MORFAI JOURNAL
Multidiciplinary Output Research For Actual and International Issue
Multidiciplinary Output Research For Actual and International Issue (MORFAI Journal) ISSN (e): 2808-6635
Volumes 6 No. 3 (2026)

FILLER ENGINEERING IN WOOD–PLASTIC COMPOSITES: A REVIEW OF MECHANICAL PERFORMANCE, INTERFACIAL BEHAVIOR, AND FAILURE MECHANISMS

Cahyo Budiyantoro[1*], Johanes Wawan Joharwan[2]
[1]Department of Mechanical Engineering, Faculty of Engineering, Universitas Muhammadiyah Yogyakarta. Yogyakarta, Indonesia.
[2]Program Studi D3 Teknik Mesin, Sekolah Tinggi Teknologi Warga Surakarta
E-mail: cahyo_budi@umy.ac.id

Received	: 10 February 2026	Accepted	: 12 March 2026
Revised	: 20 February 2026	Published	: 26 March 2026

Abstract

Wood–plastic composites (WPCs) have gained increasing attention as lightweight, cost-effective, and sustainable materials for applications such as construction, furniture, automotive components, and consumer products. Among the variables affecting WPC performance, filler characteristics play a central role by controlling stress transfer, interfacial adhesion, stiffness, strength, and fracture behaviour. This literature review examines the influence of filler characteristics on the mechanical performance of WPCs. The discussion includes filler type and source, particle size, particle shape, aspect ratio, filler loading, raw material composition, and chemical pretreatment, together with their interactions with coupling agents and polymer matrices. The reviewed studies show that these factors strongly influence tensile strength, flexural strength, modulus, impact resistance, and failure mechanisms. Differences in wood species, recycled lignocellulosic materials, and agricultural residues also contribute to variations in composite behaviour, driven by their distinct chemical composition, density, morphology, and thermal stability. In addition, surface modification and compatibilisation, especially using maleic anhydride-grafted polyolefins, are widely reported to improve filler–matrix adhesion and mechanical properties. Overall, WPC optimisation requires integrated control of filler morphology, composition, content, and interface quality.

Keywords: wood–plastic composites, filler characteristics, mechanical performance, wood flour, particle size, filler loading, interfacial adhesion

INTRODUCTION

Wood–plastic composites (WPCs) are hybrid materials produced by combining wood-based fillers such as flour, particles, or fibres with thermoplastic matrices under controlled processing conditions. They have gained broad industrial relevance because they offer a useful combination of processability, relatively low density, favourable stiffness, reduced maintenance requirements, and the potential to use recycled raw materials. The literature also indicates sustained growth in WPC research and applications, especially in construction, decking, cladding, furniture, automotive interiors, and consumer products[1]. Although WPCs offer several advantages, their mechanical behaviour is highly sensitive to the filler phase's characteristics. The reinforcement effect of wood particles does not depend solely on the amount of filler added, but also on particle size, particle shape, source, composition, and surface chemistry. In practice, these characteristics determine how efficiently load is transferred between matrix and filler, how easily particles debond under stress, and how the composite ultimately fails. Recent work has emphasised that the load-carrying capacity of WPCs depends strongly on flour particle characteristics and their interactions with the matrix. Larger particles, for example, may be more prone to debonding if the interface is weak, highlighting the central role of filler design in mechanical optimization. This review, therefore, focuses specifically on the influence of filler characteristics on the mechanical performance of WPCs. Rather than treating durability and environmental ageing as the main topics, they are addressed only to the extent they help explain mechanical-property changes associated with filler morphology and interface quality. The goal is to provide a focused synthesis that aligns with the title and highlights how filler engineering can enhance tensile, flexural, impact, and fracture performance in WPC systems.

LITERATURE REVIEW

1. Filler Characteristics as the Core Determinant of Mechanical Performance

Filler characteristics are among the most decisive parameters controlling the mechanical response of WPCs. In particulate or short-fibre lignocellulosic systems, the reinforcing effect of wood flour is not governed solely by filler concentration, but also by particle size distribution, aspect ratio, botanical origin, surface chemistry, and the resulting quality of interfacial bonding with the polymer matrix. Recent reviews and experimental studies consistently indicate that these factors jointly determine stiffness, tensile and flexural strength, impact behaviour, and the dominant deformation and fracture mechanisms of WPCs. From a micromechanical standpoint, filler characteristics affect composite performance by influencing stress transfer across the matrix–filler interface. When the filler is well dispersed and adequately bonded, the lignocellulosic phase can contribute effectively to load sharing and modulus enhancement. However, when particles are large, irregular, poorly wetted, or weakly adhered to the matrix, they may act as stress concentrators, leading to premature local failure. Dányádi et al. showed that wood flour particles are relatively large and therefore debond readily unless adhesion is improved. At the same time, Renner et al. further demonstrated that the properties of PP/wood composites depend strongly on both interfacial adhesion and particle characteristics, with better reinforcement achieved with fillers of larger anisotropy and smaller diameter.

The role of particle size is especially complex. Earlier work showed that in wood-flour-reinforced polypropylene, particle size affected melt flow and several mechanical properties, and they linked impact-related behaviour to crack initiation around particle-rich zones. Bouafif et al. later reported that, in HDPE-based WPCs, larger fibre size produced higher strength and elasticity but lower energy to break and elongation, indicating that coarser particles may improve stiffness and strength while also promoting a more brittle mechanical response. By contrast, more recent studies have shown that decreasing particle size can improve modulus and strength when particle refinement is accompanied by better dispersion and limited aggregation. For example, Delviawan et al. found that reducing wood-particle size through wet milling enhanced tensile strength and flexural modulus up to an optimum condition, after which excessive milling promoted aggregation and slightly reduced performance. Similarly, Çavuş and Mengeloğlu reported that decreasing particle size increased flexural modulus, tensile modulus, and impact strength in PP- and recycled-PP-based WPCs, while the addition of MAPP further improved flexural and tensile properties across particle-size ranges. These results indicate that particle size should not be interpreted independently, but rather in conjunction wit dispersion state and interface quality.

The effect of filler source and morphology is equally important. Variations in wood species alter density, cell-wall structure, lignin/cellulose balance, and surface characteristics, all of which affect composite mechanics. Ratanawilai et al. demonstrated that recycled polypropylene composites filled with rubberwood flour showed higher flexural, tensile, compressive, and hardness properties than those filled with oil-palm mesocarp flour at equivalent particle sizes; they also showed that decreasing particle size increased mechanical properties for both filler types. These findings support the view that filler source is not a secondary material-selection issue, but a structural parameter that directly influences reinforcement efficiency. Broader reviews reach the same conclusion, noting that wood flour fraction, morphology, and additive strategy govern the extent to which WPCs gain stiffness without sacrificing strength and toughness The influence of filler characteristics can be formalised using classical composite mechanics. The rule of mixtures often expresses a first-order estimate of composite stiffness:

$$E_c = V_f E_f + V_m E_m \quad (1)$$

where E_c is the composite modulus, E_f and E_m are the elastic moduli of filler and matrix, and V_f and V_m are their respective volume fractions. Although this relation captures the general tendency for modulus to increase with the incorporation of a stiffer filler, it overestimates performance in WPCs because wood flour is discontinuous, randomly oriented, and imperfectly bonded. A more realistic representation introduces an efficiency factor:

$$E_c = E_m(1 - V_f) + \eta_E E_f V_f \quad (2)$$

where η_E accounts for particle geometry, orientation, dispersion, and interfacial adhesion. In WPCs, η_E is especially sensitive to filler aspect ratio and bonding quality, which explains why two formulations with the same filler loading may show markedly different stiffness values. More generally, Halpin–Tsai-type approaches are often used in composite mechanics because they allow the effect of particle aspect ratio and morphology to be incorporated into modulus prediction; such formulations are particularly useful when reinforcement deviates from the ideal assumptions of the simple rule of mixtures.

