Transforming Machining Waste into Value-Added Materials: A Sustainable Approach for Industrial Innovation and Resource Efficiency

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ABSTRACT

Industrial manufacturing is a major driver of economic development; however, it also generates significant material waste and environmental impact. Wire Electrical Discharge Machining (WEDM), in particular, produces substantial quantities of brass wire waste that are typically discarded after a single use. This study investigates the direct reuse of WEDM brass wire waste as a reinforcement material in composite manufacturing, eliminating the need for energy-intensive recycling processes. Composite samples were fabricated and evaluated through mechanical testing in accordance with ASTM standards. The incorporation of WEDM brass wire waste significantly enhances the mechanical performance of the composite system. At an optimal loading of approximately 20 wt.% (particulate form), the developed composite achieved tensile strength of up to 332 MPa, compared to 19.7 MPa for neat epoxy. This represents a substantial improvement in load-bearing capability, primarily due to enhanced stress transfer and crack resistance mechanisms introduced by the metallic reinforcement. More importantly, the optimized composite demonstrates tensile performance comparable to, and slightly exceeding, conventional fibreglass-reinforced epoxy (GFRE), highlighting its potential as a viable alternative reinforcement material.Overall, this work presents a potentially scalable approach, subject to further industrial validation and process optimization. The findings contribute to SDG 12 (Responsible Consumption and Production), SDG 9 (Industry, Innovation and Infrastructure), and SDG 13 (Climate Action).

Keywords: Circular Economy; Sustainable Manufacturing; Waste Utilization; Composite Materials; Machining Waste

INTRODUCTION

Industrial manufacturing plays a critical role in global economic development; however, it also contributes significantly to material waste generation and environmental degradation. The increasing volume of industrial by-products has intensified concerns related to resource depletion, waste management, and sustainability. Conventional production systems are predominantly based on a linear “take–make–dispose” model, which leads to inefficient resource utilization. This limitation has driven a transition toward circular economy approaches that emphasize resource efficiency, waste minimization, and material reuse (Geissdoerfer et al., 2017; Ghisellini et al., 2016).

Among advanced manufacturing technologies, Wire Electrical Discharge Machining (WEDM) is widely utilized due to its ability to produce high-precision and geometrically complex components. Despite its advantages, WEDM generates substantial quantities of brass wire waste, which is typically discarded after a single use. This practice results in both economic loss and environmental burden. Consequently, there is increasing interest in developing effective strategies for reutilizing such waste within industrial systems (Duflou et al., 2012).

In parallel, composite materials have become indispensable in sectors such as automotive, construction, and structural engineering due to their high strength-to-weight ratio and design flexibility. However, conventional composite manufacturing relies heavily on virgin raw materials, leading to increased energy consumption and resource demand. To address these challenges, recent research has explored the incorporation of recycled and waste-derived materials into composite systems as partial replacements for traditional reinforcements, with the aim of enhancing sustainability without compromising mechanical performance (Pickering, 2006; Pimenta & Pinho, 2011).

The circular economy framework provides a systematic approach for addressing these issues by promoting the retention and reuse of materials within production cycles. In this context, machining waste should be viewed not as a disposal challenge but as a potential resource for value-added applications (Kirchherr et al., 2017). However, existing studies are largely limited to conventional recycling approaches involving remelting or material reprocessing, which are often energy-intensive. Furthermore, there is a lack of comprehensive experimental validation on the direct reuse of machining waste, particularly in terms of comparative mechanical performance, sustainability benefits, and economic feasibility.

To address these gaps, this study investigates the direct reutilization of WEDM brass wire waste as a reinforcement material in composite manufacturing. The research emphasizes a low-processing approach, aiming to minimize energy consumption while maintaining material functionality. Mechanical performance is evaluated through standardized testing, supported by microstructural analysis and preliminary cost–environment assessment.

The primary objective of this work is to develop a practical and scalable method for transforming machining waste into functional composite materials while reducing material costs and dependence on virgin resources. By integrating material performance evaluation with sustainability considerations, this study aims to demonstrate that direct waste reutilization can serve as an effective strategy for advancing sustainable manufacturing, resource efficiency, and industrial innovation.

LITERATURE REVIEW

The increasing global emphasis on sustainability has significantly influenced research and practice in manufacturing, particularly in the areas of waste management, material innovation, and resource efficiency. Conventional industrial systems have long been characterized by a linear production model, where materials are extracted, processed, and eventually discarded. Recent studies have therefore advocated a transition toward circular economy models that prioritize the reuse and recovery of materials within production systems (Geissdoerfer et al., 2017; Ghisellini et al., 2016).

Sustainability in Composite Materials

Despite these advantages, concerns have emerged regarding their environmental impact, particularly in relation to raw material consumption and end-of-life disposal. Traditional composite manufacturing relies heavily on virgin materials and involves processes that are often energy-intensive. As a result, researchers have increasingly explored the incorporation of recycled and waste-derived materials as partial replacements for conventional reinforcement phases (Pickering, 2006).

Studies have shown that hybrid composites containing recycled fillers can maintain acceptable performance while offering improved environmental outcomes. The integration of secondary materials not only reduces the demand for virgin resources but also enhances the overall sustainability profile of composite systems (Pimenta & Pinho, 2011). These developments indicate a growing shift from purely performance-driven material design toward approaches that consider environmental and lifecycle aspects.

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Waste Recycling and Utilization in Materials Engineering

This approach aligns closely with circular economy principles by extending material lifecycles and maximizing resource efficiency (Kirchherr et al., 2017).

