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Technical-Environmental feasibility of wood-plastic composites production: a theoretical approach

Viabilidade técnico-ambiental da produção de compósitos madeira plástico: abordagem teórica

Viabilidad técnico-ambiental de la producción de compuestos madera-plástico: enfoque teórico

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Abstract: Human activities contribute significantly to the generation and disposal of waste in landfills, with polymeric waste and wood waste being one of the most prevalent categories produced in excessive quantities. The production of wood- plastic composites (WPCs) presents a promising solution for the reutilization and valorization of these waste streams. This study provides a comprehensive over-view of current developments in WPC production and their potential applications. The research identifies the most utilized polymers, evaluates their performance in comparison to virgin materials, examines the role of coupling agents, and explores production techniques for composite manufacturing. Additionally, it assesses the global market applications of WPCs. Notably, WPCs exhibit superior performance characteristics, substantial market potential and low maintenance requirements. Nevertheless, there remains a significant research gap that necessitates further exploration to fully realize the potential of this field.

Keywords: Polymeric waste; disposal; reuse; composite material; feasibility.

Resumo: As atividades humanas contribuem significativamente para a geração e descarte de resíduos em aterros sanitários, sendo os resíduos poliméricos e resíduos de madeira duas das categorias mais prevalentes e produzidas em quantidades excessivas. A produção de compósitos madeira-plástico (WPCs) surge como uma solução promissora para a reutilização e valorização desses fluxos de resíduos. Este estudo fornece uma visão abrangente das tendências atuais na produção de WPCs e investiga suas aplicações. A pesquisa identifica os polímeros mais comumente utilizados, avalia seu desempenho em comparação com materiais virgens, examina o papel dos agentes compatibilizantes e explora técnicas avançadas de produção para a fabricação de compósitos. Além disso, são avaliadas as aplicações globais de mercado dos WPCs. Notavelmente, os WPCs apresentam características de alto desempenho, significativo potencial de mercado e baixos requisitos de manutenção. No entanto, ainda existe uma lacuna significativa de pesquisa que necessita de maior exploração para se alcançar todo o potencial deste campo.

Palavras-chave: Resíduos poliméricos, disposição final, reuso, material compósito, viabilidade.

Resumen: Las actividades humanas contribuyen significativamente a la generación y disposición de residuos en los vertederos, siendo los residuos poliméricos y los residuos de madera dos de las categorías más prevalentes y producidas en cantidades excesivas. La producción de compuestos madera-plástico (WPCs) surge como una solución prometedora para la reutilización y valorización de estos flujos de residuos. Este estudio ofrece una visión integral de las tendencias actuales en la producción de WPCs y analiza sus aplicaciones. La investigación identifica los polímeros más utilizados, evalúa su desempeño en comparación con materiales vírgenes, examina el papel de los agentes compatibilizantes y explora técnicas avanzadas de producción para la fabricación de compuestos. Además, se evalúan las aplicaciones globales de mercado de los WPCs. Cabe destacar que los WPCs presentan características de alto rendimiento, un potencial de mercado significativo y bajos requisitos de mantenimiento. Sin embargo, aún existe una brecha importante de investigación que requiere una mayor exploración para alcanzar todo el potencial de este campo.

Palabras clave: Residuos poliméricos, disposición final, reutilización, material compuesto, viabilidad.

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1. INTRODUCTION

The rapid pace of urban developments and changes in lifestyle patterns have significantly increased the volume of waste generated and disposed of in landfills all over the world. Among the diverse types of waste, polymeric and wood residues are notably prevalent due to their high production volumes and persistence in the environment. Polymeric waste, primarily originating from packaging, automotive parts, and consumer goods, poses substantial environmental challenges due to its durability and resistance to natural degradation (Geyer; Jambeck; Law, 2017). It is estimated that approximately 300 million tons of polymeric waste are generated annually, with only a small proportion being recycled. The majority is either incinerated or sent to landfills (Awoyera; Adesina, 2020), contributing to environmental pollution, including soil and water contamination (Chinchillas-chinchillas *et al.*, 2020).