Strength is even more sensitive than stiffness to filler characteristics because it depends on the effectiveness of stress transfer before interfacial failure occurs. In simplified form, tensile strength may be expressed as

$$\sigma_c \approx \sigma_m(1 - V_f) + \eta_\sigma \sigma_f V_f \quad (3)$$

where σ_c, and σ_f denote the strengths of the composite, matrix, and filler, respectively, and $\eta\sigma$ is a stress-transfer efficiency factor. In practice, $\eta\sigma$ decreases when particles are too coarse, poorly dispersed, or weakly bonded, because debonding and void formation occur before the filler can carry significant load. This condition helps explain why increasing wood content often increases modulus, but produces inconsistent trends in tensile strength unless compatibilisers are used. Reviews focused on high wood-filler content likewise note that increasing the wood fraction may enhance stiffness and, in some cases, tensile strength, but often reduces impact resistance, flexibility, and toughness due to interface-related limitations and increased defect sensitivity

2. Influence of Filler Type and Source

The first major aspect of filler characteristics is filler type and source. WPC fillers can be derived from virgin wood flour, recycled wood particles, sawdust, agricultural residues, and other natural fibres. According to Delviawan et al., filler materials include wood-based fillers, other natural fibres, and recycled materials, all of which can affect the composite's final mechanical properties. This fact is important because different filler sources exhibit distinct chemical compositions, densities, lignin–cellulose ratios, moisture affinities, and particle morphologies. Wood species is a particularly important variable. The same review notes that different wood species produce WPCs with different properties. Even when the polymer matrix remains the same, changing the wood source can alter not only appearance and durability-related characteristics but also the composite's mechanical response. This response occurs because different species exhibit distinct cell-wall structures and distributions of cellulose, hemicellulose, lignin, and extractives, all of which influence stiffness, interface formation, and filler integrity during processing. The literature also shows that recycled fillers are viable alternatives to virgin materials. Delviawan et al. summarise evidence that composites made from recycled wood particles may show properties comparable to those made from virgin wood particles or wood flour. This finding is mechanically important because it indicates that a carefully selected recycled filler can still provide sufficient reinforcement, supporting both cost reduction and sustainability without necessarily sacrificing performance. At the same time, not all waste-derived fillers behave the same way. Studies summarised in the review indicate that some lignocellulosic fillers may increase water absorption or thickness swelling more than others, which can, in turn, affect mechanical properties over time in service. From a mechanical design perspective, this means filler selection should not be based solely on availability or cost, but also on how the source material contributes to stress transfer, dimensional stability, and structural reliability.

3. Particle Size and Mechanical Behaviour

Particle size is a governing structural variable in WPCs because it directly affects the available interfacial area, particle packing, dispersion homogeneity, local stress concentration, and the efficiency of load transfer between lignocellulosic filler and polymer matrix. In practice, the mechanical influence of particle size is not independent, but coupled with filler morphology, wood species, matrix type, processing history, and compatibiliser content[2]. For this reason, the relationship between particle size and tensile, flexural, and impact performance is often non-monotonic across the literature, with finer particles sometimes improving stiffness and strength, and coarser particles proving advantageous in other formulations. This variability is now widely recognised in both experimental papers and recent reviews on particulate wood–polymer composites. A substantial body of evidence indicates that reducing particle size can improve selected mechanical properties by promoting better packing and more homogeneous dispersion. Ashori and Nourbakhsh found that, in wood flour/polypropylene composites, smaller particles generally improved the mechanical response, and their analysis linked this behaviour to more effective stress transfer and reduced defect severity when the filler was sufficiently well distributed. Similarly, Kociszewski et al. showed that particle size significantly influenced the mechanical properties of wood–PVC composites made from industrial particles, confirming that filler refinement alters structural performance even when the matrix and processing route are kept constant. More recently, Murayama et al. reported that wet ball-milling of wood flour improved the mechanical properties of WPCs up to an optimum milling condition, beyond which further refinement did not continue to improve performance, indicating that excessive size reduction may become counterproductive. Optimum particle size behaviour is especially important for interpreting contradictory trends in the literature. Murayama et al. observed that mechanical properties increased as particle size decreased up to a certain milling time. However, they then slightly declined after further milling, which they attributed to aggregation-related effects and changes in particle morphology. This finding suggests that particle-size optimisation is not simply a matter of maximising fineness; rather, an intermediate particle-size range is often mechanically preferable because it provides a sufficiently large interfacial area without severely increasing agglomeration tendency or reducing processability. A similar interpretation is consistent with general composite-mechanics analyses showing that excessively fine fillers may increase viscosity, complicate dispersion, and promote defect formation during compounding and moulding. At the same time, several studies have shown that coarser particles may improve stiffness and, in some systems, even strength. Kociszewski et al. reported that particle size significantly affected stiffness and strength in wood–PVC composites prepared by injection moulding, demonstrating that larger industrial particles can still provide effective mechanical reinforcement, depending on specimen geometry and processing conditions. Related studies on reprocessed wood-flour/polypropylene systems also found that the initial wood particle size influences the final tensile and flexural response after repeated moulding cycles, indicating that coarse particles may remain beneficial when the interface is adequately preserved or compatibilised. These observations support the broader conclusion that larger particles may act as more effective load-bearing inclusions when they are sufficiently bonded and well distributed, even though they may also increase brittleness and stress concentration if the interface is weak.

Particle size also affects impact behaviour and ductility. Across the literature, finer particles often delay catastrophic crack propagation by reducing the severity of local stress concentrations and improving filler distribution. In contrast, larger particles can promote a stiffer but more brittle response. This tendency is consistent with studies showing that particle refinement may improve impact-related properties in polyolefin-based WPCs, while coarser particles can reduce elongation at break and increase embrittlement. Because crack initiation in WPCs often occurs at or near particle–matrix interfaces, particle size becomes a controlling factor in the transition between more ductile deformation and more brittle fracture. Another major consequence of particle size is its effect on rheology and processing. Very fine particles tend to increase melt viscosity and reduce flow, which may complicate extrusion or injection moulding and lead to poor wetting, void formation, or particle agglomeration. Coarser particles, by contrast, may facilitate flow to some extent, but often at the cost of increased local heterogeneity. Murayama et al. showed that different milling conditions altered particle characteristics sufficiently to affect mechanical performance. At the same time, broader reviews of particulate WPCs emphasise that processing-related variables cannot be separated from particle-size effects when interpreting composite performance. Thus, the role of particle size must always be analysed together with the route of compounding and shaping .

4. Particle Shape, Aspect Ratio, and Stress Transfer

Besides particle size, particle shape and aspect ratio are among the most important filler descriptors controlling the mechanical performance of WPCs. Their importance arises from the fact that reinforcement efficiency depends not only on filler content but also on whether the lignocellulosic particles' geometry permits effective stress transfer from the polymer matrix to the filler. Experimental evidence shows that fillers with a higher aspect ratio generally provide greater tensile and flexural reinforcement than low-aspect-ratio wood flour. In contrast, irregular or blocky particles are more likely to behave as stress concentrators, especially when interfacial adhesion is limited. In polypropylene-based composites, Stark and Rowlands reported that wood fibre with an aspect ratio much higher than that of conventional wood flour produced higher tensile and flexural strengths at both 20 and 40 wt.% loading, and higher moduli at 40 wt.% loading, demonstrating that reinforcement efficiency improves as particle anisotropy increases. Their paper also states that the higher aspect ratio enhanced stress transfer, even though the effect on impact energy was limited.

