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Mechanical Performance and Engineering Applications of Waste Plastic–Derived Materials: A Structured Review

Abhinab Borah
Department of Mechanical Engineering, Dibrugarh University Institute of Engineering and Technology (DUIET), Dibrugarh University,Assam, India
E-mail: borahabhinab233@gmail.com
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Abstract - **The increasing generation of plastic waste presents significant environmental challenges while simultaneously creating opportunities for the development of sustainable engineering materials. In recent years, waste-plastic–derived materials have gained considerable attention as potential alternatives to conventional polymers and composites in engineering applications. This paper presents a critical review of the mechanical performance and industrial applicability of materials derived from waste plastics, with particular emphasis on engineering systems. A systematic qualitative review methodology is adopted, encompassing peer-reviewed literature on mechanically recycled polymers, plastic-based composites, and plastic-modified construction materials. Key mechanical properties-including tensile, compressive, flexural, impact, fatigue, and creep behavior-are examined, along with the influence of recycling processes, material composition, and reinforcement strategies on performance. The reviewed studies indicate that unreinforced recycled plastics generally exhibit reduced mechanical properties compared to virgin polymers due to degradation during reprocessing. However, significant performance improvements are consistently reported through fiber reinforcement, hybrid composite design, nanofiller incorporation, and optimized processing techniques. The applicability of waste-plastic–derived materials in the construction, automotive, consumer goods, energy, and public utility sectors is discussed in relation to technical, economic, and regulatory considerations. In addition, key research directions emphasizing advanced recycling technologies, material optimization, standardization, and circular-economy integration are identified. The findings establish performance trends, design strategies, and application boundaries for waste-plastic–derived materials in engineering systems.**
Keywords: **Waste Plastic–Derived Materials, Mechanical Properties, Recycled Polymers, Composite Reinforcement, Sustainable Engineering Materials**

I. INTRODUCTION

A. Global Plastic Proliferation and Environmental Engineering Constraints

Plastics have become an indispensable cornerstone of modern industrial infrastructure, favored for their low density, inherent corrosion resistance, and high degree of processability [1], [2]. Over the past several decades, global production has followed an exponential trajectory, driven by rapid urbanization and the expansion of the packaging, automotive, and construction sectors [3], [4]. However, the same molecular durability and chemical stability that grant polymers their engineering utility simultaneously create critical end-of-life management challenges [5]. A significant volume of post-consumer plastic waste continues to accumulate in landfills or permeates terrestrial and marine ecosystems due to inadequate recovery infrastructure [6], [7]. Being predominantly non-biodegradable, these polymers persist for decades, leading to long-term soil contamination and disruption of marine ecosystems [8], [9]. Furthermore, uncontrolled thermal disposal (incineration) results in the release of toxic volatile organic compounds (VOCs) and greenhouse gases, thereby exacerbating the industrial carbon footprint [10], [11]. From an engineering sustainability perspective, this accumulation necessitates a transition from conventional disposal pathways to high-value material recovery, aligning circular material use with rigorous mechanical performance requirements [12].

B. Engineering Utility of Waste Plastic–Derived (WPD) Materials

Waste plastic–derived materials encompass secondary polymers recovered from post-consumer or post-industrial streams and re-engineered for technical applications [13]. These materials range from neat recycled resins-predominantly high-density polyethylene (HDPE), polypropylene (PP), and polyethylene terephthalate (PET)-to advanced composite systems reinforced with particulate fillers, fibers, or chemical modifiers [14]–[16].

While early recycling efforts primarily resulted in "downcycling" into low-performance consumer products, advancements in melt-processing technologies, including twin-screw extrusion and precision injection molding, have enabled the structural "upcycling" of recycled polymers [17]–[19].

From a mechanical engineering standpoint, WPD materials offer favorable strength-to-weight ratios and chemical resistance; however, the primary barrier to widespread industrial adoption remains the "property gap" caused by mechanical inconsistency and thermal-oxidative degradation during repeated processing cycles [20]–[22]. Establishing a robust understanding of these performance trade-offs is therefore essential for the reliable integration of recycled polymers into mission-critical engineering systems [23].

C. Objectives and Systematic Scope

This review critically evaluates the mechanical performance and industrial viability of waste plastic–derived materials within the framework of engineering systems analysis [24]. The primary objective is to synthesize existing experimental findings to determine how thermal history, material composition, and reinforcement strategies influence tensile, compressive, flexural, and fatigue behavior [25]–[27]. The scope of this work focuses on mechanically recycled thermoplastic matrices and their associated composite systems. Although chemical recycling and energy-recovery routes are discussed for comparison, the emphasis remains on structural applications relevant to automotive components, civil infrastructure, and industrial manufacturing sectors [28]–[30].