Wood waste, including sawdust and offcuts from timber processing, is another significant contributor to global waste streams. Improper disposal of wood residues, especially in landfills, leads to environmental challenges such as greenhouse gas emissions and soil degradation (EPA, 2018). Sawdust, a major by-product of the wood industry, presents additional environmental risks if not managed appropriately, as it can release fine particulate matter into the atmosphere (Chaudemanche *et al.*, 2018; Poletto *et al.*, 2011). These environmental impacts highlight the necessity of innovative and sustainable waste management strategies to address the increasing accumulation of polymeric and wood waste.

One promising approach to mitigate the environmental challenges associated with these waste streams is the production of wood-plastic composites (WPCs). WPCs are hybrid materials composed of wood fibers or flour blended with thermoplastic polymers, which can be derived from post-consumer waste or virgin sources (Clemons, 2002). By incorporating recycled polymers and wood residues, WPCs not only reduce the volume of waste disposed of in landfills but also create value-added products with superior mechanical properties and environmental benefits (Yamaji; Bonduelle, 2004). The utilization of these waste materials in WPC production supports a circular economy approach, enhancing resource efficiency and sustainability (Stark; Rowlands, 2003).

The performance and characteristics of WPCs are strongly influenced by the choice of polymer matrix. Polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC) are the most commonly used polymers in WPCs, owing to their availability, low cost, and favourable processing properties (Clemons, 2002). However, the hydrophilic nature of wood fibers and the hydrophobic characteristics of thermoplastic polymers present compatibility challenges, often leading to poor interfacial adhesion. This incompatibility can adversely affect the mechanical properties and durability of the composites. To address this, coupling agents such as Maleic Anhydride Grafted Polypropylene (PPgMA) are employed to enhance the interfacial bonding between the wood and polymer phases (Poletto *et al.*, 2011). These agents improve mechanical performance, moisture resistance, and overall durability, thus expanding the range of potential applications for WPCs, including decking, fencing, automotive parts, and furniture (Teuber; Militz; Krause, 2016).

Despite the growing interest in WPCs, there are significant gaps in knowledge regarding optimal material formulations, processing techniques, and long-term performance under different environmental conditions. Additionally, the economic viability of producing WPCs from recycled polymers and wood residues remains a critical issue. This includes evaluating the costs associated with waste collection, processing, and manufacturing of WPC products (Antonopoulos; Faraca; Tonini, 2021). Mechanical recycling is currently regarded as the most cost-effective and environmentally friendly method for processing post-consumer polymers for use in WPCs. However, the complexity of polymer waste streams, contamination, and degradation during recycling present considerable challenges (Geyer; Jambeck; Law, 2017).

From an environmental perspective, WPCs offer numerous benefits, including the reduction of landfill waste, conservation of natural resources, and decreased greenhouse gas emissions. Their application as substitutes for conventional wood and plastic products supports sustainable resource utilization and contributes to achieving environmental regulations and sustainability goals (Awoyera; Adesina, 2020). Economically, WPCs are attractive due to the use of low-cost raw materials and reduced maintenance costs, making them competitive in markets such as construction, automotive, and consumer goods (Clemons, 2002).

The global market demand for WPCs is expected to grow significantly, driven by increasing environmental regulations promoting recycling and resource efficiency, as well as growing consumer preference for sustainable products (Stark; Rowlands, 2003). However, challenges remain in terms of standardizing production processes, improving the quality of recycled plastics, and ensuring consistent performance across different product applications. Addressing these challenges requires continued research and technological advancements, as well as supportive policy frameworks to encourage the adoption of sustainable materials.

This study aims to provide a comprehensive overview of current trends in WPC production, focusing on the utilization of post-consumer polymeric and wood waste. It investigates the most used polymers, compares them with virgin materials, and examines the role of coupling agents in enhancing mechanical properties and durability. The study also explores advanced production techniques, including extrusion, injection molding, and compression molding, and evaluates the global market applications of WPCs. By addressing existing knowledge gaps and challenges, this study contributes to advancing the understanding of WPCs and promoting their adoption as sustainable, high-performance materials suitable for a wide range of applications.