Comparative studies of different wood-fibre forms also support the significance of particle geometry. Peltola et al. compared wood flour, refined fibers, and pelletised fibers in PLA- and PP-based composites and found that fiber type strongly affected morphology, dispersion, and the resulting composite properties; pelletised wood fibers showed a clear reinforcing effect compared with conventionally used wood flour or refined fibers. This result is important because it suggests that not all "wood fillers" are mechanically equivalent: even at the same nominal loading, changes in fibre form, shape retention, and morphology after processing alter stiffness and strength . A more direct demonstration of the effects of geometry on WPCs was reported by Khonsari et al., who investigated mixtures of sawdust and ground shavings in HDPE-baed WPCs. They found that increasing the proportion of shaving-derived particles tended to improve flexural properties, and their interpretation explicitly linked this trend to the higher aspect ratio of the shaving particles compared with that of ordinary wood flour. Their results reinforce the general principle that higher-aspect-ratio particles provide more efficient stress transfer because they interact with the surrounding matrix over a longer effective load path. From a micromechanical standpoint, the role of aspect ratio can be expressed through a geometry-sensitive formulation provided by the Halpin–Tsai equation, which is widely used for discontinuous-fibre and particle-reinforced composites:

$$E_c = E_m \frac{1+\xi\eta V_f}{1-\eta V_f} \quad (4)$$

With

$$\eta = \frac{(E_f/E_m)-1}{(E_f/E_m)+\xi} \quad (5)$$

where
ξ is a shape parameter related to reinforcement geometry and aspect ratio. Although wood flour in WPCs is not an ideal continuous fibre, this framework remains useful because it captures the dependence of stiffness on filler anisotropy. Reviews on natural-fibre composite mechanics have highlighted Halpin–Tsai-type relations as effective tools for predicting Young's modulus when reinforcement geometry departs from simple spherical assumptions, and more recent WPC-related modelling work has likewise emphasised that aspect ratio and particle morphology must be explicitly represented to interpret stiffness development realistically

The influence of particle shape and aspect ratio is also evident in deformation and fracture behaviour. When particles are short, equiaxed, or irregular, their edges and corners act as local sites of stress concentration, promoting interfacial debonding and early matrix cracking. By contrast, more anisotropic particles tend to distribute load more effectively. They can shift the failure mode toward particle fracture or matrix deformation if adhesion is good enough to prevent pull-out. Renner et al. found that deformation and failure in PP composites reinforced with lignocellulosic fibres are controlled by the inherent strength of the particles and their geometry. They concluded that further improvement in composite strength requires optimisation of particle size, aspect ratio, and intrinsic particle strength. Processing-induced orientation further complicates the effect of aspect ratio. Ansari et al. showed that injection-moulded wood-fibre composites exhibit substantial mechanical anisotropy due to orientation developed during moulding, demonstrating that the mechanical contribution of high-aspect-ratio particles depends not only on their intrinsic geometry but also on how they align during processing. Similarly, Hao et al. reported that the anisotropy of poplar wood fibre/HDPE composites is strongly related to the high aspect ratio of the wood fibres and their orientation distribution, showing that geometry and orientation jointly determine directional stiffness and strength.

These studies make it clear that aspect ratio cannot be considered separately from the manufacturing route: extrusion and injection moulding may enhance reinforcement in one direction while increasing anisotropy in the final product. More recently, Golmakani et al. reviewed the effects of wood flour size and aspect ratio in WPC systems and summarised prior findings showing that increasing aspect ratio can substantially raise the tensile modulus. At the same time, smaller dimensions may improve impact-related response in some formulations. Although that paper includes broader structural factors, it reinforces the view that shape and aspect ratio are not secondary descriptors, but fundamental variables that determine whether a lignocellulosic filler acts as a true reinforcement or merely as a filler phase with limited stress-transfer capability. The literature indicates that particle shape and aspect ratio are central determinants of stress transfer in WPCs. Higher-aspect-ratio and more anisotropic particles generally improve stiffness and strength because they increase the efficiency of load transfer, but only when dispersion, wetting, and interfacial bonding are sufficiently controlled. Conversely, irregular or low-aspect-ratio particles may reduce reinforcement efficiency and increase defect sensitivity, especially under poor adhesion conditions. Therefore, optimising WPC mechanical performance requires not only selecting suitable filler loading and particle size, but also engineering the morphology of the lignocellulosic phase and preserving favourable orientation during processing.

5. Effect of Filler Loading

Filler loading is one of the most critical formulation variables in WPCs because it directly controls the balance between stiffness enhancement, matrix continuity, interfacial quality, and damage tolerance. In general, increasing lignocellulosic filler content increases composite stiffness because the wood phase is less compliant than the polymer matrix. However, the effect of filler loading on strength, impact resistance, and ductility is considerably more complex, since higher filler fractions also increase the probability of particle crowding, insufficient wetting, agglomeration, and interfacial debonding. Recent reviews on WPCs and natural-filler polymer composites consistently note that filler content must be optimised rather than maximised, because mechanical benefits at moderate loading may be offset by brittleness and structural heterogeneity at higher loading levels[3].

This behaviour has been demonstrated in multiple experimental studies using different polymer matrices. Petchwattana and Covavisaruch found that increasing the sawdust content in polyvinyl chloride-based WPCs made the composites more brittle, with reductions in impact strength and tensile elongation at break across all filler contents examined. Their work showed that although stiffness-related properties can remain favourable, increasing the filler content progressively reduces the composite's ductility and increases its susceptibility to brittle failure. Similarly, Balasuriya et al. reported that the mechanical response of wood flake–polyethylene composites depends strongly on formulation and processing, indicating that filler loading cannot be interpreted separately from matrix flow and interfacial development during fabrication.

A broader formulation-based interpretation is provided by Sobczak et al., who reviewed polyolefin composites filled with natural fibres and wood flour and summarised several studies in which moderate wood contents improved tensile behaviour, whereas further increases in filler content led to diminishing returns or property deterioration because the polymer matrix could no longer encapsulate and bind the filler efficiently. That review also notes examples where around 40 wt.% filler produced improved tensile behaviour, but simple addition of filler without adequate compatibilisation often failed to yield consistent gains in strength. This review supports the general conclusion that filler loading must always be evaluated together with interface quality and dispersion state.

The effect of filler loading on toughness and impact resistance is especially important. Experimental work on PVC-based WPCs showed that increasing sawdust content reduced both impact strength and elongation at break, confirming that high filler loading promotes a more brittle response. From a fracture perspective, higher filler fractions increase the number of particles–matrix interfaces and the likelihood of weak regions where cracks can initiate. Once matrix continuity is reduced and filler–filler interactions become more frequent, the composite absorbs less energy before fracture. This makes high-loading formulations less tolerant to impact and less capable of stable plastic deformation. A practical implication of these findings is that there is usually an optimum filler-loading window, rather than a single universal best value. Reviews of particulate WPCs emphasise that the optimum depends on the matrix type, filler morphology, compatibiliser system, and processing route. In many practical systems, moderate wood contents provide the most balanced combination of stiffness, strength, and processability. In contrast, excessive filler addition may increase stiffness at the expense of impact strength, elongation, and long-term reliability. Recent review articles also stress that the desire to maximise renewable content must be balanced against the need to preserve matrix continuity and adequate interfacial wetting.

6. Raw Material Composition and Mechanical Response

Raw material composition is a major filler-related variable in WPCs because it affects not only the intrinsic stiffness and thermal stability of the lignocellulosic phase, but also interfacial affinity, defect formation, and the efficiency of stress transfer in the composite. Hung et al. explicitly showed that the physico-mechanical performance of HDPE-based WPCs depends on the chemical composition, morphology, and thermal stability of the lignocellulosic material, noting that cellulose, hemicellulose, lignin, extractives, and related constituents differ substantially among species and affect composite behaviour accordingly. In their study, composites made with different lignocellulosic materials at the same nominal filler loading exhibited different morphologies and distinct property responses, confirming that raw material composition cannot be reduced to filler fraction alone. The underlying reason is that lignocellulosic fillers are chemically heterogeneous. Cellulose generally contributes to axial stiffness and strength. In contrast, hemicellulose is more thermally labile and hydrophilic, lignin contributes aromatic rigidity and influences thermal behaviour, and extractives and ash can alter polarity, wetting, and interfacial interactions. Hung et al. note that the major chemical species present in lignocellulosic materials significantly affect their physical and mechanical properties and report that different species exhibit distinct extractives, holocellulose, α-cellulose, and lignin contents, as well as different aspect ratios and thermal decomposition behaviour. They further note that high cellulose content and low microfibril angle tend to promote longer fibres and higher aspect ratios, which are mechanically relevant because these features favour more efficient reinforcement.