By consolidating quantitative performance data, this review identifies current limitations and outlines a roadmap for material optimization and standardization, providing a technical foundation for engineers and policymakers engaged in sustainable material selection and circular-economy implementation [31]. Recent reviews further emphasize that reinforcement strategies and optimized processing can significantly mitigate performance degradation in recycled polymers, enabling their use in functional engineering applications [32]–[34].

II. METHODOLOGY

A. Literature Search Strategy and Database Selection

This review is based on a systematic survey of peer-reviewed research focused on the mechanical performance of waste plastic–derived (WPD) materials. To ensure high technical reliability, relevant literature was sourced from authoritative databases, including Google Scholar, SpringerLink, ScienceDirect (Elsevier), and Wiley Online Library. The search utilized specific Boolean strings to isolate high-relevance studies:

1. (“waste plastic” OR “recycled polymer”) AND (“mechanical properties” OR “tensile strength”)
2. (“recycled plastic composites”) AND (“industrial applications” OR “engineering systems”)

The temporal scope was primarily constrained to articles published between 2000 and 2024, with particular emphasis on publications from the last five years to capture advancements in reinforcement strategies and processing techniques. Only English-language, peer-reviewed journal articles were included.

B. Data Collection and Quality Appraisal Protocol

Following the initial identification of approximately 90 candidate publications, a secondary screening process was conducted to select 50 core studies based on experimental depth and relevance to engineering systems. The quality appraisal prioritized experimental studies reporting measurable mechanical properties-specifically tensile, compressive, flexural, and fatigue behavior-conducted under standardized testing conditions (e.g., ASTM or ISO protocols). Articles focusing exclusively on chemical recycling or non-engineering applications were excluded to maintain the structural and industrial focus of this review.

C. Analysis and Synthesis Methodology

The analysis follows a primarily qualitative, trend-based synthesis. Extracted data points were examined to identify consistencies and variations in mechanical performance arising from polymer type, processing parameters, and reinforcement strategies. Rather than evaluating studies in isolation, this review adopts a comparative framework to understand broader performance trends relative to virgin polymer benchmarks. Tabular summaries (Tables I and II) are used to present key mechanical properties and industrial use-cases, enabling clear visualization of performance trends without reliance on complex statistical modeling. A formal meta-analysis was not conducted due to variations in material formulations, processing histories, and testing protocols across the reviewed studies.

III. CLASSIFICATION AND PROCESSING OF WASTE PLASTIC–DERIVED MATERIALS

A. Classification of Waste Plastic Precursors

Waste plastics utilized for engineering material development are categorized primarily by their thermal behavior into thermoplastics and thermosetting polymers. Thermoplastics represent the most viable candidates for mechanical recycling due to their ability to undergo repeated reversible phase transitions from solid to melt without immediate chemical disintegration. The primary thermoplastic streams used in structural and semi-structural engineering include:

1. *High-Density Polyethylene (HDPE) and Polypropylene (PP):* Favored for their high strength-to-weight ratios, chemical resistance, and processing stability.
2. *Polyethylene Terephthalate (PET):* Sourced largely from post-consumer packaging; PET offers a superior tensile modulus but requires strict moisture control during processing to prevent hydrolytic degradation.
3. *Low-Density Polyethylene (LDPE) and Polystyrene (PS):* Typically limited to non-structural or auxiliary applications due to lower mechanical performance thresholds.

Effective classification and sorting-commonly achieved using near-infrared (NIR) spectroscopy and density-based separation-are critical for ensuring mechanical reliability. Heterogeneous waste streams often result in immiscible polymer blends, leading to weak interfacial adhesion and unpredictable mechanical failure.

B. Mechanical Recycling and Manufacturing Techniques

Mechanical recycling is the dominant industrial pathway for converting waste plastics into usable engineering feedstock. This multi-stage process-comprising collection, shredding, decontamination, melting, and pelletization-aims to restore a consistent material form suitable for secondary manufacturing. The final mechanical performance of waste plastic–derived (WPD) materials is strongly influenced by the selected forming process:

1. *Extrusion and Injection Molding:* Widely used for high-volume production of profiles and components with controlled geometry and acceptable dimensional tolerances.
2. *Compression Molding:* Preferred for high-viscosity recycled blends and composite systems in which minimizing shear-induced fiber damage and void formation is critical.