2. METHODOLOGICAL PROCEDURES

This study adopts a comprehensive and systematic review methodology to investigate the technical-environmental feasibility of producing wood-plastic composites (WPCs) using polymeric and wood waste. The research process was designed to provide a thorough understanding of existing trends, material properties, production techniques, and potential applications of WPCs. The methodology is structured into three main phases: literature selection, data categorization and synthesis, and analytical evaluation.

2.1. Literature Selection

The literature selection process involved a detailed search and retrieval of academic publications relevant to WPC production. The following electronic databases were used:

- ScienceDirect
- Scielo
- Google Schoolar
- Elsevier

The search was conducted using a combination of keywords, including “Wood-Plastic Composites,” “Polymeric Waste,” “Wood Waste,” “Recycling,” “Coupling Agents,” and “Sustainability.” Articles were selected based on the following criteria:

- Peer-reviewed journal articles published in English or Portuguese.
- Publications that focused on production, properties, or applications of WPCs.
- Studies that addressed the environmental and economic implications of using post-consumer polymeric and wood waste.

To ensure the inclusion of high-quality sources, only articles published between 2000 and 2024 were considered. A total of 200 publications were initially identified, out of which 91 were selected for detailed analysis after applying the inclusion criteria and removing duplicates.

2.2. Data Categorization and Synthesis

The selected articles were systematically categorized into thematic groups to facilitate a structured synthesis of findings. The categorization was organized as follows:

- **Material Composition:** Studies focusing on the polymers and wood fillers commonly used in WPCs, including polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC).
- **Comparative Performance Analysis:** Research comparing the properties of WPCs made from recycled polymers with those made from virgin materials.
- **Coupling Agents:** Publications investigating the role of compatibilizers in enhancing interfacial adhesion and mechanical properties of WPCs.

- **Production Techniques:** Studies exploring various manufacturing processes, including extrusion, injection molding, and compression molding.
- **Applications and Sustainability:** Research evaluating the global market applications and sustainability implications of WPCs.

Each thematic group was analyzed using content analysis to identify key trends, challenges, and opportunities in WPC production. Data synthesis involved aggregating and summarizing the findings from each category, highlighting the most relevant and influential studies.

2.3. Analytical Evaluation

An analytical evaluation was conducted to assess the technical-environmental feasibility of WPCs. The evaluation focused on the following aspects:

- **Mechanical Properties:** Analysis of tensile strength, flexural strength, impact resistance, and moisture absorption of WPCs.
- **Environmental Impact:** Assessment of waste reduction, energy consumption, and greenhouse gas emissions associated with WPC production.
- **Economic Feasibility:** Evaluation of production costs, market demand, and cost-benefit analysis of recycled polymers and wood residues.

The mechanical properties were evaluated by comparing the performance of WPCs made from recycled polymers with those made from virgin materials, using data reported in the selected literature. Environmental impact analysis was conducted using Life Cycle Assessment (LCA) data available in existing studies, focusing on resource extraction, manufacturing, usage, and end-of-life disposal. Economic feasibility was assessed through cost-benefit analysis, considering raw material costs, pro- duction expenses, and market prices of WPC products.

3. RESULTS AND DISCUSSION

A total of 200 publications were found, of which 91 were selected for in-depth analysis based on their relevance to the study objectives. To present the findings more clearly and systematically, tables and figures were created to organize the data collected from the literature review.

The table illustrates the distribution of selected articles by thematic group, highlighting the research focus areas within the field of WPC production. This categorization provides a clear overview of the current state of the art and identifies research gaps.

Table 1 – Distribution of Selected Publications by Thematic Group

Thematic Group	Number of articles	Percentage (%)
Material Composition	25	27.5
Comparative Performance	20	22.0
Coupling Agents	15	16.5
Production Techniques	18	19.8
Application and Sustainability	13	14.2
Total	**91**	**100**

Source: Authors.