This composition–property relationship is also supported by comparative studies using non-wood lignocellulosic particles. Núñez-Decap et al. compared polypropylene composites filled with peach stones, cherry stones, and radiata pine wood, and reported that these fillers differed in extractives, soluble and insoluble lignin, holocellulose, alpha cellulose, and ash. They specifically note that radiata pine had much lower extractives than peach and, especially, cherry stones, and that prior studies have linked higher extractive levels to poorer mechanical properties in wood composites. These findings are important because they show that even fillers with broadly similar lignocellulosic characteristics can produce different mechanical responses when their detailed chemistry differs. Wood species effects provide further support for this interpretation. Fabiyi et al. showed that the wood species used in HDPE-based WPCs influenced mechanical, thermal, and weathering performance, reinforcing the view that species-specific chemistry and structure matter even when the matrix is unchanged. More broadly, the same result is consistent with Hung et al., who found that different lignocellulosic materials passing through the same sieve still differed in morphology and chemical composition, and therefore yielded different WPC behaviours. In mechanical terms, this means that two fillers with similar nominal sizes can still differ in their effective reinforcing ability because their composition affects particle integrity during processing, interface formation, and the likelihood of voids or flaws. Thermal stability is another important composition-related issue because WPC processing typically occurs at temperatures where hemicellulose-rich or impurity-rich fillers may begin to degrade. Hung et al. explicitly evaluated the thermal decomposition behaviour of different lignocellulosic materials because degradation during composite processing can affect final properties. Their work emphasises that the selection of the raw material must account not only for its composition at room temperature, but also for how that composition behaves at the temperatures required for compounding and moulding. In practical terms, a filler with lower thermal stability may lose structural integrity or generate interfacial defects during processing, which will subsequently reduce tensile and flexural performance. The same logic extends to recycled feedstocks. Recycled polymers and recycled wood-derived fillers may contain contaminants, oxidation products, altered surface chemistry, or partially degraded cell walls, all of which can influence wetting and stress transfer. However, recycled raw materials can still provide comparable mechanical performance if their composition is sufficiently controlled. Adhikary et al. found that WPCs made from recycled HDPE and wood flour had tensile and flexural properties equivalent to those of WPCs based on virgin HDPE, and that the addition of a coupling agent further improved interfacial bonding and performance. Their results suggest that, from a mechanical standpoint, quality control of composition and interfaces is often more important than whether the feedstock is virgin or recycled.

A similar message appears in more recent work on alternative waste fibres. Talcott et al. compared HDPE composites reinforced with hop, hemp, and commercial pine fibres, characterising the fibres by density, size, and chemical composition. They found that pine-fibre composites had higher tensile and flexural strengths than hop- and hemp-based composites, while also showing lower water absorption. Their interpretation linked these differences to fibre characteristics, including size, surface area, and chemistry, further confirming that different lignocellulosic feedstocks—even when all are technically viable—do not yield identical mechanical outcomes. The literature indicates that the raw material composition governs the mechanical response of WPC through several coupled pathways: it affects the intrinsic stiffness of the lignocellulosic phase, its thermal stability during processing, its wettability and compatibility with the polymer matrix, and the likelihood of interface defects. Consequently, fillers with similar particle sizes but different chemical composition, botanical origin, or recycling history may yield significantly different tensile and flexural properties. The most reliable WPC formulations are therefore not those that maximise renewable or recycled content, but those in which the chemical composition, morphology, and interface quality of the filler are jointly controlled to preserve efficient stress transfer and structural integrity.

7. Chemical Pretreatment and Surface Modification of Fillers

Because filler characteristics are inseparable from interface quality, chemical pretreatment and surface modification of lignocellulosic fillers have become central strategies for improving the mechanical performance of WPCs. Recent review literature concludes that the main route for enhancing WPC strength and stiffness is to improve interfacial bonding through surface pretreatment of the filler and/or use of coupling systems, since the hydrophilic nature of wood flour is inherently incompatible with hydrophobic polyolefin matrices. These treatments modify the filler surface, remove weak boundary layers or impurities, reduce surface polarity when needed, and promote stronger stress transfer across the interface. Direct experimental evidence shows that different chemical treatments do not act equally; they can significantly alter adhesion and mechanical response. Farsi reported that alkaline, silane, acrylic acid, and benzoyl chloride modifications of wood flour altered the mechanical performance of PP/wood composites, confirming that surface chemistry of the filler is a major variable rather than a secondary processing detail. In another comparative study, Dányádi et al. examined several interfacial modification routes in PP/wood-flour composites. They found that maleated polypropylene improved adhesion and reinforcement most effectively, while surfactants such as stearic acid primarily improved processability and homogeneity rather than generating the same level of reinforcement. Their results are important because they show that pretreatment must be selected based on the target mechanism: some treatments primarily improve wetting, whereas others create stronger stress-bearing interfaces.

Silane-based modification is one of the most frequently reported and effective pretreatment strategies. In PP composites containing untreated and silane-treated wood flour, Ilieva and Kiryakova reported that silane functionalisation reduced water absorption and altered the mechanical response across filler loadings. At the same time, NaOH pretreatment also changed the elongation behaviour relative to the untreated filler. More broadly, silane chemistry is understood to improve interfacial interactions by introducing a more compatible surface state between lignocellulosic hydroxyl groups and the polymer environment, thereby reducing interfacial voids and improving load transfer when processing conditions are well controlled. Other surface-engineering routes also support the same conclusion. Charlet et al. showed that direct fluorination of wood flour improved the mechanical properties of wood–polyester composites by modifying the wood/polymer interface, and the later Heliyon discussion specifically cites this improvement for tensile and flexural behaviour. Nachtigall et al. investigated an organosilane-modified polypropylene coupling system for PP/wood-flour composites. They reported improved tensile behaviour, water-absorption response, and morphology relative to non-coupled systems, and compared performance with maleic anhydride-modified PP. Together, these results reinforce the view that the mechanically relevant "filler characteristic" is not limited to size, shape, or source, but also includes the engineered surface state of the lignocellulosic phase and/or the chemistry of the compatibilised interface. From a mechanical viewpoint, pretreatment improves WPC performance through three coupled pathways. First, it improves wetting, thereby reducing the volume fraction of interfacial voids and other flaw-like defects. Second, it increases the stress-transfer efficiency between the matrix and the filler. Third, it reduces the probability of premature debonding and crack initiation under load. Fracture-mechanics language can also be used to explain the benefit of pretreatment. Crack propagation begins when the local stress intensity reaches the critical toughness:

$$K_I = Y\sigma\sqrt{\pi a} \qquad (5)$$

where “a” is the effective flaw size and Y is a geometry factor. If pretreatment reduces interfacial voids and weakly bonded regions, it effectively reduces aaa, thereby raising the critical stress needed for crack initiation:

$$\sigma_c = \frac{K_{Ic}}{Y\sqrt{\pi a}} \qquad (6)$$

Thus, surface modification not only improves average adhesion but also reduces defect severity at the particle–matrix boundary, thereby delaying brittle failure. This framework aligns with experimental observations that better-coupled systems exhibit improved tensile and flexural properties and a more coherent morphology [37].

8. Coupling Agents and the Filler–Matrix Interface

Although this review emphasises filler characteristics, the mechanical performance of WPCs cannot be interpreted adequately without considering coupling agents, because the reinforcing efficiency of lignocellulosic fillers depends fundamentally on the quality of the filler–matrix interface. Recent reviews and experimental studies consistently show that the weak compatibility between hydrophilic wood flour and hydrophobic polyolefins can be substantially improved by functionalised polymers such as maleic anhydride grafted polypropylene (MAPP) or maleic anhydride grafted polyethene (MAPE), as well as by silane-based systems and isocyanate-type modifiers. These coupling agents reduce interfacial incompatibility, improve wetting, and enhance load transfer from the matrix to the filler. A central result repeatedly reported in the literature is that coupling agents affect strength more strongly than stiffness. Baig et al. found that in PP/wood composites, MAPP improved resistance to mechanical degradation and enhanced tensile performance, while its effect on stiffness was comparatively limited. Likewise, Dányádi et al. reported that, in uncoupled systems, tensile and flexural strengths often decrease with increasing filler loading. In contrast, functionalised polymers can reverse this trend and produce considerable strength gains. This distinction is mechanically important because modulus is largely governed by the stiffness and volume fraction of the phases. At the same time, strength is controlled much more strongly by interfacial stress transfer and the onset of debonding.