In materials engineering, various forms of waste—including agricultural residues, plastic waste, and metallic by-products—have been successfully used as reinforcement or filler materials in composite systems. Metallic wastes, in particular, provide additional advantages due to their inherent strength and durability. Research has demonstrated that incorporating metal particles or fibres into polymer matrices can improve mechanical properties such as stiffness, impact resistance, and wear performance while simultaneously reducing material costs (Duflou et al., 2012).

Industrial Reuse Practices and Machining Waste

Machining processes, including cutting, milling, and Electrical Discharge Machining (EDM), produce metallic waste that is often treated as scrap rather than a potential resource. This is particularly evident in WEDM operations, where brass wire is typically discarded after a single use cycle.

While general research on metal recycling is well established, the direct reuse of machining waste in advanced material systems remains relatively limited. Existing studies have primarily focused on remelting or conventional recycling rather than material reuse in composite applications. This represents a missed opportunity, as machining waste can often be utilized in its existing form with minimal processing, thereby reducing energy consumption and environmental impact.

The concept of industrial symbiosis supports this approach by promoting the exchange of waste materials between different production systems. By integrating waste streams into new applications, industries can reduce disposal requirements while simultaneously improving resource efficiency and economic performance (Ghisellini et al., 2016).

Green Manufacturing and Environmental Management

The integration of waste materials into manufacturing aligns directly with green manufacturing objectives. By substituting virgin materials with recycled inputs, industries can lower energy consumption, reduce emissions, and minimize waste generation. Furthermore, such strategies provide opportunities for cost savings and improved competitiveness, making sustainability both an environmental and economic priority (Duflou et al., 2012). Lifecycle assessment studies indicate that direct reuse strategies has the potential to reduce energy consumption based on trends reported in the literature; however, quantitative validation through life cycle assessment is required. However, economic feasibility and scalability assessments remain insufficiently explored.

Synthesis and Research Gap

Despite existing work on recycled composites, while previous studies have explored recycled metallic fillers, limited work has focused on the direct reuse of WEDM brass wire waste without reprocessing. Most studies focus either on conventional recycling or on non-metallic waste sources, leaving a gap in understanding the potential of metallic machining by-products as functional reinforcement materials. Previous studies have shown that recycled metallic fillers can achieve mechanical properties comparable to glass fibre composites at optimized loading; however, direct comparisons remain limited.

This study addresses this gap by exploring the transformation of WEDM brass wire waste into value-added composite materials. Unlike traditional approaches that treat waste as a disposal challenge, this research considers it as a resource with both functional and economic value. By integrating machining waste into composite systems, the study contributes to advancing sustainable manufacturing practices while offering a practical model for industrial waste reutilization. However, these studies largely focus on processed waste materials rather than direct reuse of machining waste, highlighting a limitation in existing approaches.

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METHODOLOGY

This study employs an experimental approach to evaluate the feasibility of utilizing WEDM brass wire waste in composite materials.

Materials Selection and Preparation

The primary materials used in this study include an epoxy resin matrix, glass fibre reinforcement, and recycled brass wire obtained from Wire Electrical Discharge Machining (WEDM) processes. The brass wire had an average diameter of 0.25 mm. Short fibres were cut to lengths of 1-10 mm, while long fibres were cut to lengths of 10–50 mm. Material densities were recorded for accurate volume fraction calculations.

The brass wire waste, primarily composed of copper and zinc, was collected directly from industrial WEDM operations as shown in Figure 1. Prior to use, the waste material underwent a cleaning process to remove contaminants such as machining residues and surface impurities. The cleaned wire was then processed into three different forms: long fibres, short fibres, and fine particulates.

The use of minimal processing for the waste material reflects the study's objective of promoting energy-efficient and low-cost reuse strategies, which are consistent with sustainable manufacturing principles (Duflou et al., 2012).

(a) (b) (c)