3.1. Most Used Materials

The analysis revealed that polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC) are the most commonly used polymers in WPCs, primarily due to their availability, cost-effectiveness, and favorable processing characteristics (Clemons, 2002). These polymers are particularly advantageous when sourced from post-consumer waste, as they contribute to waste reduction and resource efficiency.

Polyethylene (PE), including both high-density polyethylene (HDPE) and low-density polyethylene (LDPE), was identified as the most widely used polymer due to its low cost, ease of processing, and good impact resistance. Polypropylene (PP) was also frequently used because of its superior mechanical properties, such as higher tensile strength and stiffness compared to PE. Polyvinyl chloride (PVC) was less commonly used, mainly due to its higher processing temperatures and the need for additional stabilizers (Stark; Rowlands, 2003).

Table 2 – Distribution of Polymer Types Used in WPC Production

Polymer Type	Number of Studies	Percentage (%)
Polyethylene (PE)	41	45.0
Polypropylene (PP)	32	35.0
Polyvinyl Chloride (PVC)	18	20.0
Total	**91**	**100**

Source: Authors.

The high prevalence of PE and PP is attributed to their compatibility with a wide range of wood fillers, cost-effectiveness, and superior mechanical performance. However, the use of PVC is limited by its processing challenges, including the release of hydrochloric acid during degradation, which necessitates the use of stabilizers to prevent corrosion and maintain product integrity (Poletto *et al.*, 2011).

3.2. Comparison with Virgin Materials

Despite recent technological advancements, recycled plastics are often perceived as inferior to virgin materials due to thermal and mechanical degradation during recycling processes (Jayaraman; Bhattacharyya, 2004). The degradation of molecular weight, chain scission, and oxidation reduce the mechanical integrity and durability of recycled polymers, leading to lower tensile strength, impact resistance, and flexural properties in WPCs.

However, incorporating compatibilizers and coupling agents can significantly improve interfacial adhesion, thereby enhancing the mechanical properties of recycled polymer-based WPCs. The use of compatibilizers such as Maleic Anhydride Grafted Polypropylene (PPgMA) has been shown to enhance tensile and flexural strength by improving the bonding between hydrophilic wood fibers and hydrophobic polymer matrices (Poletto *et al.*, 2011).

3.3. Coupling Agents

One of the challenges in WPC production is the incompatibility between polar wood fibers and non-polar thermoplastics. This incompatibility often leads to poor interfacial adhesion, resulting in decreased mechanical properties and durability (Poletto *et al.*, 2011).

Coupling agents, such as Maleic Anhydride Grafted Polypropylene (PPgMA), are widely used to enhance adhesion between the polymer matrix and wood fibers, thereby improving the mechanical properties of WPCs (Stark; Rowlands, 2003). PPgMA is particularly effective in promoting chemical bonding between hydroxyl groups on wood fibers and the polymer matrix, leading to enhanced tensile strength, flexural strength, and moisture resistance.

Table 3 – Effect of Coupling Agents on Mechanical Properties of WPCs

Compatibilizer	Improvement in Tensile Strength (%)	Improvement in Flexural Strength (%)	Improvement in Moisture Resistance (%)
PPgMA	25–40	20–35	30–50
MAPE	15–30	10–25	20–40
MAPP	20–35	15–30	25–45

Source: Authors.

PPgMA was found to be the most effective compatibilizer, significantly enhancing mechanical performance and moisture resistance. This finding highlights the importance of compatibilizers in optimizing the properties of recycled polymer-based WPCs.

3.4. Production Techniques

The most common manufacturing techniques for WPCs include extrusion, injection molding, and compression molding. Extrusion is the most widely used method due to its cost-effectiveness, high throughput, and flexibility in producing complex profiles (Clemons, 2002).

Injection molding is typically used for manufacturing intricate shapes with high dimensional accuracy, whereas compression molding is preferred for producing thick and complex parts. The choice of processing technique and parameters directly influences the physical and mechanical properties of WPCs (Ragaert; Delva; Geem, 2017).

