviations, realized savings

Statistically, the eventual empirical paper can use mixed-effects regression because lots are nested within recipes, machines, suppliers and time periods. DOE/response-surface methodology can optimize recycle ratio, wood content, compatibilizer and process settings. Structural-equation modeling may be used only if the study collects sufficiently large multi-plant managerial datasets for the

organizational propositions; it should not be forced onto small process datasets. For quality outcomes, multivariate SPC and partial least squares can be useful where line variables are highly collinear.

10. IMPLEMENTATION MATURITY MODEL

WPC circular-manufacturing maturity path



Advance only after performance gates are stable; recycled content is not sustainable when it increases scrap, energy use, premature failure or hazardous contamination.

The maturity model acknowledges that AI-driven circular manufacturing should start with, and incorporate, control in the plant. Level 1 is Reactive and Controlled by manual decisions. Level 2 sets specifications and internal segregation of scrap. The Strategies for Success rubric contain a cross connection to using data and tracing the cycle of success to identify performance indicators at Level 3. Level 4 is a step toward controlled, qualified post-consumer flows and 'design for recycling'. The Level

5 is predictive analytics and digital twins. What is needed for advancement is proof of stability at the previous level; digital maturity, without feedstock discipline, would only be a repeat of crazy waste of resources on unreliable inputs.

11. MANAGERIAL IMPLEMENTATION CHECKLIST

Table 9. Practical IIMF-WPC implementation scorecard.

Control area	Audit question	Status / evidence
Material governance	All polymer and wood feedstocks have approved specifications and unique lot IDs.	Not started / partial / complete
Moisture control	Wood moisture is measured at receipt, after drying and near feeding.	
Polymer identity	Recycled polymer identity and MFI/MFR are verified at risk-based frequency.	
Recipe control	Formulation revisions and substitutions require formal approval.	
Thermal history	Melt-temperature excursions and recycle-cycle history are traceable.	
Scrap segregation	Clean internal scrap is physically separated from mixed/contaminated waste.	
Recycle gate	Each recycle class has a validated maximum blend range and requalification plan.	

Quality capability	Critical dimensions/properties have capability targets and SPC where suitable.	
Energy performance	Specific energy per conforming tonne is monitored and normalized.	
LCA/TEA	Major circularity changes are screened for carbon, cost and service-life effects.	
Compliance	Product tests are mapped to relevant standards and markets.	
Traceability	Material, process and quality genealogy can be reconstructed for every shipment.	
Governance	Cross-functional review approves high-risk material/process changes.	
Customer feedback	Claims and field failures are linked back to material/process lots.	
Continuous improvement	Savings are verified after implementation; recurring causes are permanently corrected.	

12. LIMITATIONS AND FUTURE RESEARCH

This paper is designed to be thought-provoking in nature and should not be taken as an indication that there is an optimal single all-purpose WPC recipe, recycle ratio or processing window. WPC behavior depends on the specific formulation of the material, with significant variations possible between polymer families, fiber species, particle morphology, additives, and machine design and intended use. The principles of the management are derived from representative evidence but the numerical thresholds for each plant and product must be validated. More specifically, the recycling of post-consumer WPC is not as mature as internal-loop recycling, and there is an interest in establishing long-term durability through field tests after one or more recycling processes. There are four important areas for future research. One preliminary step would be for standardized protocols for recyclability to include the name of the polymer, wood content, additive package, number of cycles, processing conditions and multiple retention of property measures, to make studies comparable. Second, the application of industrial LCA should use true scrap, start-up losses, drying energy data, line efficiency and service-life. Third, good sorting and material-passport systems should be validated for the recovery of WPCs after the consumption. Fourth, digital twin models should be judged for the avoidance of scrap, reduction of energy and property prediction, and more than in terms of their algorithmic accuracy.

13. CONCLUSION

To realize sustainable WPC manufacturing, the industry is best perceived as an integrated system of manufacturing and not only a material innovation in itself. Results highlight that recycling thermoplastics and lignocellulosic residues for making WPC composites is technically viable and that, in some instances, a clean stream of thermoplastics, at least at the laboratory level, can be mechanically recycled with significant preservation of characteristics. Variability in moisture, polymer types, contamination, interface chemistry and thermal history also pose potential risks, strongly increasing when dealing with uncontrolled circular material flows. The proposed IIMF-WPC measures handle these risks under eight pillars; feedstock qualification, formulation engineering, process-window control, quality/compliance, closed-loop valorization, LCA and techno-economic control, digital traceability and governance and continuous improvement. It is based on constrained circularity: valorize as much as possible waste and extraction of second use materials within validated limits of product performance, process

capacity, energy and environmental load as well as economic viability. The biggest challenge today is not the newest and greatest technology but rather information and segregation: Know the polymer, know the wood, know the additive package, know the thermal history, and keep the material surface clean. Plant-scale validation through longitudinally oriented lot-level data, statistically designed recycle trials, integrated LCA–TEA, as well as predictive models are the next steps for conducting research. In combination, these elements could lead to a more developed WPC manufacturing scenario that is more than an opportunistic use of waste, and more of a measurable circular-manufacturing platform on which the value of material is purposefully preserved across industrial cycles.

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Appendix A. Minimum Dataset for an Empirical IIMF-WPC Study

Dataset	Minimum variables
Raw-material lot	Supplier, material ID, polymer family, MFI/MFR, moisture, ash, color, wood source, particle distribution, recycled-content certificate
Recipe	Wood %, polymer %, recycled %, compatibilizer %, lubricant/additive %, pigment, recipe revision
Process	Line ID, screw design, temperatures, screw speed, torque, melt pressure/temp, throughput, vacuum, cooling, cycle time

Energy	Extruder/molding kWh, dryer kWh, grinder kWh, auxiliaries, production time, conforming output
Quality	Density, tensile/flexural strength/modulus, impact, water absorption, dimensions, color, surface defects, weathering where applicable
Waste	Start-up scrap, trim, off-spec, purge, fines, eligible recycle, actual recycled mass, disposed mass, contamination reason
Economics	Raw materials, energy, labor, maintenance, disposal, quality loss, transport, product price
Lifecycle	Upstream emission factors, electricity mix, transport, product lifetime assumption, EoL route and allocation rule
Digital genealogy	Lot links, cycle count, sensor alarms, interventions, model predictions, operator/maintenance event