# EXPLORING WOOD POLYMER COMPOSITES: A SYSTEMATIC VISUAL REVIEW OF COMPOSITION, PRODUCTION, AND PROPERTIES

## *EXPLORANDO COMPÓSITOS MADEIRA-POLÍMERO: UMA REVISÃO SISTEMÁTICA VISUAL SOBRE COMPOSIÇÃO, PROCESSOS DE PRODUÇÃO E PROPRIEDADES*

## *EXPLORANDO LOS COMPUESTOS DE MADERA Y POLÍMERO: UNA REVISIÓN SISTEMÁTICA VISUAL DE LA COMPOSICIÓN, PRODUCCIÓN Y PROPIEDADES*

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**ABSTRACT**
This systematic review investigates recent advances in wood polymer composites (WPCs), focusing on their composition, processing methods, and physical-mechanical performance for potential structural and sustainable construction applications. Using the adapted Systematic Search Flow methodology, the study analyzed the composition, manufacturing strategies, and physical-mechanical performance of 283 distinct WPC formulations reported in 134 research articles. Extrusion, whether applied independently or in combination with other techniques, emerged as the dominant process for thermoplastic-based WPCs, enabling continuous production and high throughput. Polypropylene (PP) and high-density polyethylene (HDPE) were the most common matrices, typically reinforced with lignocellulosic fillers that enhance stiffness and strength, although often at the cost of increased water absorption, a drawback effectively mitigated by compatibilizing agents. Statistical analyses of tensile, flexural, and water absorption data, presented through detailed graphical representations, serve as a key strength of this work, functioning as powerful visual tools to highlight trends, compare formulations, and facilitate the interpretation of results. The review underscores the versatility of WPCs in addressing environmental challenges such as plastic waste and deforestation, while also highlighting critical gaps in long-term durability, the effects of recycling cycles, and the harmonization of performance benchmarks in international standards. The study concludes that WPCs, when optimally formulated and processed, offer high potential for applications such as decking, facade panels, and modular structural elements, and that aligning future developments with sustainability principles and global standardization will be key to expanding their adoption in engineering and construction sectors.

**KEYWORDS**
Wood Polymer Composites; Physico-mechanical properties; Production Processes; Sustainability.

***RESUMO***
*Esta revisão sistemática apresenta os avanços recentes em compósitos madeira-polímero (Wood Polymer Composites - WPCs), com ênfase em sua composição, métodos de processamento e desempenho físico-mecânico, visando aplicações estruturais e sustentáveis na construção civil. A partir da metodologia Systematic Search Flow adaptada, foram analisadas 283 formulações distintas de WPCs descritas em 134 artigos científicos. A extrusão, utilizada de forma isolada ou combinada*



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*com outras técnicas, destacou-se como o principal processo de produção para compósitos termoplásticos, viabilizando manufatura contínua e em larga escala. Entre as matrizes mais empregadas, o polipropileno (PP) e o polietileno de alta densidade (PEAD) foram predominantes, geralmente reforçados com cargas lignocelulósicas, que aumentam rigidez e resistência, ainda que elevem a absorção de água, aspecto frequentemente minimizado pelo uso de agentes compatibilizantes. A análise estatística de dados de tração, flexão e absorção de água, organizada em representações gráficas detalhadas, constitui um dos pontos fortes desta revisão, funcionando como ferramenta visual eficaz para destacar tendências, comparar formulações e interpretar resultados. Os achados evidenciam a versatilidade dos WPCs no enfrentamento de desafios ambientais, como o acúmulo de resíduos plásticos e o desmatamento. Contudo, permanecem lacunas relacionadas à durabilidade em longo prazo, aos efeitos de múltiplos ciclos de reciclagem e à necessidade de harmonização de critérios de desempenho em normas internacionais. Conclui-se que, quando formulados e processados de maneira otimizada, os WPCs apresentam elevado potencial para aplicações como decks, painéis de fachada e elementos estruturais modulares. O alinhamento dos futuros desenvolvimentos aos princípios da sustentabilidade e à padronização global será determinante para ampliar sua adoção nos setores de engenharia e construção.*

## PALAVRAS-CHAVE

*Compósitos madeira-polímero; Propriedades físico-mecânicas; Processos de produção; Sustentabilidade.*

## RESUMEN

*Esta revisión sistemática examina los avances recientes en los compuestos de madera y polímero (Wood Polymer Composites - WPCs), con énfasis en su composición, métodos de procesamiento y desempeño físico-mecánico para posibles aplicaciones estructurales y de construcción sostenible. Mediante la metodología adaptada Systematic Search Flow, el estudio analizó la composición, las estrategias de fabricación y el desempeño físico-mecánico de 283 formulaciones distintas de WPC reportadas en 134 artículos de investigación. La extrusión, empleada de forma independiente o en combinación con otras técnicas, se consolidó como el proceso predominante para los WPC basados en termoplásticos, al permitir producción continua y alta eficiencia. El polipropileno (PP) y el polietileno de alta densidad (PEAD) fueron las matrices más utilizadas, comúnmente reforzadas con cargas lignocelulósicas que mejoran la rigidez y la resistencia, aunque con el inconveniente de un incremento en la absorción de agua, limitación que puede mitigarse de manera efectiva mediante agentes compatibilizantes. Los análisis estadísticos de datos de tracción, flexión y absorción de agua, presentados a través de representaciones gráficas detalladas, constituyen una de las principales fortalezas de este trabajo, al servir como herramientas visuales para destacar tendencias, comparar formulaciones y facilitar la interpretación de resultados. La revisión resalta la versatilidad de los WPC para afrontar desafíos ambientales como los residuos plásticos y la deforestación, al tiempo que señala vacíos críticos relacionados con la durabilidad a largo plazo, los efectos de los ciclos de reciclaje y la armonización de los parámetros de desempeño en normas internacionales. Se concluye que los WPC, cuando son formulados y procesados de manera óptima, poseen un alto potencial para aplicaciones como tarimas, paneles de fachada y elementos estructurales modulares; y que la alineación de futuros desarrollos con los principios de sostenibilidad y la estandarización global será clave para ampliar su adopción en los sectores de la ingeniería y la construcción.*

## PALABRAS CLAVE

*Compuestos de madera y polímero; Propiedades físico-mecánicas; Procesos de producción; Sostenibilidad.*

## 1. INTRODUCTION

The composite structures sector faces numerous challenges and opportunities in a rapidly changing business environment, with increasing global pressures to adopt sustainable practices [1,2]. Investors and consumers are paying closer attention to companies' ESG (Environmental, Social and Governance) practices [3], driving demand for materials and processes that minimize environmental impact and align with the principles of the circular economy.

In this context, Wood Polymer Composites (WPC) emerge as a promising sustainable alternative. They combine a polymeric matrix with a reinforcing filler, generally wood waste, enabling the reuse of polymeric and lignocellulosic residues, thereby reducing environmental liabilities and lessening the demand for natural resources. Beyond their environmental appeal, WPC offers significant technological advantages: the polymeric matrix distributes mechanical stresses and protects the filler from damage, while the filler enhances the material's strength and stiffness [4,5].

Their resistance to moisture, fungi, pests, and mold makes WPC suitable for external applications where natural wood would be unsuitable [6,7]. Consequently, they find applications in construction elements such as profiles, beams, decks, and panels [8-10], as well as in the automotive industry for components like interior panels and vehicle doors [11]. The performance of these products depends on an integrated design approach that considers both optimal material selection and manufacturing parameters.