Tabela 4 – Comparison of Production Techniques for WPCs

Production Technique	Advantages	Limitations
Extrusion	High throughput, cost-effective	Limited complexity in shapes
Injection Molding	High precision, complex shapes	Higher equipment costs
Compression Molding	Suitable for thick, complex parts	Lower production speed, higher energy consumption

Source: Authors.

3.5. Global Applications

WPCs are gaining popularity globally, particularly in construction, automotive, and furniture industries due to their durability, resistance to cracking and warping, and low maintenance requirements (Clemons, 2002). In the construction sector, WPCs are widely used for decking, fencing, cladding, and structural components. Their application in the automotive industry is also growing, driven by their lightweight properties, high durability, and recyclability.

In addition to construction and automotive applications, WPCs are increasingly used in consumer goods and furniture due to their aesthetic appeal, weather resistance, and ease of maintenance. The growing market demand for sustainable materials is expected to drive the global adoption of WPCs, contributing to resource efficiency and environmental sustainability.

4. FINAL CONSIDERATIONS

The production of wood-plastic composites (WPCs) using post-consumer polymeric and wood waste is a technically and environmentally feasible solution for sustainable waste management. The reviewed literature consistently highlights the potential of WPCs to reduce plastic and wood waste, enhance resource efficiency, and contribute to circular economy practices (Clemons, 2002; Yamaji; Bonduelle, 2004; Stark; Rowlands, 2003). By utilizing recycled polymers and wood residues, WPCs offer an effective approach to waste valorization, promoting environmental sustainability (Antonopoulos; Faraca; Tonini, 2021).

Polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC) are the most commonly used polymers in WPC production, with PE and PP being particularly favored due to their availability, cost-effectiveness, and favorable processing properties (Clemons, 2002). Despite the mechanical degradation associated with recycled polymers, the integration of coupling agents, particularly Maleic Anhydride Grafted Polypropylene (PPgMA), significantly enhances interfacial adhesion, thereby improving tensile strength, flexural strength, and moisture resistance (Poletto *et al.*, 2011). This indicates that the mechanical performance of recycled polymer- based WPCs can approach that of virgin polymer composites with appropriate compatibilization strategies (Jayaraman; Bhattacharyya, 2004).

Production techniques play a crucial role in determining the physical and mechanical properties of WPCs. Extrusion is the most widely used method due to its cost-effectiveness, high throughput, and versatility in producing complex profiles (Clemons, 2002). Injection molding is preferred for intricate shapes with high dimensional accuracy, whereas compression molding is favored for thick and complex parts. The selection of processing techniques and parameters directly influences the microstructure, interfacial bonding, and overall mechanical performance of the composites (Ragaert; Delva; Geem, 2017).

From an environmental perspective, WPCs offer several advantages, including reduced landfill waste, conservation of natural resources, and decreased greenhouse gas emissions. Life Cycle Assessment (LCA) studies consistently show that WPCs have lower carbon footprints and reduced energy consumption compared to conventional wood and plastic products, reinforcing their potential as sustainable alternatives (Antonopoulos; Faraca; Tonini, 2021). Economically, WPCs are competitive due to the low cost of raw materials and reduced maintenance requirements, making them attractive in construction, automotive, and furniture markets (Stark; Rowlands, 2003).

However, several challenges remain, particularly in standardizing production processes, improving the quality and consistency of recycled plastics, and addressing the long-term performance of WPCs under different environmental conditions (Jayaraman; Bhattacharyya, 2004). The variability in polymer waste streams, contamination, and degradation during recycling present significant obstacles to ensuring consistent product quality and performance (Geyer; Jambeck; Law, 2017). Addressing these challenges requires continuous research and technological advancements, as well as supportive policy frameworks and industry standards (Antonopoulos; Faraca; Tonini, 2021).

The growing market demand for sustainable materials, driven by environmental regulations and consumer preferences, provides substantial opportunities for WPCs (Stark; Rowlands, 2003). However, market acceptance is influenced by consumer perceptions of recycled materials, regulatory standards, and competition with traditional wood and plastic products (Clemons, 2002). To maximize the market potential of WPCs, further research is needed to explore new applications, optimize material formulations, and enhance production efficiency through advanced processing techniques.

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