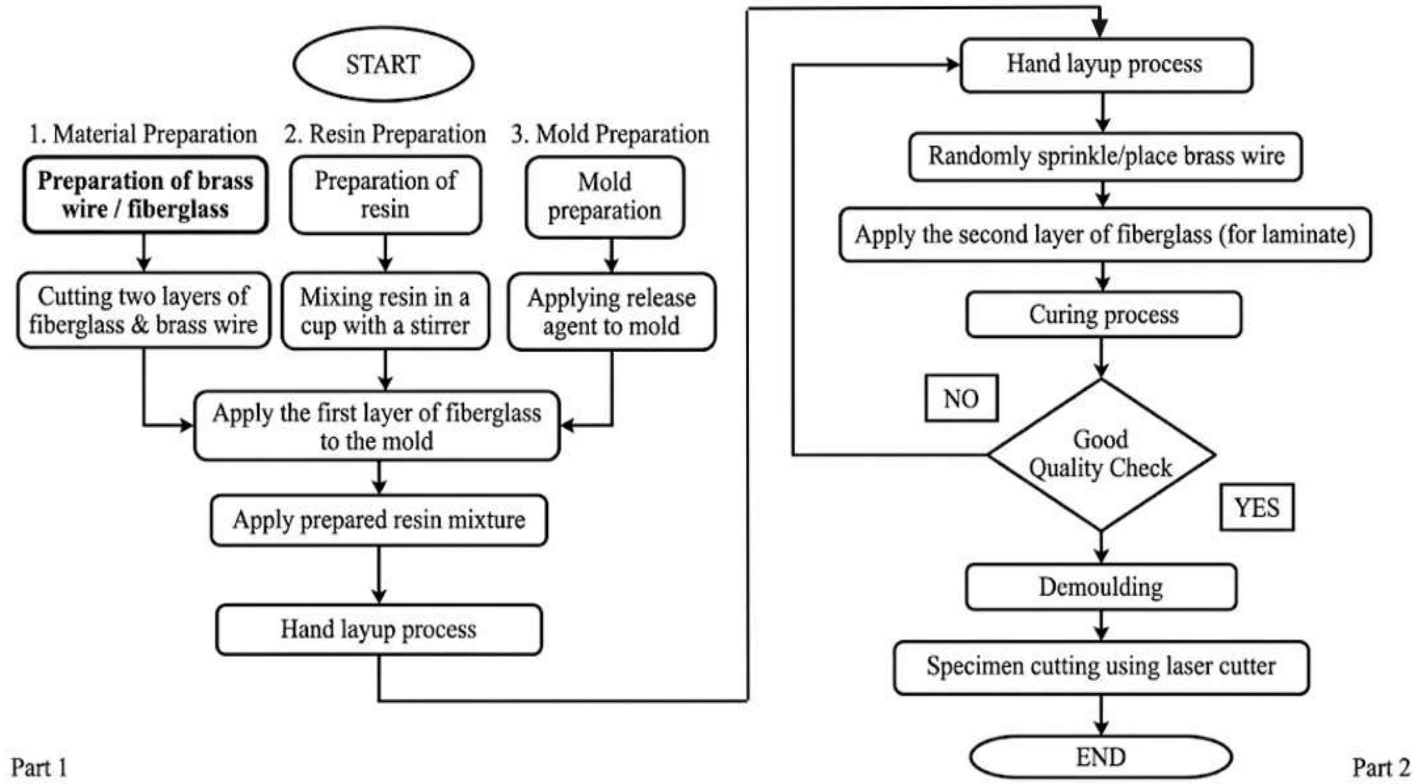
Figure 1: (a) WEDM brass wire (b) Scrap wire collected (c) Laminate composite panels

Composite Fabrication Process

Composite samples were fabricated using the hand lay-up technique, as shown in Figure 2, which was selected due to its simplicity, cost-effectiveness, and compatibility with existing industrial practices. This method is widely used in composite manufacturing and allows for easy integration of different reinforcement materials without requiring specialized equipment (Pickering, 2006).

Different weight percentages of brass wire waste were incorporated into the composite samples to evaluate their effect on performance. The range of waste content was selected based on preliminary observations and practical considerations related to material handling and dispersion.

Figure 2: Flowchart of the fabrication process for brass wire-reinforced fibreglass composites.



Manual mixing was performed to achieve uniform distribution, with efforts made to minimize agglomeration and void formation. which are known to reduce composite performance (Pimenta & Pinho, 2011). The hand lay-up technique has been widely used for fabricating hybrid composites due to its simplicity and adaptability (Bhoi & Satapathy, 2024).

Experimental Design and Variable Control

The experimental design focused on investigating the influence of waste content and type/form of reinforcement on composite behavior. Key variables considered in this study include: waste loading percentage, physical form of reinforcement (long, short, particulate), and dispersion quality within the matrix

This controlled approach allows comparative evaluation of the influence of reinforcement parameters on composite performance. Each configuration as shown in Table 1 was fabricated with a minimum of three replications to ensure reproducibility and consistency of results.

Table 1. Experimental Sample Configurations for WEDM Brass Wire Reinforced GFRE Composites

Samples			**Brass wire waste, %**	**Brass wire waste, g**	**Woven Fibreglass, g**	**Epoxy Resin Ratio**	
						Epoxy	**Hardener**
Epoxy (EP)			0	0	0	46.74	13.26
Waste Wire (WW)			100	60	0		
Fibreglass (FG)			0	0	60		
L10	S10	P10	10	6	60		
L20	S20	P20	20	12			
L30	S30	P30	30	18			
L40	S40	P40	40	24			
L50	S50	P50	50	30			
L60	S60	P60	60	36			

L70	S70	P70	70	42			
L80	S80	P80	80	48			
L90	S90	P90	90	54			

Mechanical Testing and Performance Evaluation

The fabricated composite samples were subjected to mechanical testing to evaluate their structural performance. The primary tests carried out include: tensile strength testing, flexural strength testing and impact testing.

Mechanical testing was conducted in accordance with established ASTM standards to ensure reproducibility and comparability with existing studies.

Tensile testing was performed according to ASTM D3039 using an Instron universal testing machine (UTM). Specimens were prepared with dimensions of 250 mm × 25 mm × 3 mm and tested at a crosshead speed of 2 mm/min.

Flexural testing followed ASTM D790 using a three-point bending configuration with specimen dimensions of 127 mm × 12.7 mm × 9 mm and a loading rate of 2 mm/min. Impact strength was evaluated using the Charpy impact test in accordance with ASTM D6110. Notched specimens were used to assess energy absorption characteristics.

For each composite configuration, a minimum of five specimens were tested. The average values and standard deviations were calculated to ensure statistical reliability. The results obtained from these tests were not only analyzed for performance trends but also interpreted in relation to reinforcement distribution, bonding quality, and material interaction mechanisms.

Microstructural Analysis

Observations were conducted using a LEICA DVM6 digital microscope under reflected light mode. Magnifications ranging from 50× to 500× were applied depending on the feature of interest. At lower magnification, overall fibre orientation and void distribution were assessed, while higher magnification was used to evaluate fibre pull-out, matrix cracking, and bonding quality. Images were captured digitally and annotated with arrows and labels to highlight critical features.