Figure 1 presents a chronological overview of investigations into WPC, as detailed in the review by Kieling, Santana, and Dos Santos [12]. While WPC is not a recent technological innovation, the field continues to evolve, with research focusing on expanding applications, incorporating new waste streams, improving production methods, and embedding circular economy practices in manufacturing – efforts that collectively strengthen the benchmarking of these materials.

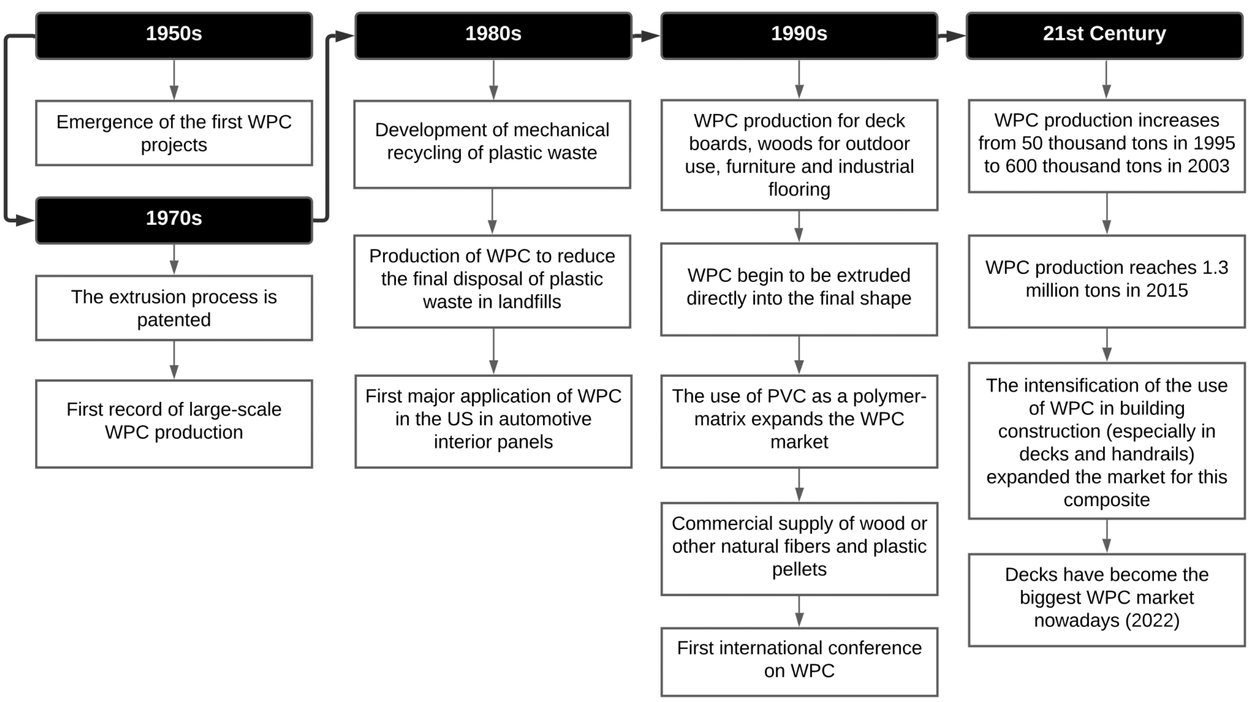


**Figure 1:** Historical evolution of the Wood Polymer Composite.
**Source**: The Authors. Adapted from Kieling et al. [12].

Proper WPC design is fundamental to achieving desired performance. This includes selecting appropriate polymers and fillers, often from recyclable sources [11,13,14]. Such a multifaceted approach not only advances material recycling and waste reduction but also supports several United Nations (UN) Sustainable Development Goals (SDGs), including SDG 12 (Responsible Consumption and Production), SDG 14 (Life Below Water), and SDG 15 (Life on Land). Furthermore, fostering cross-sector collaboration to develop sustainable solutions such as WPC directly contributes to SDG 17 (Partnerships for the Goals) [2].

The existing literature often addresses WPC through specific lenses, focusing separately on matrices [15], types of fillers [16], production methods [17], compatibilizing agents [18], or material properties [19]. In contrast, this study offers an integrated perspective, employing graphical tools to clarify the complexities involved and conducting in-depth analyses of how these variables influence the physical-mechanical behavior of WPC. By exploring data distributions and identifying outliers, this work provides a comprehensive and updated view that can help expand the structural applications of WPC in strategic industrial sectors.

## 2. METHODOLOGY

To develop a broad understanding of the characteristics, properties, and processing methods of WPC, a comprehensive literature review was conducted using the adapted Systematic Search Flow (SSF) method [20], which structures the search process to minimize researcher bias. The research protocol (Figure 2) comprised four sequential stages. Searches were performed in Scopus® and Web of Science®, with the most recent search completed in August 2025, using the keywords "wood polymer composite" and propert* with Boolean operators. The scope was restricted to journal articles published between 2016 and 2023, without language limitations. Newspaper articles, book chapters, and other sources were excluded, as evidence from previous studies suggests they often add complexity without offering substantial contributions [21,22].