This interface-controlled behaviour is particularly clear in highly filled systems. Hao et al. investigated ultra-highly filled WPCs and reported that, compared with uncompatibilized composites containing 80 wt% wood flour, tensile and flexural strengths increased dramatically when MAPE was introduced either as matrix or compatibiliser. Their results further showed that the absolute grafted-maleic-anhydride content did not simply determine mechanical performance, but rather the manner in which the interfacial adhesion mechanism developed within the composite structure. This confirms that filler characteristics are only fully effective when interfacial coupling enables them to act as true reinforcing phases rather than defect-generating inclusions. The same conclusion is supported by studies using alternative interface modifiers. Zhou et al. compared MAPE, bis(triethoxysilylpropyl)tetrasulfide (Si69), and vinyltrimethoxysilane (VTMS) in WPCs and showed that coupling-agent selection changed both in situ interfacial bonding and bulk mechanical response. Similarly, Shen et al. found that coupling agents such as KH550 and MDI improved the interfacial bond strength between wood and thermoplastics under dry conditions. These studies show that the phrase “filler characteristic” should be interpreted broadly: the performance of a given filler depends not only on its size, shape, and source, but also on the engineered chemical state of the interface that surrounds it.

For strength, an informative framework is the Pukánszky-type relation, which explicitly links composite strength to interfacial interaction in particulate-filled polymers:

$$\sigma_c = \sigma_m \frac{1-\phi_f}{1+2.5\phi_f} \exp\,(B\phi_f) \qquad (7)$$

where σ_c is composite tensile strength, σm\sigma_mσm is matrix tensile strength, ϕ_f is filler volume fraction, and B is an interaction parameter reflecting the extent of interfacial adhesion and load-bearing contribution of the filler. In this model, larger B values indicate stronger interfacial stress transfer. This formulation is widely used in wood-filled polyolefin composites. It is especially useful here because it mathematically captures why a filler that appears ineffective in an uncoupled system may perform much better once compatibilisation improves the interface. The broader compatibilisation literature on lignocellulose-reinforced polypropylene systems supports exactly this interpretation. Coupling agents also influence moisture sensitivity and swelling, which, in turn, indirectly affect long-term mechanical performance. Gao et al. showed that grafting PP/PE blends with maleic anhydride reduced water uptake and dimensional swelling while improving tensile and flexural properties, indicating that better interfacial compatibility simultaneously improves both mechanical integrity and environmental resistance. Reviews of WPC processing and rheology similarly note that MAH-functionalised polyolefins are among the most effective compatibilisers for polyolefin-based WPCs, as they promote adhesion while improving filler dispersion and melt behavior.

9. Fracture and Failure Behaviour

A deeper understanding of filler effects in WPCs emerges when fracture and failure mechanisms are examined directly, as bulk properties such as tensile and flexural strength describe only the macroscopic response. In contrast, fracture analysis reveals the local processes that control final failure. Experimental studies on polypropylene/wood flour composites have shown that several micromechanical deformation mechanisms may occur during loading, including matrix yielding, interfacial debonding, fibre pull-out, and fibre fracture, and that the dominant mechanism depends strongly on interfacial adhesion and particle characteristics. In particular, poor adhesion tends to favour debonding and pull-out, whereas stronger interfaces promote particle or fibre fracture[5]. This distinction is mechanically important because each failure mode contributes differently to composite performance. Pérez et al. reported that, in unmodified PP/wood flour composites, debonding and fibre pull-out were the main energy-absorbing mechanisms. In contrast, in MAPP-modified composites, fibre fracture became dominant, indicating a much stronger filler–matrix interface. Similarly, the work summarised in another journal states that debonding and pull-out dominate when PP/wood adhesion is poor, while fibre fracture dominates when adhesion is strong. These observations support the interpretation that when particles crack, the interface is no longer the weakest link; conversely, when particles debond, interfacial failure controls the strength of the composite.

Renner et al. further showed that the micromechanical deformation of PP/wood composites depends on particle characteristics and adhesion, and that debonding can create internal voids that accelerate premature failure. Their results demonstrate that the apparent effect of filler size, shape, or stiffness cannot be interpreted independently of fracture mode: a filler that increases stiffness may still lower composite strength if it also promotes interfacial void formation and crack initiation. This is why some fillers appear beneficial in modulus measurements but less effective in tensile or impact performance unless compatibilisation is also improved In WPCs, the effective flaw size "a" may correspond to an interfacial void, a debonded particle boundary, or a stress-concentrating particle cluster. Thus, weakly bonded or overly large particles effectively increase aaa, lowering the stress required for fracture. This model explains why interfacial debonding often precedes catastrophic failure in poorly compatibilised systems and why better adhesion can shift failure toward filler fracture rather than pull-out. The same qualitative trend is directly observed in the experimental literature on PP/wood composites. The Griffith-type energy criterion provides a complementary interpretation:

$$G = \frac{\pi \sigma^2 a}{E'} \quad (8)$$

where G is the energy release rate and E′ is the effective elastic modulus term. A fracture occurs when

$$G = G_c \quad (9)$$

with G_c being the critical fracture energy of the composite system. In practical terms, larger debonded regions or poorly bonded interfaces increase the effective crack size and therefore the energy released during crack growth. This helps explain why coarse particles or weak interfaces can shift the response toward brittle fracture, while well-bonded, well-dispersed fillers can delay crack propagation and improve the apparent damage tolerance of the material. General reviews of impact and fracture in natural-fibre composites identify matrix fracture, fibre fracture, fibre–matrix debonding, and pull-out as the principal energy-absorption mechanisms, which is fully consistent with the specific behaviour reported for WPCs. The limiting role of particle fracture has also been discussed explicitly by Faludi et al., who showed that in highly filled bio-based composites, good interfacial adhesion often results in fracture of the wood particles themselves, and that the inherent strength of the wood flour can become the limiting factor in composite performance. This is a crucial point for interpreting filler effects: once compatibilisation is sufficiently strong, the weak link may move from the interface to the lignocellulosic particle itself. In that situation, further improving the interface may yield diminishing returns unless filler integrity, morphology, or intrinsic strength are also improved.

Additional support comes from interfacial-bond-strength studies. Yuan et al. reported that in wood-fibre-reinforced polyethene and polypropylene composites, strong bonding can shift the fracture mechanism from fibre pull-out to fibre fracture. In contrast, the effect of fibre length becomes less dominant once the interface is sufficiently strong. This reinforces the broader conclusion that filler characteristics must be interpreted together with interface quality: a filler that seems ineffective in one formulation may become highly effective when the interface is improved, but its failure mode may also change from debonding-dominated to particle-fracture-dominated.

10. Secondary Relevance of Moisture and Environmental Exposure

Because this review is centred on mechanical performance, moisture uptake, and environmental weathering are not treated as primary themes here. Nevertheless, they remain highly relevant because they reveal how filler characteristics govern the retention of mechanical properties over time. In WPCs, absorbed moisture is associated mainly with the lignocellulosic phase and with defects at the filler–matrix interface. As a result, water exposure does not merely produce dimensional change; it also modifies stress transfer, promotes interfacial degradation, and alters the effective flaw population in the composite. Reviews of WPC processing and durability likewise note that moisture resistance is strongly influenced by wood content, interfacial bonding, and pretreatment strategy, confirming that environmental sensitivity is structurally linked to filler design rather than a separate issue [27].

A useful starting point for describing moisture uptake is the Fickian diffusion model, which is commonly pplied to WPCs and other natural-fibre thermoplastic composites. In simplified one-dimensional form, moisture transport may be written as:

$$\frac{\delta C}{\delta t} = D\frac{\delta^2 C}{\delta x^2} \qquad (10)$$

where C is the local moisture concentration, t is time, x is position, and D is the effective diffusion coefficient. The moisture uptake at time ttt is commonly reported as

$$M_t = \frac{W_t - W_o}{W_o} \times 100 \qquad (11)$$

where W_0 and W_t are the initial and time-dependent specimen masses. In WPCs, the effective diffusion coefficient is not a pure material constant, but is influenced by filler loading, particle size, interface quality, and exposed surface morphology. Therefore, the same moisture model that describes sorption also indirectly reflects filler-related pathways that lead to subsequent mechanical degradation. Experimental studies show that moisture uptake is strongly associated with a loss of mechanical properties. Machado et al. reported that WPCs subjected to high-moisture exposure or soaking/freezing/drying cycles exhibited significant reductions in modulus of elasticity, and that the loss of stiffness increased approximately linearly with water intake. This is a particularly important result for the present review because it demonstrates that moisture-related degradation is not an isolated durability issue; rather, it is a mechanically measurable consequence of how filler morphology, loading, and interface structure control the entry and accumulation of water in the composite.