Sustainability and Practical Assessment

In addition to mechanical performance, the study incorporates a sustainability-oriented evaluation of the proposed approach. This includes: assessment of waste reutilization potential, reduction in reliance on virgin materials, consideration of processing simplicity and scalability as well as evaluation of cost-saving opportunities. The methodology therefore extends beyond traditional materials testing by integrating industrial and environmental considerations. This holistic approach aligns with green manufacturing and circular economy frameworks, where both technical performance and sustainability outcomes are equally important (Ghisellini et al., 2016).

Data Analysis Approach

The collected data were analyzed using comparative and trend-based methods to identify optimal reinforcement conditions. Emphasis was placed on: identifying peak performance zones, understanding performance decline at higher loadings and evaluating trade-offs between strength and sustainability. This approach supports a more comprehensive understanding of the role of waste materials in composite systems.

RESULTS AND DISCUSSION

The experimental results suggest that machining waste in the form of WEDM brass wire can be effectively utilized as a reinforcement material in composite manufacturing. The results shown in Table 2 demonstrate the

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feasibility of using WEDM brass wire waste as reinforcement in composite materials. These observations are discussed in terms of mechanical behaviour, waste reutilization efficiency, and broader industrial and environmental implications.

Table 2: Simplified Performance Summary (EP, WW, GFRE, GBRE Hybrids)

Composite Type	Tensile Strength (MPa)	Flexural Strength (MPa)	Flexural Displacement (mm)	Areal Energy Absorption (kJ/m²)
EP	~19.7	~22.8	~15.0	~331 (average)
WW	~17.8	~107 (average)	~12.6	~383 (average)
GFRE (FG)	~258 (average)	~197 (average)	~12.8	~318 (average)
Long (L10–L90)	333 → 48	392 → 8	11.5 → 8.8	513 → 97
Short (S10–S90)	235 → 201	113 → 52	11.3 → 8.9	274 → 260
Particulate (P10–P90)	254 → 223	182 → 169	9.2 → 5.5	325 → 313

Effect of Waste Content on Mechanical Performance

The variation of mechanical properties with increasing brass wire content reveals a distinct trend characterized by initial improvement followed by gradual decline.

As shown in Figure 3(a)–(c), the mechanical performance of the composites varies significantly with both reinforcement form and waste content. Tensile strength (Figure 3(a)) peaks at 10% for long fibres, while short and particulate reinforcements exhibit optimal performance at 40% and 50%, respectively. A similar trend is observed for flexural strength (Figure 3(b)), whereas impact strength (Figure 3(c)) demonstrates improved energy absorption at moderate reinforcement levels followed by a gradual decline. These results support the conclusion that optimal mechanical performance depends on both reinforcement morphology and loading ratio.

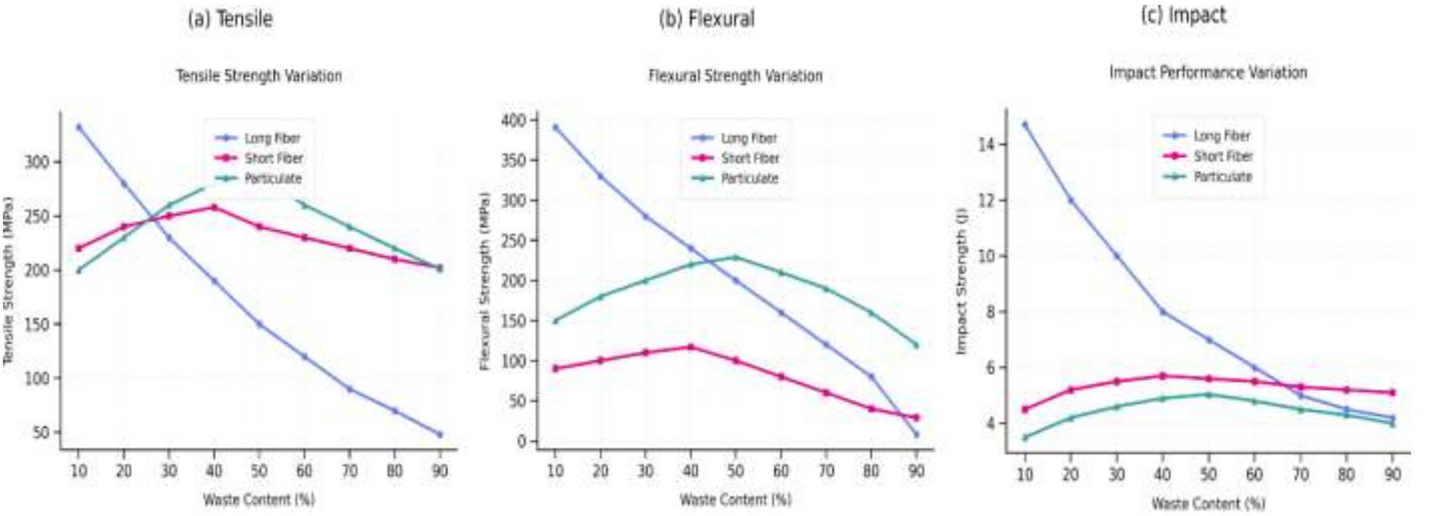

Figure 3: Mechanical performance of WEDM brass wire–reinforced GFRE composites: (a) tensile strength, (b) flexural strength, and (c) impact strength as a function of waste content.