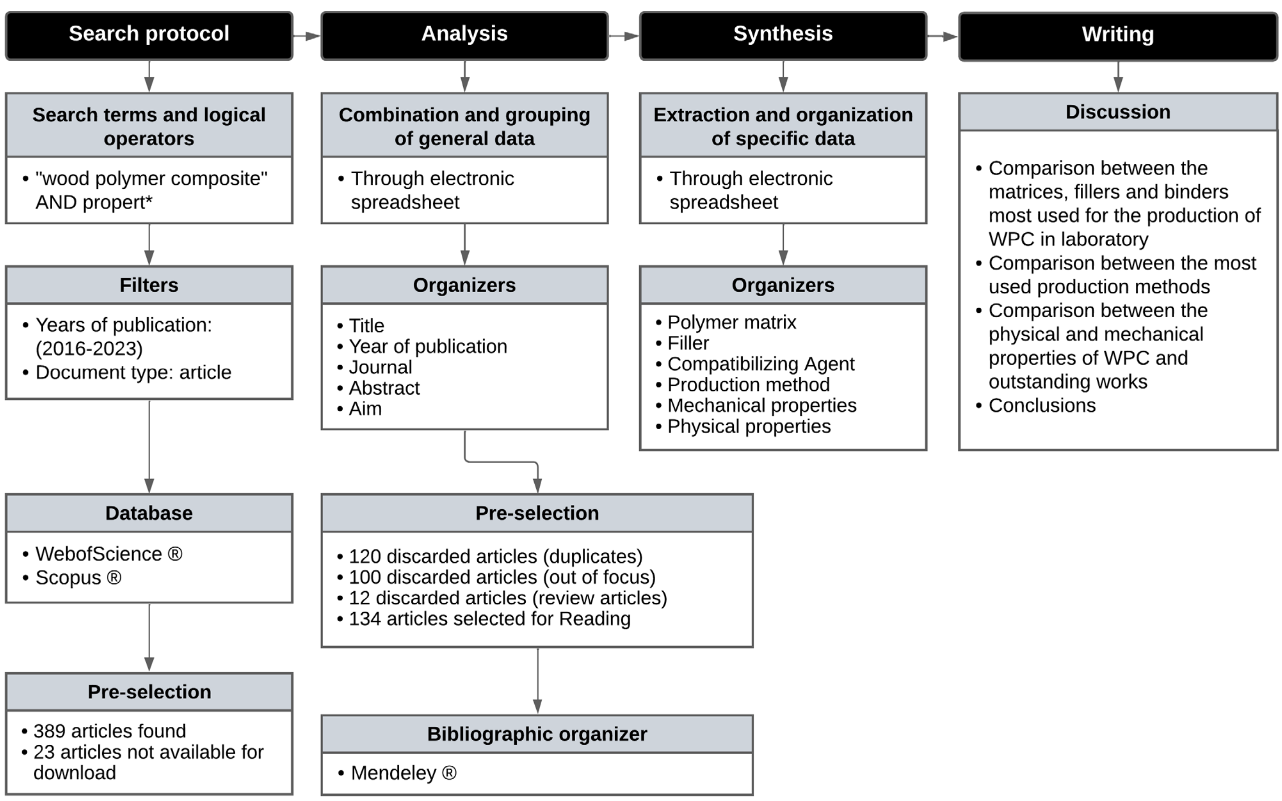


**Figure 2:** Steps of the literature review process using the adapted SSF method [20].
**Source**: The Authors.

From the initial 389 records retrieved, 23 were inaccessible and 120 were duplicates, leaving 246 unique articles. Screening excluded 112 papers for being literature reviews or for not addressing WPC materials, processing techniques, or properties. This resulted in a final set of 134 relevant studies. Thus, the final set comprised only original research articles reporting experimental data on WPC materials, processing, or properties.

Notably, these 134 articles encompassed 283 distinct WPC, since many studies examined multiple composite variations. In this context, a “distinct” WPC was defined as one differing in the raw materials used or in the production methods, even if reported within the same study. This approach ensured that each variation was evaluated individually, rather than grouping results by article.

## 3. POLYMERIC MATRICES

The results of the literature review reveal a clear predominance of thermoplastic polymer matrices in the WPC investigated, particularly polypropylene (PP) (37.8%) and high-density polyethylene (HDPE) (18.4%) [23-39], compared to thermosetting polymers such as polyester (PES), polyurethane (PU), and epoxy resin (ER), which represent less than 2% of the reviewed cases. Thermoplastics are favored for their low cost, ease of processing and recycling due to their ability to be remelted, and chemical resistance from their non-crosslinked polymer chains [40]. Additionally, thermoplastics, especially PP and PE, process at relatively low temperatures (below 200 °C), which helps prevent degradation of wood-based fillers [41,42]. These results are summarized in Figure 3.

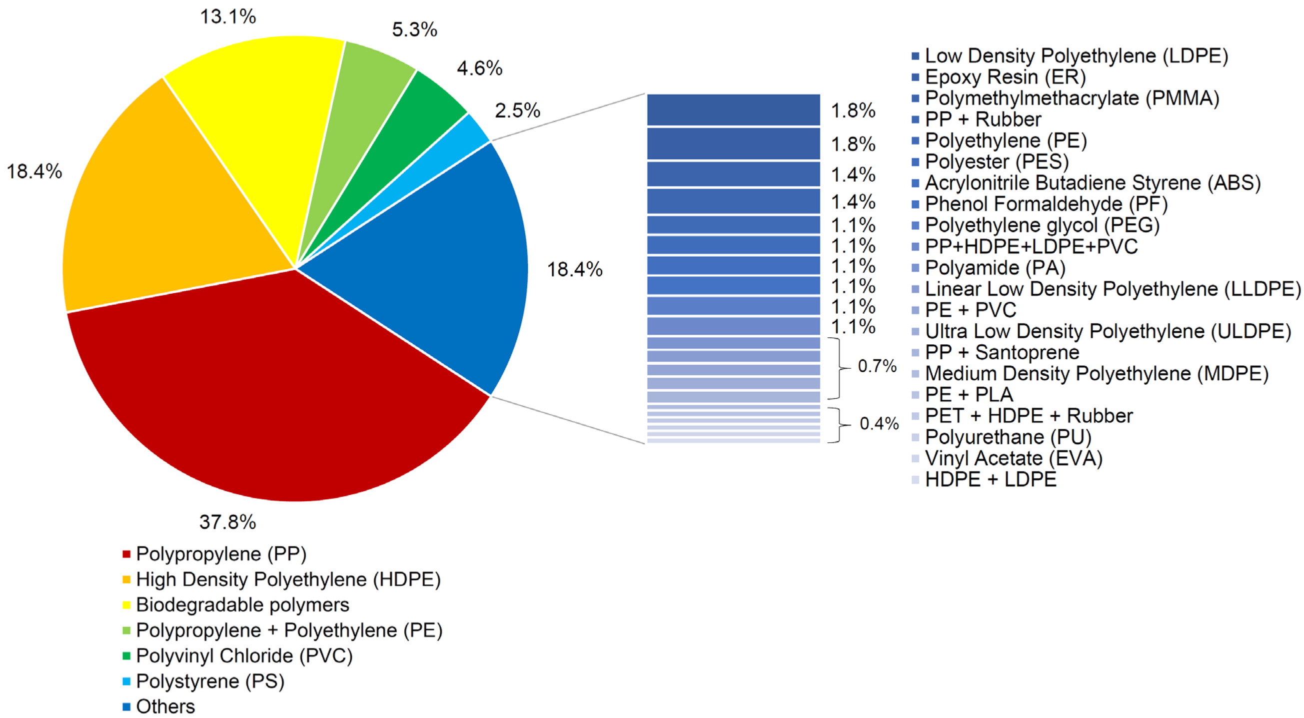


**Figure 3:** Steps of the literature review process using the adapted SSF method [20].
**Source**: The Authors.

Among thermoplastics, notable matrices also include blends of PP with polyethylene (PE) (5.3%) [43,44], polyvinyl chloride (PVC) (4.6%) [45-48], and polystyrene (PS) (2.5%) [49,50]. PVC offers greater compatibility with lignocellulosic materials due to its hydrophilic molecular structure and the presence of chlorine, which acts as a flame retardant [51]. However, PVC can release dioxins during manufacturing, posing environmental concerns for the WPC industry [41].

Biodegradable polymers represent 13.1% of the identified WPC, enabling the production of fully biodegradable composites when both the filler and the matrix are biodegradable. Examples include polylactic acid (PLA) [52-54], poly(butylene succinate) (PBS) [55], polycaprolactone (PCL) [56], and modified starches [57]. Growing concerns over pollution caused by commodity plastics have driven a shift toward biodegradable alternatives. Bio-based plastics derived from biomass, when combined with renewable fillers and circular raw resources such as wood, have the potential to further boost the WPC industry. Conventional WPC contribute to microplastic pollution and often end up in landfills, leading to long-term environmental impacts. In contrast, bio-based plastics with high filler content can be relatively low-cost, exhibit excellent mechanical properties, and reduce environmental impact [55].

## 4. FILLERS

The literature review highlights the predominant use of natural wood particles, either as flour or fibers, as WPC fillers, accounting for 81% of cases, as shown in Figure 4. Incorporating wood fibers into the polymer matrix offers multiple advantages, including lower processing temperatures, reduced molding cycles, lower density, and low abrasiveness [58]. Moreover, wood is a renewable and biodegradable resource, enhancing the sustainability of WPCs [59]. These benefits extend to WPC structural elements, reinforcing their potential for sustainable construction applications.

Among these composites, 54% use a single wood species as filler, while 5% employ two or more species simultaneously [60-65]. Additionally, 4% of studies explore combining wood with inorganic reinforcements such as chalk [47], glass [66], aramid [67], and printed circuit boards [68]. Other fillers include fiber or particle panels (4%), microcrystalline cellulose (2%) [55], and reprocessed WPC particles (1%) [69].