The physical mechanism behind this stiffness loss is consistent with the broader WPC weathering literature. Stark and Matuana showed that water exposure causes wood particles to swell, creating microcracks in the surrounding polymer matrix, degrading the wood/HDPE interface, and even shearing the wood particles themselves. Their characterisation of weathered WPC surfaces further revealed loosening of wood particles and surface degradation after environmental exposure. These observations are mechanically important because they show how absorbed water transforms filler-related microstructural heterogeneities into active crack-initiation sites, thereby reducing the composite's ability to sustain load. Additional support comes from recent processing studies that measured both water uptake and retained mechanical properties after immersion. Schirp et al. found that compounding conditions, wood treatment, and matrix formulation affected both the tensile properties and the water-uptake/swelling response of WPCs after cold-water immersion. Their results indicate that the same variables which improve the dry-state interface also influence how well that interface survives humid exposure. This reinforces the idea that a filler system should not be evaluated solely by dry tensile or flexural tests, because morphology and interface quality also govern the stability of those properties under service conditions.

Moisture sensitivity can also be expressed in terms of property retention, for example:

$$R_E = \frac{E_{wet}}{E_{dry}} \times 100 \qquad (12)$$

$$R_\sigma = \frac{\sigma_{wet}}{\sigma_{dry}} \times 100 \qquad (12)$$

where R_E and $R\sigma$ are the modulus-retention and strength-retention ratios, respectively; these relations are useful because they connect environmental exposure directly to mechanical performance. In practical WPC systems, lower retention is often observed when wood content is high, encapsulation is incomplete, or the interface is poorly compatibilised. Thus, the retention ratio can be interpreted as a composite-level outcome of filler distribution, particle geometry, and interfacial integrity under wet conditions . Weathering studies provide a complementary perspective. Chen et al. showed that the weathering characteristics of HDPE-based WPCs depend on the condition of the wood flour itself, including whether extractives or lignin fractions have been altered prior to composite manufacture. Their results indicate that the wood phase governs not only moisture sensitivity but also photochemical response, surface cracking, and property evolution during outdoor exposure. In this sense, environmental degradation confirms rather than contradicts the main thesis of this review: filler characteristics remain central even when the performance metric is long-term property retention rather than initial dry-state stiffness or strength. A related modern example is the study by Oliveros-Gaviria et al. on recycled-HDPE-based WPCs, which showed that moisture absorption increased dimensional changes and reduced mechanical properties because the hydrophilic hydroxyl groups of the wood sawdust absorbed water, inducing swelling. Although their study also considered UV exposure, it explicitly noted that moisture uptake reached saturation, contributing to a loss of strength and dimensional stability. This supports the broader conclusion that service performance of WPCs depends not only on the dry-state formulation but also on how filler chemistry and morphology control moisture ingress and interfacial degradation during use.

11. Current Trends and Future Research Directions

Recent advances in WPC research point toward a more integrated and design-oriented approach to filler engineering. Rather than treating wood flour as a generic reinforcement, recent reviews emphasise that future WPC development must simultaneously control filler source, particle morphology, surface chemistry, compatibilisation strategy, and processing conditions in order to achieve reliable mechanical performance. An overview of WPC systems similarly notes that the current research trend is shifting from simple filler addition toward formulation optimisation based on the interaction among constituents. At the same time, another recent review on WPC manufacturing and rheology highlights the need to connect material composition with process-induced structure and final properties. These studies collectively suggest that future research should move beyond isolated one-factor experiments and instead investigate the coupled effects of filler size, loading, aspect ratio, moisture sensitivity, and interface modification on tensile, flexural, impact, creep, and fracture behaviour. One important direction is the development of structure–property–processing relationships that can support predictive engineering. Traditional WPC formulations have often relied on empirical optimisation, but recent work increasingly emphasises the need for rheology-informed, mechanics-based design. The review on manufacturing, rheology, and mechanics argues that understanding how filler distribution, interfacial bonding, and melt-flow behaviour evolve during processing is essential for predicting final performance, rather than merely describing it after fabrication. This indicates that future research should link compounding history, particle breakage, orientation, and dispersion to mechanical outcomes, thereby enabling a shift from trial-and-error formulation to process-aware composite design.

Another major research direction is the optimisation of recycled and non-traditional fillers for sustainable WPC manufacture. Recent literature on sustainable WPCs emphasises that waste-derived lignocellulosic feedstocks and recycled polymers can produce viable composites. However, performance consistency remains a central challenge because recycled and non-traditional inputs are inherently more variable in morphology, chemistry, contamination level, and thermal history. A sustainability-focused review notes that balancing environmental responsibility with mechanical performance requires a deeper understanding of how waste wood flour, agricultural residues, and recycled polymers behave as engineering feedstocks rather than merely as low-cost fillers. Likewise, a study using pandemic-related waste streams in PP-based WPCs shows growing interest in broader waste valorisation strategies coupled with microstructural and mechanical characterisation. Future work should therefore identify which filler characteristics most strongly control reproducibility across variable feedstocks and how these characteristics can be standardised for industrial-scale production.

A further emerging trend is the design of high-performance or structural WPCs that overcome the traditional limitations of brittleness, creep, and poor dimensional stability. A recent 2025 study on temporary concrete formwork using WPCs specifically targeted high strength, high ductility, creep resistance, and dimensional stability to address the gap between conventional WPCs and load-bearing applications. This is significant because it reflects a broader transition in the field: future research is no longer focused only on replacing wood-like materials for non-structural products, but on engineering WPCs with mechanical performance suitable for more demanding service environments. This direction will likely require tighter control of filler morphology, more efficient interface design, and a better understanding of damage tolerance and long-term deformation. Equally important is the need to connect macroscopic mechanical tests with microstructural characterisation. Since debonding, crack initiation, void growth, and particle or fibre fracture govern composite failure, future research should combine tensile, flexural, fracture, and impact testing with microscopy, interface analysis, and failure mapping. Broader fracture reviews in composite materials emphasise that meaningful progress in fracture-resistant design depends on linking microscopic damage evolution to macroscopic failure metrics. Applied to WPCs, this means that future studies should more systematically integrate SEM-based fracture observation, interfacial characterisation, and in situ mechanical testing to explain why specific filler characteristics succeed or fail in different matrices. Such integration would enable distinguishing whether poor performance arises from weak adhesion, filler breakage, void formation, poor dispersion, or environmentally induced interface degradation.

A related opportunity lies in interface modelling and multiscale prediction. Much of the published WPC literature still reports property trends descriptively. In contrast, future research will benefit from micromechanical and fracture-based models that explicitly incorporate filler geometry, interfacial efficiency, and defect evolution. In practical terms, this means combining modulus and strength models with morphological descriptors, rheological behaviour, and interfacial measurements so that formulation changes can be evaluated before full-scale production trials. Recent reviews on WPC rheology and functional enhancement imply that predictive modelling will become increasingly necessary as formulations become more complex and multifunctional Finally, future research is likely to move toward multifunctional WPCs, in which mechanical performance is designed alongside durability, fire resistance, antimicrobial behaviour, ageing resistance, and processability. A 2025 review of functional WPCs highlights the growing use of additives such as flame retardants, anti-ageing agents, and antimicrobial components, indicating that next-generation WPCs will be evaluated not only by stiffness and strength, but by how well these properties are retained under realistic service conditions while meeting additional functional requirements. This means that future filler engineering will need to consider not just reinforcement efficiency, but also how filler characteristics interact with additives, stabilisation systems, and environmental ageing mechanisms.