Tensile Performance

The tensile strength results indicate that the incorporation of brass wire waste leads to enhanced load-bearing capacity up to an optimal reinforcement level. As the waste content increases from 0% to approximately 20%, tensile strength improves significantly due to better stress transfer between the matrix and reinforcement. The presence of metallic inclusions contributes to improved crack resistance and load distribution.

Beyond the optimal loading, a reduction in tensile strength is observed. This decline is primarily attributed to poor dispersion and agglomeration of the waste particles, which create stress concentration zones and weaken the interfacial bonding. Similar behaviour has been reported in previous studies involving recycled metal fillers, where excessive reinforcement leads to reduced mechanical integrity due to clustering effects (Pimenta & Pinho, 2011).

This highlights the importance of identifying an optimal reinforcement window rather than maximizing waste content. The observed trend is consistent with previous studies on hybrid composites incorporating metallic fillers, where optimal loading enhances stress transfer before agglomeration reduces performance (Vinayaka et al., 2022; Dani & Venkateshwaran, 2020).

Impact Performance

A similar trend is observed in the impact strength results. The introduction of brass wire waste enhances the composite's ability to absorb energy, particularly at moderate loading levels. Previous studies have demonstrated that metallic fillers improve impact resistance through crack deflection mechanisms at moderate loadings (Joseph & Panneerselvam, 2021).

At higher reinforcement levels, however, impact strength decreases due to reduced matrix continuity and insufficient bonding between phases. These findings align with earlier work on composite systems incorporating recycled materials, where mechanical performance is highly sensitive to reinforcement dispersion and matrix compatibility (Pickering, 2006).

Influence of Reinforcement Type/Form of Reinforcement

The form of the brass wire waste (long, short, particulate) plays a significant role in determining composite performance. Long fibres provide improved reinforcement efficiency due to their ability to bridge cracks and transfer loads effectively, while shorter and particulate forms enhance isotropy but may contribute less to structural strength.

As illustrated in Figure 4, a clear trade-off exists between mechanical performance and sustainability benefits as the proportion of WEDM brass wire waste increases. Mechanical performance improves initially, reaching an optimum at approximately 20% waste content due to enhanced load transfer and reinforcement interaction. Beyond this level, performance declines as a result of agglomeration, poor dispersion, and weakened interfacial bonding. In contrast, sustainability benefits increase progressively with increasing waste content, reflecting reduced reliance on virgin materials and improved waste reutilization. This relationship highlights the importance of optimizing reinforcement content to achieve a balanced performance–sustainability outcome rather than maximizing waste incorporation.

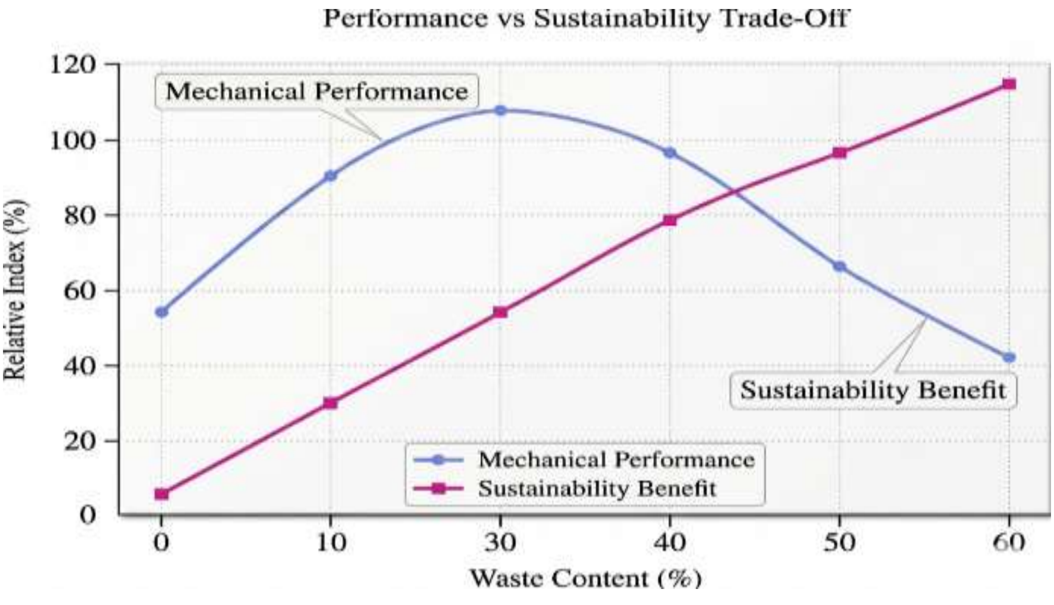

Figure 4. Performance–sustainability trade-off as a function of WEDM brass wire waste content.

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Optical microscopy observations provide direct evidence of the microstructural features influencing mechanical performance. Specimen S40, as shown in Figure 5, which contains 40% EDM short brass wire waste, shows a relatively uniform internal structure. The embedded fibres are visibly aligned and uniformly distributed within the matrix. This arrangement allows the resin to fully penetrate and bond with the short fibres, creating a cohesive composite material. Additionally, the brass wires appear to be well integrated, with minimal signs of voids or resin-starved zones. The microstructure suggests improved fibre-matrix interface, which is crucial for effective stress transfer during tensile loading.