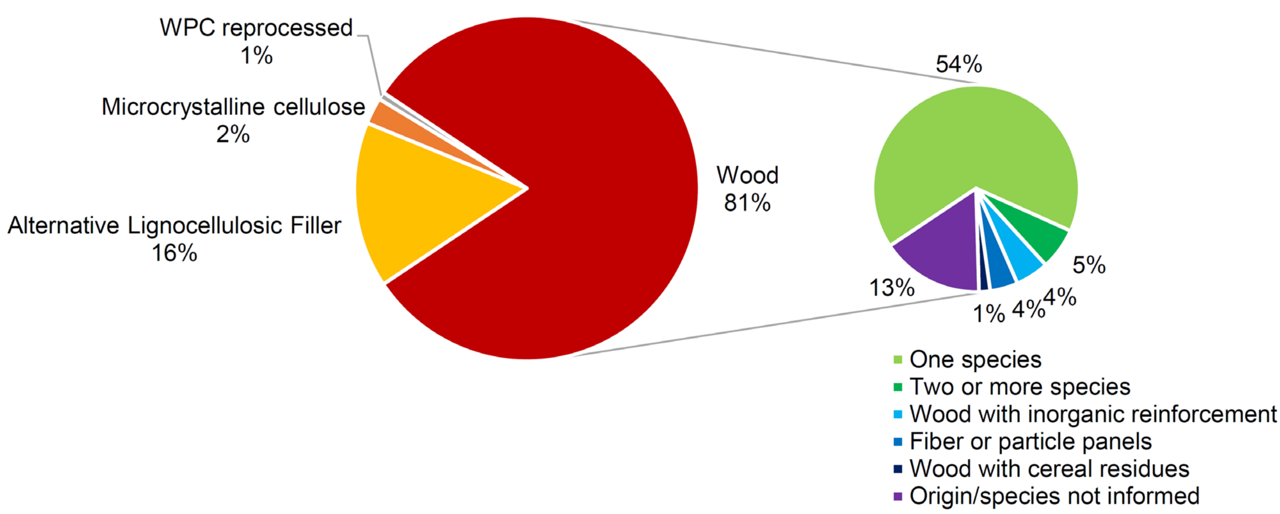




**Figure 4:** Types of fillers most used in WPC.
**Source**: The Authors.

Alternative lignocellulosic fillers represent 16% of WPC compositions and include grasses, cereal residues, and fruit byproducts. Examples are bamboo [70, 71], brown coals [72], rice husk [73, 74], rapeseed straw [75], tangerine peel [76], oat husk [77], wheat bran [78], sunflower husk [79], corn straw and cob [80, 81], palm leaves [82], olive pits [83], coffee husks [84], among others. Some studies investigate mixed fillers combining wood and cereal residues, such as coffee husks with brewery grains [85] or coconut shell [86]. Notably, 13% of WPC with wood fillers do not specify the species or origin of the wood [87].

Among those specifying wood species, the most common are Pine (27.0%), Poplar and Fir (16.7% each) and Beech (15.5%) as presented in Figure 5 [23, 68, 88-97]. Less frequently used species (24.1%) include Neem, Flamboyant, Eucalyptus, Birch, Teak, Willow, Sal Tree and Oak, among others [35, 60, 62,98-103], as well as fruit trees such as Olive [104], Black Cherry [105], and Jackfruit [106].

It is important to note that all natural wood fillers contain cellulose, hemicellulose, and lignin. Cellulose enhances certain mechanical properties of WPC, such as reduced thermal expansion/ contraction. Lignin, however, can weaken WPC by reducing density and accelerating discoloration upon outdoor exposure. Hemicellulose is susceptible to decomposition at the polymer matrix's melting temperature, producing acetic acid that can severely corrode processing equipment [107]. Understanding these components is essential for optimizing the behavior and properties of natural fiber-reinforced composites, particularly for structural applications.

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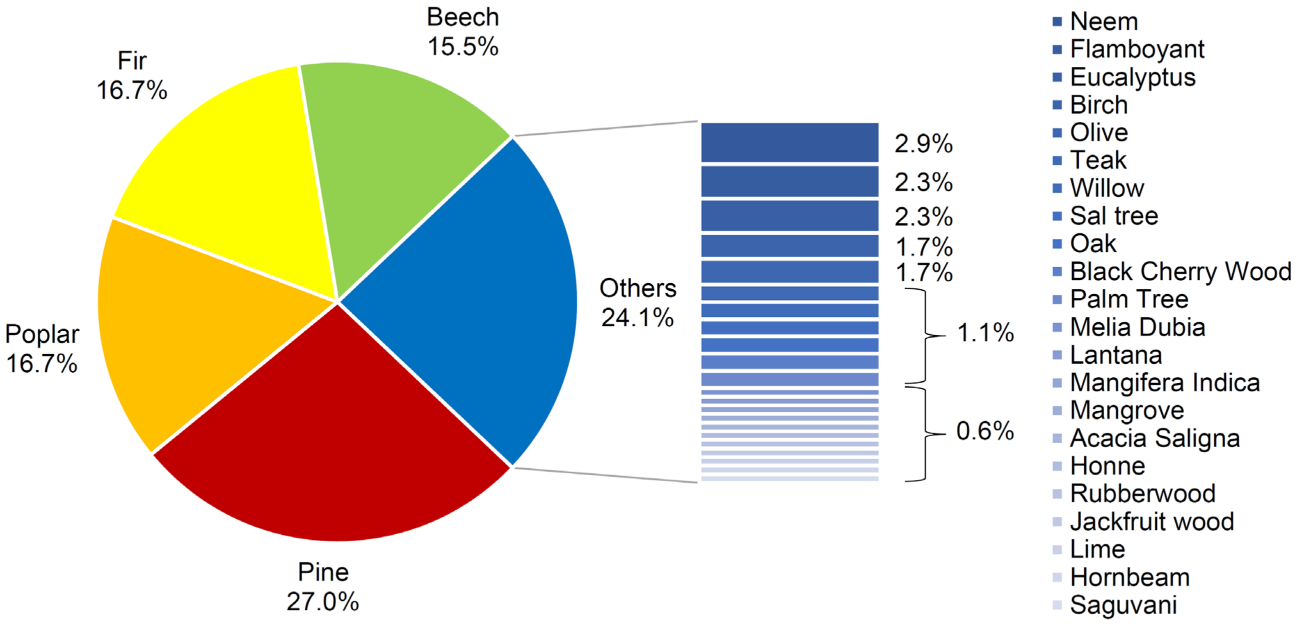


**Figure 5:** Types of fillers most used in WPC.
**Source**: The Authors.

## 5. COMPATIBILIZING AGENTS

Although wood and other lignocellulosic fillers are widely used in WPCs, their hydrophilic nature can cause incompatibility with hydrophobic polymer matrices, hindering interfacial adhesion and reducing load transfer efficiency [108]. To address this issue, compatibilizing agents are incorporated in 64.3% of the analyzed cases (Figure 6), acting as chemical intermediaries that enhance matrix-filler interaction, resulting in more homogeneous and stable composites [109]. Maleic anhydride (MA) is the most commonly used agent either in pure form (7.1%) [24,110,111] or grafted onto PP (MAPP) (5.3%) [57,104,112-114] and PE (MAPE) (4.6%) [115-119]. Its mechanism involves reacting with hydroxyl groups in wood fibers, creating chemical bonds or stronger interactions with the polymer, thereby reducing defects such as porosity and micro-voids [120]. In some cases, adding up to 4 wt% MAPP can increase the flexural modulus of rupture and modulus of elasticity by up to 12.7% and 39.1%, respectively, in composites based on PP, rubber, and rubberwood sawdust [112]. However, not all compatibilizers yield improvements, for instance, ethylene-1-butene weakened the strength of PP composites containing ground tire rubber and pine flour [121].