METHOD

This study employs a qualitative descriptive approach using a literature review method to systematically analyze the influence of filler characteristics on the mechanical performance of wood–plastic composites (WPC). The research relies on secondary data obtained from peer-reviewed journal articles, scientific review papers, conference proceedings, and relevant textbooks in the field of polymer composites and materials science. The selected literature primarily focuses on WPC systems composed of lignocellulosic fillers and thermoplastic matrices such as polypropylene (PP) and polyethylene (PE). The selection of references is based on several criteria, including studies that discuss mechanical properties of WPC, examine filler characteristics such as particle size, shape, source, composition, and surface chemistry, and analyze interfacial adhesion, coupling agents, and fracture mechanisms. Only publications from reputable international journals and those providing experimental, theoretical, or modeling insights are included.

Data collection is conducted through systematic searches using academic databases such as Google Scholar, ScienceDirect, SpringerLink, and Wiley Online Library, with keywords including wood-plastic composites, filler characteristics, particle size, interfacial adhesion, coupling agents, mechanical properties, fracture behavior, and moisture effects. The data are analyzed using a comparative and integrative approach, which involves classifying studies based on key variables, identifying thematic patterns in mechanical behavior such as stiffness, strength, and toughness, and interpreting results through micromechanical principles including stress transfer, interfacial bonding, and defect formation. The findings are then synthesized into a comprehensive framework that links filler characteristics, interfacial quality, processing conditions, and overall mechanical performance. The research is guided by a conceptual framework that emphasizes the interaction between filler design, interfacial engineering, and processing conditions in determining the structural and mechanical behavior of WPC. However, this study is limited to secondary data analysis and does not involve experimental validation. Therefore, the conclusions are dependent on previously reported results and may be influenced by variations in materials, processing techniques, and testing conditions across different studies.

RESULTS AND DISCUSSION

Wood–plastic composite (WPC) is a hybrid material that combines wood-based fillers with a thermoplastic matrix and offers ease of processing, low density, favourable stiffness, reduced maintenance requirements, and the potential for recycled feedstock, with wide applications in construction, decking, wall cladding, furniture, automotive interiors, and consumer products. However, its mechanical behaviour is highly sensitive to the characteristics of the filler phase, including particle size, shape, source, composition, and surface chemistry, which determine load transfer efficiency, particle release, and failure mechanisms. Filler characteristics are the primary parameters controlling the mechanical response of WPC, including particle size distribution, aspect ratio, botanical origin, surface chemistry, and interfacial bonding quality. These factors collectively determine stiffness, strength, impact behavior, as well as deformation and fracture mechanisms. From a micromechanical perspective, composite performance is governed by the effectiveness of stress transfer at the matrix–filler interface, where good dispersion and adhesion enhance load sharing, while large, irregular, and poorly bonded particles act as stress concentrators.

Particle size plays a complex role: larger particles can increase stiffness and strength but tend to produce more brittle behavior, whereas smaller particles can improve modulus and strength when accompanied by good dispersion, although excessive grinding may lead to aggregation. In addition, filler source and morphology influence mechanical properties through variations in structure and surface characteristics, making them critical structural parameters rather than secondary choices. Theoretically, composite performance is described using the rule of mixtures and efficiency factors that account for geometry, orientation, dispersion, and adhesion. Modulus generally increases with the addition of rigid fillers, but strength is more sensitive to interfacial quality. Consequently, increasing wood content typically enhances stiffness but does not consistently improve tensile strength and often reduces toughness and impact resistance due to interfacial limitations and increased defect sensitivity.

The main aspect of filler characteristics is the type and source of filler. WPC fillers can originate from pure wood flour, recycled wood particles, sawdust, agricultural residues, and other natural fibers, all of which influence mechanical properties due to differences in chemical composition, density, lignin–cellulose ratio, moisture affinity, and particle morphology. Wood species is a highly important variable, as different species produce WPC with different properties. Even with the same polymer matrix, changes in wood source affect the mechanical response due to variations in cell wall structure and the distribution of cellulose, hemicellulose, lignin, and extractives, which influence stiffness, interfacial formation, and filler integrity. Recycled fillers are a viable alternative, as they can exhibit properties comparable to virgin fillers, providing sufficient reinforcement while supporting cost reduction and sustainability. However, not all waste-derived fillers behave similarly, since some may increase water absorption or thickness swelling, affecting mechanical properties over time. Therefore, filler selection should consider not only availability or cost, but also its contribution to stress transfer, dimensional stability, and structural reliability.

Particle size is a determining structural variable in WPC because it directly affects interfacial surface area, particle arrangement, dispersion homogeneity, local stress concentration, and load transfer efficiency between lignocellulosic filler and polymer matrix. Its mechanical influence is not independent but related to filler morphology, wood type, matrix type, processing history, and compatibilizer content, resulting in a non-monotonic relationship where finer particles sometimes improve stiffness and strength, while coarser particles can be advantageous in other formulations. Evidence shows that reducing particle size can improve mechanical properties by promoting better packing and more homogeneous dispersion. Smaller particles generally enhance stress transfer and reduce defect severity, although excessive size reduction can be counterproductive due to aggregation and morphological changes. Therefore, optimal particle size is not simply the finest scale, but often an intermediate range that provides sufficient interfacial area without increasing agglomeration or reducing processability, as overly fine fillers can increase viscosity, hinder dispersion, and promote defect formation.

Conversely, coarser particles can improve stiffness and, in some systems, strength, particularly when interfacial adhesion is adequate and dispersion is well maintained, although they may also increase brittleness and stress concentration. Particle size also influences impact behavior and ductility, where finer particles tend to delay crack propagation and improve toughness, while larger particles promote a stiffer but more brittle response. In addition, particle size affects rheology and processing. Very fine particles increase melt viscosity and reduce flow, complicating extrusion or injection molding and causing poor wetting, void formation, or agglomeration, whereas coarser particles may facilitate flow but increase local heterogeneity. Thus, the role of particle size must always be analyzed together with processing conditions, as both are inseparable in determining the mechanical performance of WPC.

Particle shape and aspect ratio are important descriptors that control the mechanical performance of WPC because they determine the efficiency of stress transfer. Fillers with higher aspect ratio generally provide greater tensile and flexural reinforcement, whereas irregular particles tend to act as stress concentrators. Various studies show that particle geometry affects morphology, dispersion, and composite properties, and that high-aspect-ratio particles enhance stress transfer through more effective load-bearing paths. From a micromechanical perspective, this effect is described by approaches such as Halpin–Tsai, which relate stiffness to filler geometry and anisotropy. Anisotropic particles distribute load more effectively and can shift failure mechanisms, while short or irregular particles promote debonding and early cracking. In addition, particle orientation during processing plays an important role, as it can enhance reinforcement in certain directions while increasing anisotropy. Thus, particle shape and aspect ratio are fundamental variables determining whether the filler acts as an effective reinforcement or merely as a filler phase. Filler content controls the balance between stiffness, matrix continuity, interfacial quality, and damage tolerance. Increasing filler content generally improves stiffness, but its effects on strength, impact resistance, and ductility are more complex due to increased risks of agglomeration, poor wetting, and interfacial debonding. Therefore, filler loading should be optimized rather than maximized. Studies show that high filler content tends to increase brittleness, reduce impact strength and elongation, and limit plastic deformation due to reduced matrix continuity and increased weak interfaces. Moderate filler content often provides the best balance between stiffness, strength, and processability, whereas excessive loading increases stiffness at the expense of toughness and long-term reliability. Therefore, filler loading must be considered together with interfacial quality, dispersion, and processing conditions.

Raw material composition is a key variable that influences intrinsic stiffness, thermal stability, interfacial affinity, defect formation, and stress transfer efficiency in WPC. Differences in chemical composition such as cellulose, hemicellulose, lignin, extractives, and ash lead to variations in mechanical properties, morphology, and composite response even at the same filler loading. Cellulose contributes to stiffness and strength, hemicellulose is more thermally labile and hydrophilic, lignin affects stiffness and thermal behavior, while extractives influence polarity and interfacial interactions. These compositional differences are also observed in non-wood fillers and different wood species, resulting in varying mechanical properties due to differences in chemistry, morphology, and thermal stability. Thermal stability is critical because degradation during processing can reduce mechanical performance. Recycled raw materials can still provide comparable properties to virgin materials if composition and interfacial quality are well controlled. Overall, raw material composition governs mechanical response through its influence on stiffness, stability, compatibility, and defect formation, making simultaneous control of composition, morphology, and interfacial quality essential for optimal formulation.