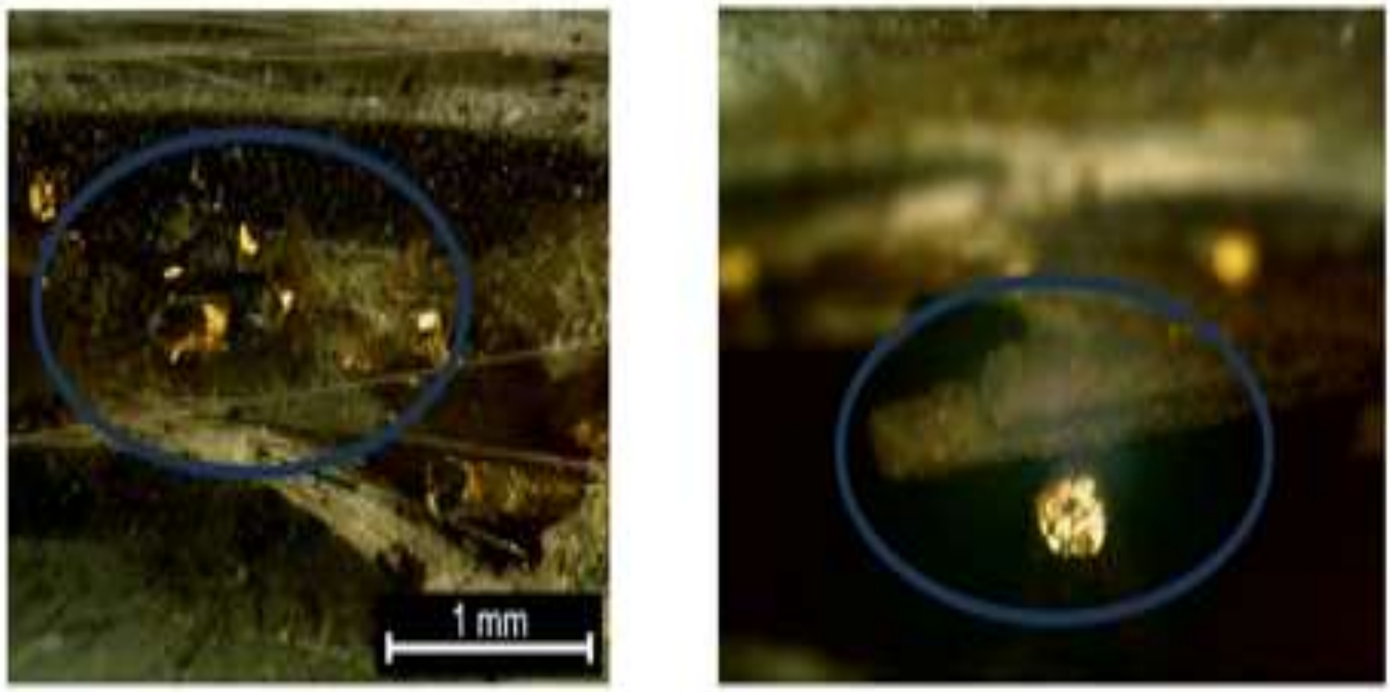

Figure 5: Optical microscopy images (a): S40, (b): S90

On the other hand, the second image, corresponding to S90, which contains 90% EDM wire waste, exhibits a less desirable structure. The micrograph reveals scattered brass particles and uneven fibre distribution, along with apparent voids and areas where the resin appears to be lacking. These inconsistencies result in poor bonding between the fibres and the matrix. The excessive inclusion of short brass wire in S90 limits the ability of the resin to fully coat and encapsulate the fibres, thus weakening the overall structure and performance of the composite.

These observations are consistent with Mahmud et al. (2024), who emphasized that void-free interfaces enhance mechanical properties, and with Ramesh (2022), who linked fibre pull-out mechanisms to improved toughness. By integrating morphological evidence with mechanical results, the discussion confirms that microstructural integrity is the key determinant of composite performance.

The results suggest that a combination of reinforcement forms may offer an optimal balance between strength and processability. This observation is consistent with hybrid composite theories, where multiple reinforcement scales improve mechanical performance through complementary mechanisms (Pimenta & Pinho, 2011).

Comparison With Traditional Reinforcement Materials

A comparative evaluation was conducted between the developed composite, neat epoxy (EP), and conventional fibreglass-reinforced epoxy (GFRE). As shown in Table 3, neat epoxy exhibits low tensile strength (~19.7 MPa), while GFRE achieves significantly higher strength (~258 MPa) due to effective fibre reinforcement.

The developed composite, incorporating WEDM brass wire waste at an optimal content of approximately 20 wt.%, achieved tensile strength of up to ~332 MPa. This represents an improvement of more than 15 times compared to epoxy and approximately 28% higher than GFRE, as summarized in Table 3.

Table 3: Comparative Mechanical Performance of Developed Composite and Conventional Reinforcement Materials

Material	Tensile Strength (MPa)	Relative Performance
Epoxy (EP)	19.7	Baseline
GFRE (Fibreglass)	258	~13× higher than EP
Developed Composite (20%)	332	~16× higher than EP; ~28% higher than GFRE

These results indicate that brass wire waste can serve as an effective alternative reinforcement material, capable of delivering comparable or superior mechanical performance. However, performance is dependent on proper dispersion and optimal loading, as excessive waste content can reduce composite integrity.

Overall, the findings confirm the potential of machining waste as a viable and sustainable substitute for conventional composite reinforcement materials. This quantitative comparison demonstrates the competitive performance of the developed composite relative to conventional reinforcement systems.