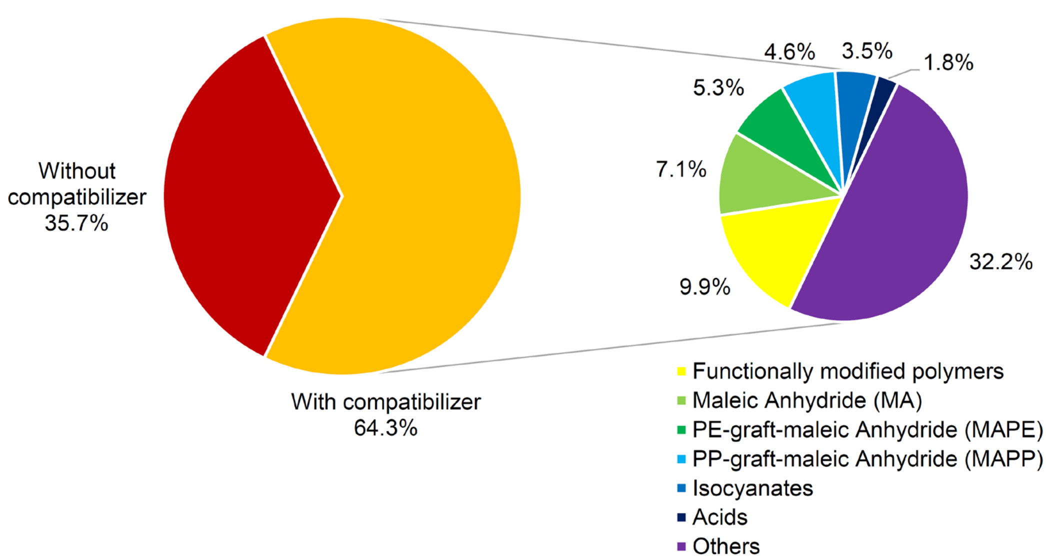


**Figure 6:** Compatibilizing agents used in the production of WPC.
**Source**: The Authors.

Despite these benefits, 35.7% of WPCs are produced without compatibilizers [88,122-125], offering simpler formulations and lower costs, although potentially at the expense of mechanical and thermal performance. Beyond MA, MAPP and MAPE, alternative compatibilizers are also employed, such as functionally modified polymers (9.9%) [44,94] and isocyanates (3.5%) [55,56]. Functionally modified polymers incorporate specific groups that enhance adhesion, wettability, or reactivity [126-128], while isocyanates improve phase compatibility to levels equal to or exceeding those of anhydrides [56]. However, due to their toxicity, isocyanates must be used cautiously, with environmental and safety considerations being essential for the development of more sustainable WPCs [18].

## 6. PROCESSING METHODS

Extrusion is the predominant WPC processing method, used in 39.9% of studies (Figure 7) [30, 32,44,80,129-134]. It ensures uniform component mixing, melting and plastifying materials into profiles, boards, or other shapes, promoting strong organic-inorganic adhesion and optimizing composite properties for diverse applications. Compression molding (21.6%) [135-142] and injection molding (13.1%) [31, 100, 143-147] are also relevant. In compression molding, the matrix and filler are pressed in a mold, which is generally heated, while in injection molding, the molten material is injected into a mold [41]. Compression molding is efficient at lab scale but often produces higher porosity than extrusion or injection, which yield denser, less absorbent composites [61].

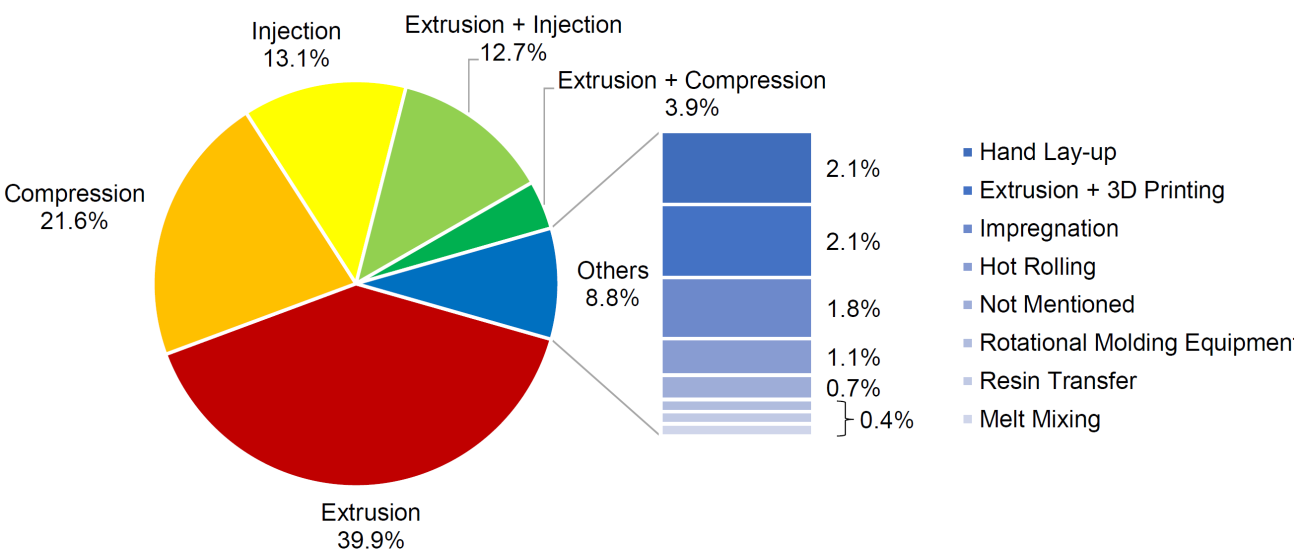


**Figure 7:** Main processing methods used in research involving WPC.
**Source**: The Authors.

Hybrid methods combine extrusion with injection (12.7%) [148-150] or compression molding (3.9%) [112,119], where extrusion generally serves as the mixing stage and the subsequent method defines the final geometry and properties [84,96,151,152]. Extrusion can also supply filaments for 3D printing, which are remelted and deposited layer by layer [53,54].

Hand lay-up, despite being labor-intensive, operator-dependent, and less consistent, remains popular for its low cost and versatility [102,103, 153,154]. Fibers are manually arranged and resin applied by hand [155], mainly for thermoset matrices (epoxy, polyester, vinyl ester) [156], whose long curing times enable handling and yield dimensionally stable, chemically, and thermally resistant composites [157]. Automation has been proposed to improve repeatability [158].

Some studies adopt a structural impregnation approach, modifying entire wood pieces instead of particulate fillers [159]. After delignification to increase porosity while preserving cell walls, polymers such as PMMA [160] or PVA [161] are infiltrated, filling cell lumens without defects and achieving tensile strengths up to 165.3 MPa [160], far above those of conventional WPCs (up to 60 MPa). Other works present prototype processing equipment, such as a rotational molding system with a 360° rotating aluminum mold and oscillating oven for uniform material distribution [162]. In all methods, precise control of temperature, pressure, and speed is critical, as

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inadequate conditions cause poor filler dispersion, voids, and reduced mechanical performance [41].