Chemical pretreatment and surface modification are key strategies to improve the mechanical performance of WPC by enhancing interfacial bonding between lignocellulosic fillers and polymer matrices. These treatments modify the filler surface, remove impurities, reduce polarity, and improve wetting and stress transfer. Methods such as alkali treatment, silane, acrylic acid, benzoyl chloride, and coupling agents demonstrate that surface chemistry significantly affects adhesion and mechanical properties. From a mechanical perspective, pretreatment improves performance by enhancing wetting, increasing stress transfer efficiency, and reducing interfacial debonding and crack initiation. By minimizing interfacial voids and defects, these treatments increase the critical stress required for crack initiation, thereby improving tensile and flexural properties and delaying brittle failure. Therefore, filler characteristics include not only size, shape, and source, but also surface condition and the quality of engineered interfacial interactions.

The mechanical performance of WPC strongly depends on the quality of the filler–matrix interface, making coupling agents such as MAPP, MAPE, silane, and isocyanate essential for improving compatibility between hydrophilic fillers and hydrophobic matrices. These agents enhance wetting, reduce incompatibility, and improve stress transfer. In general, coupling agents have a greater influence on strength than stiffness because strength is highly dependent on interfacial adhesion and the prevention of debonding. At high filler content, compatibilization becomes increasingly important as it can significantly improve tensile and flexural strength and allow fillers to act as effective reinforcing phases. Different types of coupling agents demonstrate that filler performance is not only determined by size, shape, and source, but also by the chemical condition of the interface. In addition, coupling agents improve moisture resistance and dimensional stability, thereby supporting long-term mechanical performance.

Fracture mechanisms in WPC are governed by interfacial adhesion and particle characteristics, involving matrix deformation, interfacial debonding, fiber pull-out, and fiber fracture. Weak adhesion leads to dominant debonding and pull-out, whereas strong adhesion promotes particle or fiber fracture. These failure modes determine mechanical performance because debonding creates voids that accelerate failure, while particle fracture indicates a stronger interface. The effective defect size, such as interfacial voids and detached particles, influences crack initiation and propagation, meaning that large particles or weak adhesion reduce critical stress and increase brittleness. In contrast, well-bonded and well-dispersed fillers can delay crack propagation and improve toughness. Under strong adhesion conditions, failure may shift from the interface to the particle itself, making the intrinsic strength of the filler the limiting factor. Therefore, filler characteristics must be analyzed together with interfacial quality, as both jointly determine the failure mechanisms and overall mechanical performance of WPC.

Moisture absorption and environmental exposure, although not the main focus, remain highly relevant because they reveal how filler characteristics control the retention of mechanical properties over time. In WPC, absorbed moisture is mainly associated with the lignocellulosic phase and interfacial defects, leading not only to dimensional changes but also to modified stress transfer, interfacial degradation, and increased effective defect population. Moisture resistance is strongly influenced by wood content, interfacial bonding, and pretreatment, confirming that environmental sensitivity is structurally linked to filler design. Moisture transport is commonly described using the Fickian diffusion model, where the effective diffusion coefficient depends on filler loading, particle size, interfacial quality, and morphology. Experimental studies show that increased moisture absorption leads to significant reductions in mechanical properties, particularly stiffness, due to swelling of wood particles, microcracking of the matrix, and interfacial damage. Retention of properties such as modulus and strength is therefore directly related to filler distribution, particle geometry, and interfacial integrity under wet conditions. Weathering studies further confirm that filler characteristics govern both moisture sensitivity and long-term degradation, including photochemical response, surface cracking, and dimensional instability. Overall, environmental degradation reinforces the central role of filler characteristics, as long-term performance depends on how filler chemistry and morphology control moisture ingress and interfacial stability.

Recent WPC research trends emphasize an integrated, design-oriented approach to filler engineering, where filler source, particle morphology, surface chemistry, compatibilization, and processing conditions are simultaneously controlled to achieve reliable mechanical performance. Research is shifting from simple filler addition toward optimization based on interactions between constituents, linking material composition, processing-induced structure, and final properties. Future studies should move beyond single-variable experiments and instead investigate combined effects of filler size, loading, aspect ratio, moisture sensitivity, and interfacial modification on mechanical behavior. A key direction is the development of structure–property–processing relationships to enable predictive engineering, replacing empirical trial-and-error approaches with mechanics-informed and rheology-based design. Another important focus is the optimization of recycled and non-traditional fillers, where variability in morphology, chemistry, and contamination must be controlled to ensure consistent performance. Emerging research also targets high-performance or structural WPC with improved strength, ductility, creep resistance, and dimensional stability, expanding applications beyond non-structural uses. In addition, future work must integrate macroscopic mechanical testing with microstructural characterization, including fracture analysis and interfacial evaluation, to better understand failure mechanisms.

CONCLUSION

The mechanical performance of wood–plastic composites (WPCs) is strongly influenced by filler-related factors, including filler type and source, particle size, particle shape, aspect ratio, filler loading, raw material composition, chemical pretreatment, and interfacial compatibility. The literature review shows that these variables jointly affect tensile strength, flexural strength, modulus, impact resistance, and fracture behaviour. In general, well-designed filler morphology and composition can improve reinforcement efficiency, while poor dispersion, weak adhesion, and excessive filler loading tend to reduce strength and promote brittle failure. The review also confirms that interface quality plays a decisive role in determining whether lignocellulosic fillers act as effective reinforcements or as defect-generating phases. Chemical pretreatment and coupling agents are therefore essential for improving stress transfer and mechanical reliability. Overall, the optimisation of WPCs requires an integrated approach that combines filler engineering, interface control, and an understanding of failure mechanisms to achieve more reliable mechanical performance.

Acknowledgment

The authors gratefully acknowledge the support of the Direktorat Riset dan Pengabdian Universitas Muhammadiyah Yogyakarta (UMY) for its valuable encouragement and contribution to the completion of this review article.

REFERENCES

[1] A. Delviawan, S. Suzuki, Y. Kojima, and H. Kobori, "The influence of filler characteristics on the physical and mechanical properties of wood plastic composite(s)," Rev. Agric. Sci., vol. 7, no. April, pp. 1–9, 2019, doi: 10.7831/ras.7.1.

[2] C. Budiyantoro, A. W. Nugroho, Z. Ilyas, and B. Bilyferdin, "Optimization Of Wood Powder Particle Size And Weight Fraction For Enhancing The Mechanical Properties Of Wood Plastic Composites Using Recycled EPS Matrix," vol. 28, no. 12, pp. 2715–2723, 2024.

[3] C. Budiyantoro and F. Yudhanto, "Enhancing mechanical properties of waste expanded polystyrene composites through varied coupling agents and wood powder formulations," J. Polimesin, vol. 21, no. 6, p. 589, 2023, doi: 10.30811/jpl.v21i6.4234.

[4] S. M. B. Nachtigall, G. S. Cerveira, and S. M. L. Rosa, "New polymeric-coupling agent for polypropylene / wood-flour composites," Polym. Test., vol. 26, pp. 619–628, 2007, doi: 10.1016/j.polymertesting.2007.03.007.

[5] K. Renner, C. Kenyó, J. Móczó, and B. Pukánszky, "Micromechanical deformation processes in PP / wood composites : Particle characteristics , adhesion , mechanisms," Compos. Part A, vol. 41, pp. 1653–1661, 2010, doi: 10.1016/j.compositesa.2010.08.001.

[6] A. H. Elsheikh, H. Panchal, S. Shanmugan, T. Muthuramalingam, M. El-kassas, and B. Ramesh, "Recent progresses in wood-plastic composites : Pre-processing treatments , manufacturing techniques , recyclability and eco-friendly assessment," Clean. Eng. Technol., vol. 8, no. June 2021, p. 100450, 2022, doi: 10.1016/j.clet.2022.100450.