Comparison with Existing Studies

Previous studies on waste-based composites have reported similar trends, particularly regarding the existence of an optimal filler content. For example, research on recycled metallic particles has shown that moderate inclusion improves stiffness and strength, while excessive addition leads to reduced performance due to poor interfacial bonding (Duflou et al., 2012).

However, most existing work focuses on remelted or processed materials rather than direct reuse. In contrast, this study demonstrates that WEDM brass wire waste can be reused with minimal processing, reducing both energy requirements and environmental impact. The optimized composite (20 wt.%) achieved tensile strength comparable to fibreglass composites, demonstrating its viability as an alternative reinforcement material.

Furthermore, unlike many studies that emphasize laboratory-scale results, this work considers industrial practicality by using a fabrication method that is compatible with existing manufacturing systems. This practical orientation strengthens the relevance of the findings for real-world applications. Compared with previous studies on recycled metallic fillers, the present results demonstrate comparable or improved performance at optimized reinforcement levels. For instance, similar tensile enhancement trends have been reported in glass–epoxy systems reinforced with metallic waste particles, where optimal loading ranges between 10–50 wt.% (Chiracu et al., 2024; Soudagar et al., 2024). However, unlike conventional approaches, this study emphasizes direct reuse of machining waste, reducing processing complexity.

Waste Reutilization Effectiveness

The results are consistent with WEDM brass wire waste can be successfully transformed into a functional reinforcement material. The ability to utilize the waste in different physical forms enhances its versatility and applicability across various composite systems. The effectiveness of waste reutilization can be evaluated based on: mechanical performance improvement, ease of processing and integration as well as reduction of material loss. These findings support the concept of waste utilization, where industrial by-products are converted into higher-value applications rather than being discarded. This aligns with circular economy principles, which emphasize maintaining material value within the production cycle (Geissdoerfer et al., 2017).

Industrial Practicality and Limitations

The concept of waste as a resource aligns with industrial ecology frameworks that promote circular material flows (Ben & Olubambi, 2024).

Despite these challenges, the simplicity of the fabrication process and the availability of waste materials make the approach shows potential for industrial adoption. The use of existing manufacturing techniques ensures that implementation can be achieved with minimal modification to current production systems.

Integrated Discussion: Performance vs Sustainability Trade-Off

A key contribution of this study lies in demonstrating that material performance and sustainability objectives can be achieved simultaneously, provided that waste content is properly optimized. Analysis suggests that there is a critical balance between mechanical strength, processability and sustainability benefits.

At optimal reinforcement levels, the composite system delivers both improved performance and environmental advantages. However, exceeding this threshold leads to diminishing returns, highlighting the importance of controlled design in waste-based material systems. In addition to technical performance, the findings highlight the broader relevance of waste reutilization in addressing contemporary sustainability challenges. The results demonstrate that engineering design decisions can directly influence environmental outcomes, reinforcing the importance of integrating sustainability considerations into material development. This aligns with global efforts to promote sustainable industrial practices and circular resource use.

Cost–Benefit Analysis

A preliminary cost–benefit analysis was conducted to evaluate the economic feasibility of utilizing WEDM brass wire waste. The use of waste material significantly reduces the reliance on virgin reinforcement materials such as fibreglass. Based on current market estimates, fibreglass costs approximately RM 15-30/kg, while the brass wire waste is available at minimal or no cost.

By replacing up to 20–40% of conventional reinforcement with machining waste, the overall material cost can be reduced by approximately 20–30%. Additionally, savings in waste disposal costs (estimated at RM 1–3/kg) further enhance economic benefits.

These findings indicate that the proposed approach is not only environmentally sustainable but also economically attractive for industrial implementation. It should be noted that this analysis is preliminary and does not include processing-related costs such as cleaning, cutting, and dispersion of waste materials. A detailed economic model is recommended for future research.

Sustainability And Industrial Implications

The results of this study demonstrate that the reutilization of machining waste can transcend conventional waste management strategies and provide a viable pathway toward sustainable industrial innovation. By converting WEDM brass wire waste into functional composite reinforcement, the approach integrates environmental responsibility with material performance, aligning closely with the principles of circular economy and green manufacturing. The proposed approach has the potential to reutilize up to 10–50% of machining waste within composite systems, depending on application requirements, thereby significantly reducing landfill disposal and dependence on virgin materials.

Resource Efficiency and Circular Economy Integration

A key sustainability implication of this work lies in its contribution to resource efficiency. In contrast, the approach presented in this study retains the functional value of metallic waste within the production cycle, thereby reducing the need for new material extraction.

This strategy directly supports circular economy principles, which emphasize maintaining material value through reuse, recycling, and lifecycle extension (Geissdoerfer et al., 2017; Ghisellini et al., 2016). Unlike conventional recycling processes that often require energy-intensive remelting or refining, the direct incorporation of machining waste into composite materials minimizes additional processing, resulting in a more resource-efficient system.

However, previous studies on circular material use have often been limited to conceptual frameworks or large-scale industrial systems, with less focus on practical material-level applications. This study addresses that limitation by providing a tangible, experimentally validated pathway for integrating waste materials into advanced composite systems.

Reduction of Industrial Waste and Environmental Burden

The reuse of WEDM brass wire waste contributes significantly to reducing industrial waste accumulation. By redirecting this waste into composite production, the study offers an approach that reduces landfill dependency and associated environmental risks.

Research in sustainable manufacturing has consistently shown that material substitution using recycled inputs can significantly reduce environmental footprints when compared to conventional production methods (Duflou et al., 2012). The approach enables reutilization of machining waste, significantly reducing landfill disposal.