## 7. MECHANICAL AND PHYSICAL PROPERTIES

Various mechanical and physical properties are evaluated in research involving WPC. Among the mechanical properties, the systematic review showed that tensile and flexural strength tests are the most frequently reported, applied to 75% and 48% of the composites reviewed, respectively. Regarding physical properties, water absorption was the most common, assessed in nearly 30% of the studies, with a 24-hour immersion period adopted in 21% of these cases. Other tests were reported for a smaller subset of composites (less than 30%), including impact strength, shear strength, wear resistance, weathering, color change, viscosity, hardness, and thickness swelling [77,94,95,100,116,144,141].

Statistical analysis of the compiled dataset, summarized in the boxplots of Figure 8, reveals distinct distributions for tensile and flexural strength among the evaluated WPCs. Tensile strength values (n=215) range from 1.56 MPa to 59.20 MPa, with a median of 23.63 MPa and a mean of 24.88 MPa, indicating a relatively symmetric distribution around the central tendency, though with two extreme outliers (152.08 MPa and 255.71 MPa) far exceeding the upper quartile (32 MPa). In contrast, flexural strength (n=135) spans a broader range, from 3.53 MPa to 105.39 MPa, with higher central values, a median of 37 MPa and a mean of 39.29 MPa, and no statistical outliers. Overall, flexural strength not only exhibits higher absolute values compared to tensile strength but also a wider interquartile range (19.50-55.30 MPa vs. 12.58-32 MPa), reflecting its generally higher magnitude in WPCs, since flexural loading induces a combination of tensile and compressive stresses, allowing the material to sustain higher apparent strengths than in pure tension.

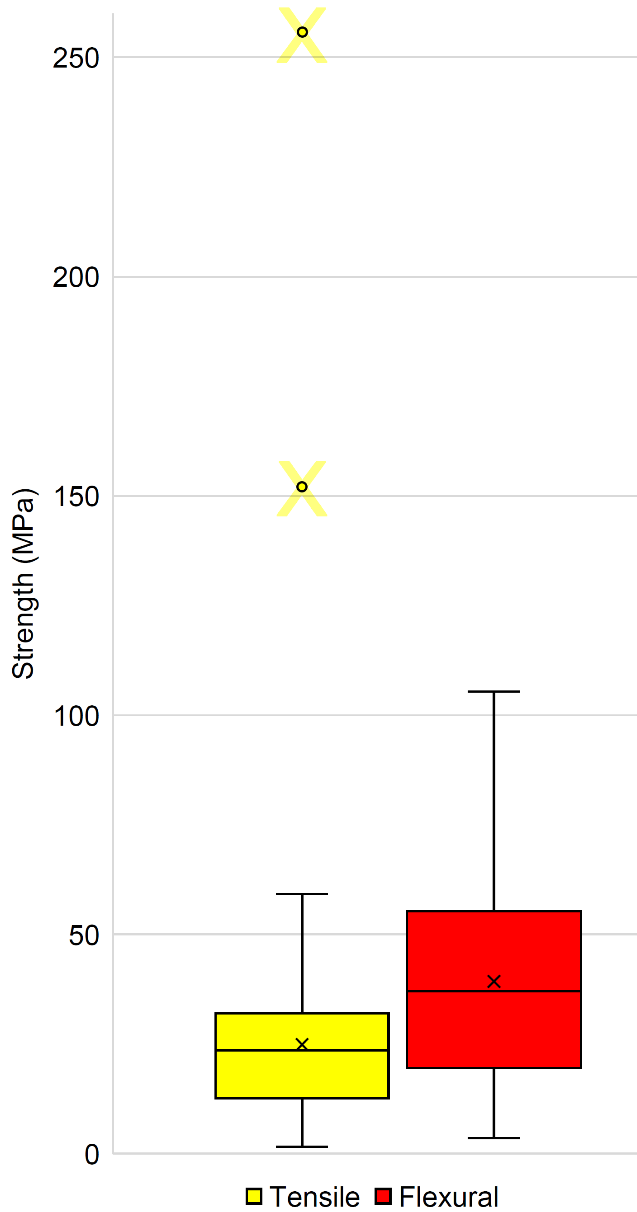


**Figure 8:** Results of composites subjected to tensile and flexural strength tests.
**Source**: The Authors.

One of the main challenges in developing WPCs is achieving efficient interfaces between the polymer matrix and lignocellulosic fillers, thereby maximizing stress transfer and, consequently, mechanical properties. For this reason, a large share of studies investigates the effect of compatibilizing agents, especially MA, on mechanical performance, with emphasis on tensile strength. The addition of moderate amounts of MA or MA-functionalized polymers promotes chemical compatibilization, enhancing macromolecular interpenetration, homogeneous particle dispersion, and improved interfacial adhesion [57].

Experimental results confirm this effect. A PP composite reinforced with bamboo fiber containing 3%

MA exhibited a tensile strength of 15.83 MPa, compared to 5.43 MPa for the same material without compatibilizer [70]. Similarly, PP-based WPCs with MA and residual MDF or MDP fillers, produced by extrusion, reached strengths above 42.00 MPa [69,113,130], while PP composites with beech and ionic liquid (47 MPa) [96], and PP with MDP and MA (59.20 MPa, the maximum value within the boxplot limits) [69] also showed high performance.

On the other hand, composites without compatibilizers generally rank among the lowest in tensile strength. Examples include PET, HDPE and rubber with oak (1.56 MPa) [99] and PP with acacia (4.55 MPa) [163], both compression molded; PP with beech (2.89 MPa) and PP with birch (3.16 MPa) by injection molding [100]; and PE with fir by extrusion (4.91 MPa) [93]. Nevertheless, there are notable exceptions: PP and melia dubia WPCs, produced by extrusion and injection, reached 53.70 MPa [152], and PP with fir flour achieved 43.26 MPa [68], even surpassing certain formulations with compatibilizers, such as PP and PE with unspecified wood flour and MA (6.81 MPa) [164], or PP with poplar and azodicarbonamide (6.91 MPa) [43].

The two outliers observed in the boxplot are associated with non-conventional manufacturing processes. In the first case, the process consists of interleaving PVC powder between wood veneers and PVC layers aligned with the fibers, followed by single-step hot molding. This approach promotes cell collapse in the wood and chemical bonding to PVC, producing a dense, interconnected structure with high density and strong bonding, resulting in a mechanical strength of 255.71 MPa, exceeding by over tenfold the average strength of the analyzed WPCs [165]. In the second case, a wood/PMMA composite achieved 165 MPa using delignified linden wood with preserved cellular structure and complete PMMA impregnation, avoiding microstructural defects and leading to outstanding performance [160]. These results reinforce that, while compatibilizers play an important role, careful selection of raw materials and the adoption of innovative manufacturing processes can exert an even greater impact on the mechanical strength of WPCs.

In terms of flexural strength, WPCs produced by extrusion and incorporating compatibilizing agents showed the highest performance. Composites with a PP matrix and MDF or MDP fillers, combined with MA, reached values exceeding 70 MPa [69,113,130]. MDF also stood out in a study assessing the influence of different fillers: three composites, produced with the same matrix (PP), processing method (extrusion followed by compression), and compatibilizer (MAPP), achieved distinct flexural strengths depending on the filler type. The formulation with MDF (39.31 MPa) outperformed those with hornbeam (37.99 MPa) and pine (31.79 MPa) [166]. The highest flexural strength, 105.39 MPa, was achieved by the same WPC that was an outlier in tensile strength, produced via a single-stage hot molding process using PVC and poplar [165].