Despite these advantages, existing literature often treats waste reduction and material performance as separate objectives. In contrast, the findings of this study demonstrate that both objectives can be achieved simultaneously when waste incorporation is optimized.

Economic and Industrial Value Creation

Reduced waste disposal requirements lead to savings in waste management and regulatory compliance expenses. Such waste-to-resource strategies are recognized as key enablers of circular economy transitions

(Caldera et al., 2020; Ben & Olubambi, 2024).

The concept of “waste as a resource” has been widely discussed in industrial ecology literature, highlighting the potential of waste streams to create new value chains and business opportunities (Kirchherr et al., 2017).

However, many previous studies emphasize high-technology recycling solutions that may not be feasible for wide industrial adoption. In contrast, the approach presented in this work relies on simple and industry-compatible fabrication techniques, making it more accessible for broader industrial implementation. This scalability represents a significant advantage over more complex or capital-intensive waste management strategies.

Life Cycle Assessment (LCA) and Environmental Impact

Unlike conventional recycling, which requires energy-intensive remelting processes, the direct reuse approach eliminates secondary processing stages. Based on literature-reported trends in metal recycling and reuse systems, this approach is expected to significantly reduce energy consumption and carbon emissions compared to conventional recycling routes. However, these values are indicative estimates rather than results of a formal Life Cycle Assessment (LCA).

A comprehensive LCA, including system boundary definition, inventory analysis, and impact assessment, is required to quantify these benefits accurately and is therefore recommended as future work. Reuse of machining waste is expected to reduce carbon emissions based on existing literature trends by eliminating energy-intensive extraction and refining processes. Each kilogram of brass waste reused is estimated to avoid approximately 4 kg CO_2-equivalent emissions, demonstrating a clear environmental advantage over virgin material production.The approach also contributes to significant waste reduction by diverting machining waste from landfills and reintegrating it into the production cycle (Graedel et al., 2015)

Industrial Practicality and Scalability

Furthermore, the continuous availability of WEDM brass wire waste in machining industries provides a reliable supply of raw material, supporting scalability and long-term application. This contrasts with some waste-based material solutions that face limitations due to inconsistent or geographically constrained waste sources.

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The scalability of the proposed approach is supported by several factors. First, WEDM brass wire waste is continuously generated in machining industries, ensuring a stable and reliable raw material supply. Second, the fabrication method (hand lay-up) is widely used in industry and does not require significant capital investment or specialized equipment, making adoption feasible for small and medium-scale manufacturers.

However, challenges related to uniform dispersion and process control at higher reinforcement levels remain and may affect large-scale production consistency. Similar limitations have been reported in previous studies involving recycled fillers, where process control becomes increasingly important as waste incorporation increases (Pimenta & Pinho, 2011). Therefore, industrial-scale validation and process optimization (e.g., automated mixing and advanced moulding techniques) are required to ensure consistent quality and manufacturability in future applications.

Sustainability–Performance Trade-Off

A key insight from this study is the identification of a sustainability–performance trade-off. While increasing waste content improves resource efficiency and reduces environmental impact, it does not necessarily lead to continuous improvement in material performance. Instead, an optimal range of waste incorporation must be identified to balance mechanical integrity and sustainability benefits.

Table 4: Relationship between waste content, performance, and sustainability indicators

Waste Content (%)	**Mechanical Performance (Relative)**	**Sustainability Benefit (Relative)**	**Processing Quality**	**Overall Assessment**
0 (Baseline)	Moderate	Very Low	Excellent	Conventional material
10	High (↑)	Low–Moderate	Excellent	Improved performance
20 (Optimum)	Very High (Peak ↑↑)	Moderate	Good	**Optimal balance**
30	High (↓ slightly)	High	Moderate	Acceptable trade-off
40	Moderate (↓ reduction)	Very High	Poor	Performance compromised
50	Low (↓ significant)	Maximum	Very Poor	Not recommended

This balance between performance and sustainability represents a critical design consideration for future composite materials and highlights the importance of integrating engineering and environmental perspectives.

Contribution to Sustainable Manufacturing Research

While previous research has extensively explored recycling technologies and environmental management frameworks, fewer studies have provided experimentally validated approaches that directly integrate waste into functional material systems.

By focusing on machining waste—an underexplored yet widely available resource—this work expands the scope of sustainable material research and provides a model that can be replicated across different industrial sectors.

Moreover, the study supports the broader transition toward cleaner production systems, where waste generation is minimized and materials are continuously repurposed within the production cycle. This study demonstrates a practical approach for integrating machining waste into functional composite materials.

CONCLUSION

This study shows that WEDM brass wire waste can be directly reused as reinforcement in composite materials, with optimal performance achieved at approximately 20 wt.% loading. The developed composites exhibit properties comparable to conventional fibreglass systems while reducing material cost, energy consumption, and waste generation. The simplicity and scalability of the process support its industrial applicability. Despite challenges in dispersion at higher loadings, the findings demonstrates the potential of machining waste as a value-added resource.

Limitations And Future Work

Despite the promising results, this study is limited to laboratory-scale experimentation and short-term mechanical performance evaluation. Future research should focus on conducting a comprehensive Life Cycle Assessment (LCA) to quantitatively evaluate environmental impacts, including carbon emissions, energy consumption, and waste reduction. In addition, detailed economic modelling and industrial-scale validation are required to assess commercial feasibility and manufacturing scalability.

These developments will enhance the robustness and practical applicability of waste-based composite systems in real industrial environments.

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