Chemically pretreated wood fillers also yielded high flexural strengths, even in composites manufactured by hand lay-up. A WPC reinforced with pine and sal tree, pretreated with silane, reached an average flexural strength of 94 MPa, while a similar composite with alkaline pretreatment achieved 84 MPa [103]. Additionally, a WPC based on epoxidized soybean oil resin, incorporating treated wood flour and MA, recorded 72.49 MPa [138].

At the other end of the spectrum, the lowest flexural strengths were found in a PU-based WPC reinforced with palm leaf fiber and palm oil (3.53 MPa) produced by extrusion [167], and in an epoxy resin-pine composite (5.36 MPa) made by hand lay-up [168]. Similarly, a PES-based WPC with teak and additives for catalysis and curing achieved 6.50 MPa, which increased to 7.11 MPa with the addition of gum resin [102]. These findings highlight the considerable potential of WPCs in flexural applications, particularly for thermoplastic matrices reinforced with chemically pretreated wood fillers.

The mechanical performance of WPCs, as observed in both tensile and flexural tests, is strongly influenced by matrix-filler interactions, filler type, compatibilizers, and processing methods. These same factors also affect physical properties such as water absorption. High filler-matrix adhesion and densely consolidated microstructures, as seen in composites with chemically treated wood or processed via innovative methods, enhance strength while limiting water uptake, mitigating dimensional instability and potential degradation.

Water absorption directly influences the long-term performance of WPCs. Excessive water uptake can cause swelling and deformation of the polymer matrix and wood fibers, weakening interfacial bonds and reducing mechanical properties such as tensile, flexural, and impact strength [169]. Therefore, assessing water absorption is essential for understanding the overall behavior and durability of WPCs.

Statistical analysis of the water absorption values after 24 hours (n=59), summarized in the boxplot of Figure 9, shows a markedly skewed distribution. Absorption rates range from 0.17% to 17.5%, with a median of 2.63% and a mean of 6.99%, indicating that most composites exhibit relatively low water uptake, but a subset presents substantially higher values. The interquartile range (0.78-8.0%) reflects considerable variability among the central 50% of the dataset, while several extreme outliers (19%, 25.83%, 27%, 31.6%, 48.6%, and 51.07%) demonstrate that, in specific formulations, water absorption can be several times greater than the typical range observed. Such dispersion highlights the strong influence of material composition, processing, and fiber-matrix interactions on the hydrophilic behavior of WPCs.

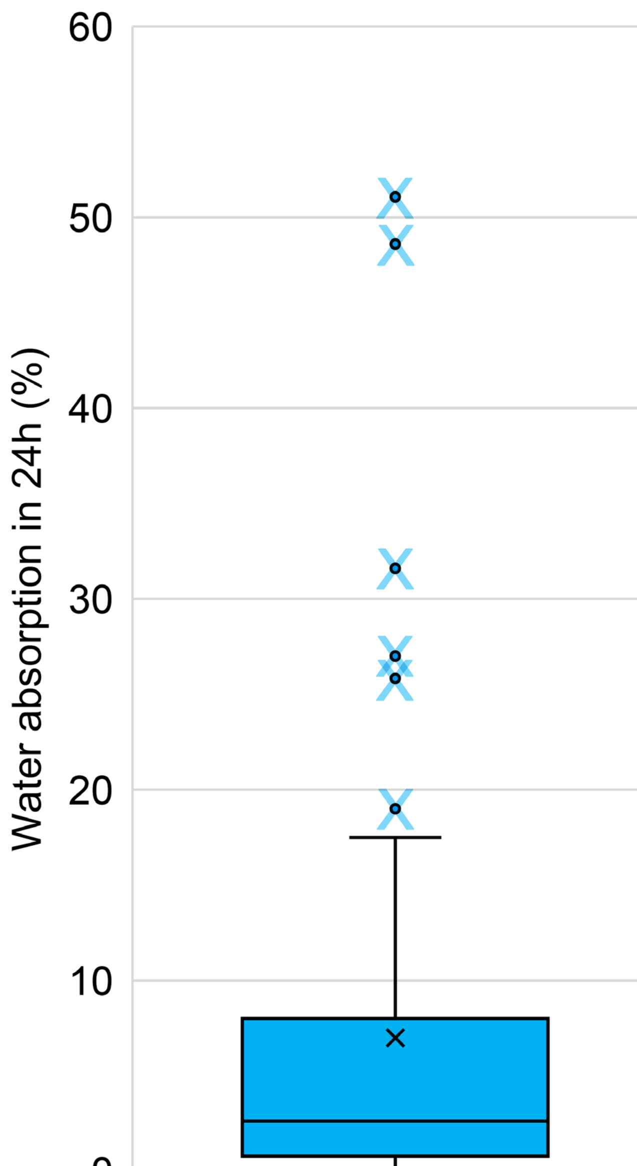


**Figure 9:** Results of composites subjected to the 24-hour water absorption test.
**Source**: The Authors.

The water absorption behavior of WPCs varies widely depending on formulation and processing parameters. The lowest mean value reported (0.17%) was obtained for a PVC-based composite with wood flour [47], in a study that extended earlier work where part of the wood filler was replaced with chalk as a mineral filler, combined with dioctyl phthalate plasticizer, to reduce water uptake [48].

Processing route plays a central role in this variability. Although some extruded composites have shown absorption levels below the second quartile (2.63%) [47,77,115], extrusion can adversely affect moisture resistance. A comparative study on composites with identical formulations demonstrated that extruded specimens absorbed more water than those produced by compression or injection molding [170]. The superior performance of injection-molded composites was attributed to the formation of a polymer-rich surface layer under high processing temperatures and pressures, providing a more effective barrier against moisture. Compression molding, however, can surpass injection molding in WPC production due to its lower shear stresses and more controlled temperatures, which better preserve fiber integrity, leading to improved tensile and flexural properties, an effect that can be enhanced through compatibilizer addition [157]. Longer exposure to pressure and heat during compression molding also contributes to reduced water ingress compared to extrusion.

Within compression molding, processing temperature is particularly influential. The most extreme outlier in the boxplot (51.07%) corresponds to a composite based on PS where absorption decreased dramatically as pressing temperature increased, from 51.07% at 413 K (~140 °C) to only 1.33% at 493 K (~220 °C) [49]. This improvement was further supported by filler refinement: composites with sifted sawdust absorbed less water than those with unsifted sawdust, a result attributed to denser packing, lower void volume, and reduced porosity. Additionally, the incorporation of additives such as calcium carbonate ($CaCO_3$) can further reduce water absorption in WPCs, particularly in composites based on recycled PP. For instance, a formulation containing 70% wood flour and 30% recycled PP showed a reduction in water uptake from 4% to 2% after 24 hours of immersion, which could be further decreased to 1.5% with the addition of 7% $CaCO_3$ by weight, effectively minimizing the influence of the PP/wood ratio [171].

Composition also plays a decisive role, as illustrated by two other extreme outliers (48.6% and 31.6%), both associated with starch-based WPCs. While starch and other natural polymers are promising for biodegradable composites, their high moisture sensitivity restricts their applicability. Incorporating appropriate fillers has proven to be an effective means of reducing this sensitivity while simultaneously enhancing mechanical performance [57].

Overall, these findings reinforce the interdependence between formulation, processing route, and microstructural development in determining the water absorption

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performance of WPCs. Optimizing these parameters – particularly processing temperature, filler characteristics, and molding technique – is essential for achieving composites with low water uptake and robust mechanical properties.

## 8. FILLER CONTENT

Filler content in polymer composites directly affects their mechanical, physical, and processing properties [130]. Figure 10 summarizes the distribution of filler contents reported in the reviewed studies. The most frequent formulations are concentrated between 20 and 40 wt%, with the 30–40 wt% range showing the highest occurrence, which is consistent with the recommendation of Kieling et al. [12], who suggest the use of up to 40 wt% vegetal fibers in WPCs produced from recyclable materials. Nonetheless, 9.8% of the analyzed formulations contain more than 60 wt% fiber, highlighting the feasibility of achieving higher loadings and, consequently, greater reuse of recycled material as filler. Although the present discussion focuses on fiber content, particle morphology also plays a significant role in composite performance. Fibrous shapes combined with a homogeneous particle-size distribution are generally associated with better dispersion within the matrix and enhanced mechanical properties [172,173].

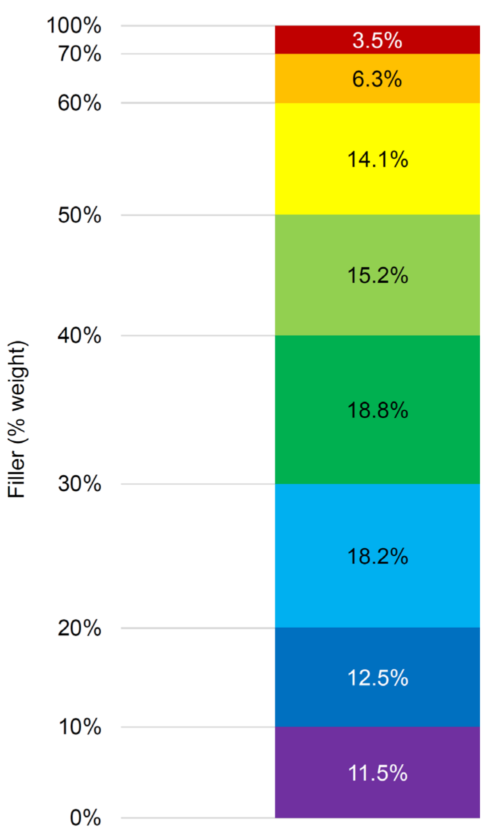


**Figure 10:** Distribution of filler content (wt%).
**Source**: The Authors.

In general, increasing filler content tends to reduce the mechanical properties of WPCs, an effect particularly evident in studies that systematically varied this parameter [46,62,76,93,154]. For instance, tensile strength decreased by 31% when coffee silverskin content increased from 2% (22.7 MPa) to 20% (15.6 MPa) [84]. In the same study, replacing the filler with wheat bran resulted in an even greater loss of 47%, from 2.5% (17 MPa) to 20% (9 MPa). These reductions were attributed to increased porosity and insufficient interfacial adhesion, exacerbated by the presence of proteins that may reduce stress transfer by allowing the polymer matrix to slide over the filler particles.

In some cases, an initial increase in tensile strength was observed with increasing filler content, followed by a decline. The initial gain was associated with improved microcellular structure and an increase in the effective load-bearing area, while the subsequent reduction was linked to intensified filler-filler interactions and particle agglomeration [164,167,174]. However, the trend for flexural strength does not always mirror that of tensile behavior. For example, increasing acacia fiber content from 50% to 70% resulted in a 43% decrease in tensile strength (from 23 to 13 MPa) and a 50% decrease in flexural strength (from 6.50 to 3.25 MPa) [163]. Conversely, another study reported only a 5% decrease in tensile strength when filler content increased from 10% to 30%, accompanied by a 30% increase in flexural strength. In this case, the incorporation of wood fibers enhanced the rigidity of the HDPE matrix, which improved its flexural performance despite the slight reduction in tensile strength [123]. Higher filler content, particularly with wood-based composites, also increases water absorption [168,175]. This behavior is attributed to the hydrophilic nature of sawdust, which hydroxyl groups form hydrogen bonds with water, compounded by deficient matrix–filler interfaces, resulting in higher water uptake and weight gain [168].

A common strategy to mitigate mechanical property losses in high-filler composites is the use of compatibilizers. Composites without compatibilizers showed decreased tensile and flexural strength with increasing filler content [114], whereas the addition of 3.5% maleic anhydride (AM) in a PP matrix enabled more effective stress transfer to lantana fibers, enhancing strength at higher loadings. Similar behavior was reported in other studies [79,145]. Moreover, the use of various compatibilizing agents (MAPP, lignin, and nanolignin) has been shown to optimize the performance of PP composites with a high filler content, containing 60% industrial wood residues [176].

Overall, these findings highlight that while high filler content offers environmental benefits by increasing the use of recycled material, it can negatively affect the mechanical and physical properties of WPCs, highlighting the importance of controlling particle morphology and considering the use of compatibilizers to improve performance.

## 9. CRITICAL REFLECTIONS AND FUTURE PERSPECTIVES

The present review was developed with a specific focus on material composition, processing, and performance trends in WPCs, and therefore did not encompass certain broader aspects that nonetheless merit attention in future research. Among these are long-term performance evaluations under aggressive environmental exposures, such as high humidity, ultraviolet radiation, freeze-thaw cycles, and saline or chemically reactive atmospheres, which are essential to validate the suitability of WPCs for demanding structural and infrastructure applications. Similarly, the effects of multiple recycling and reprocessing cycles on mechanical integrity, filler-matrix bonding, and dimensional stability represent a critical area of investigation in the context of circular economy strategies.

WPCs are increasingly applied in exterior and structural contexts, which necessitates compliance with international standards and guidelines. The most widely recognized specification is the American ASTM D7032 [177], which outlines procedures to establish performance ratings for WPC deck boards, guards, and handrails. Additional ASTM standards provide test methods for mechanical characterization, including ASTM D7264 [178] for flexural properties of polymer matrix composite materials, ASTM D790 [179] for flexural properties of plastics and electrical insulating materials, and ASTM D638 [180] for tensile properties of plastics, which may be applied to WPCs. Notably, these standards define how tests should be conducted but do not prescribe fixed benchmark values, as mechanical performance depends on variables such as wood species, polymer type, and manufacturing process. This lack of predefined performance thresholds creates a gap that hinders direct comparison between studies and complicates global standardization efforts for WPC products. Beyond ASTM, the ISO 20819-1 standard [181] specifies requirements for recycled composites, including health and safety considerations, test methods, and procedures to calculate recycled material content, thereby promoting sustainable production and responsible material sourcing in WPC manufacturing.

From an industrial and regulatory perspective, aligning future research with the requirements of international technical standards, while addressing the absence of harmonized performance benchmarks, will be crucial to enable fair comparisons, facilitate market acceptance, and support the wider adoption of WPCs. At the same time, developing scalable and resource-efficient production strategies can accelerate the integration of these composites into advanced engineering applications, ensuring not only technical reliability but also environmental and economic sustainability.

## 10. CONCLUSION

This review highlights the strong potential of WPCs as sustainable materials for civil construction, supported by their competitive mechanical performance, low water absorption, and versatility in composition and processing. The predominance of thermoplastic matrices such as PP and HDPE, often combined with compatibilizing agents and properly processed lignocellulosic fillers, enables performance levels suitable for structural use. However, advancing their adoption requires addressing critical gaps, including long-term durability under aggressive conditions, the influence of recycling cycles on properties, and alignment with international technical standards, which currently prescribe testing methods but lack harmonized benchmark values-hindering comparability and global standardization. Future developments should integrate these regulatory and performance considerations with scalable, resource-efficient manufacturing strategies, enabling applications such as decking systems, facade cladding and modular structural panels in sustainable construction.

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**ARS:** conceptualization, methodology, investigation, data curation and project administration.

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