Processing temperature, residence time, and shear rate must be carefully controlled, as excessive thermomechanical loading accelerates polymer degradation and property loss.

C. Influence of Thermomechanical History on Performance

The mechanical behavior of WPD materials is fundamentally governed by their thermomechanical history. Repeated heat–shear cycles induce polymer chain scission, resulting in reduced molecular weight and an increased melt flow index (MFI). These changes typically manifest as reductions in tensile strength, impact resistance, and fatigue performance. However, several mitigation strategies can partially restore or enhance mechanical properties:

1. *Compatibilizers and Stabilizers:* Chemical additives improve phase adhesion in mixed polymer systems and suppress oxidative degradation.
2. *Fiber Reinforcement:* Glass, carbon, or natural fibers compensate for matrix degradation by enabling effective stress transfer.
3. *Hybridization Strategies:* Blending recycled polymers with virgin resins or secondary fillers improves stiffness, creep resistance, and dimensional stability.

IV. MECHANICAL PERFORMANCE OF WASTE PLASTIC–DERIVED MATERIALS

TABLE I SUMMARY OF MECHANICAL PERFORMANCE TRENDS OF WASTE PLASTIC–DERIVED MATERIALS REPORTED IN LITERATURE

Waste Plastic Material / Composite Type	Key Mechanical Property	Performance Trend Relative to Virgin Polymers	Approximate Change Range	Representative References
Recycled PE, PP, PS (unreinforced)	Tensile strength	Reduction due to chain scission and thermal degradation during recycling	Decrease: 10–40%	[1–3]
Recycled PET	Tensile modulus	Slight reduction to moderate property retention depending on processing history	Decrease: 5–25%	[4,5]
Fiber-reinforced recycled polymer composites (glass / natural fiber)	Tensile strength	Significant improvement due to effective stress transfer from matrix to fibers	Increase: 50–150%	[6–8]
Fiber-reinforced recycled polymer composites	Elastic modulus	Strong increase resulting from high stiffness of reinforcing fibers	Increase:200–500%	[9,10]
Nanofiller-modified recycled polymers	Tensile and flexural strength	Moderate improvement at optimized nanofiller loading and dispersion	Increase: 10–40%	[11,12]
Plastic-modified concrete (PE, PET aggregates)	Compressive strength	Reduction caused by weak interfacial bonding with cement matrix	Decrease: 10–60%	[13,14]
Plastic-modified concrete	Flexural behavior	Improved crack resistance and post-cracking ductility	Increase: 10–30%	[15,16]
Recycled polymer composites	Impact resistance	Reduction in impact strength without toughening or reinforcement	Decrease: 20–50%	[1,17]
Toughened / reinforced recycled composites	Impact resistance	Improvement due to enhanced energy absorption mechanisms	Increase: 15–70%	[18,19]
Unreinforced recycled polymers	Fatigue life	Reduction caused by microstructural defects and molecular degradation	Decrease: 30–60%	[20,21]
Fiber / hybrid recycled composites	Fatigue life	Significant improvement due to delayed crack initiation and growth	Increase: 2–4×	[19,6]
Fiber / hybrid recycled composites	Creep resistance	Improved long-term dimensional stability under sustained loading	Reduction in creep strain: 30–70%	[21,22]

The mechanical performance of waste plastic–derived materials is a decisive criterion for assessing their feasibility in engineering and industrial applications. Over the past two decades, extensive research has examined the mechanical behavior of recycled plastics and plastic-based composites, focusing on tensile, compressive, flexural, impact, fatigue, and creep properties. Studies on recycled plastics span a wide range of polymer types, recycling routes, reinforcement strategies, and application domains [1]–[4].

In general, unreinforced recycled plastics exhibit degradation in mechanical properties compared with virgin polymers due to thermal degradation, oxidative aging, and polymer chain scission during repeated processing cycles [5], [6].

However, a substantial body of literature, including recent studies, demonstrates that through appropriate composite design, interface modification, and reinforcement incorporation, waste plastic–derived materials can achieve mechanical performance levels suitable for functional engineering applications [7], [8], [33], [34].

A consolidated overview of mechanical performance trends reported in the literature is presented in Table I, highlighting the influence of recycling, reinforcement, and material modification strategies on key mechanical properties. The reported ranges represent approximate trends and may vary depending on formulation, testing standards, and processing history. Among the reported mechanical properties, tensile behavior remains the most extensively investigated parameter due to its direct relevance to structural and load-bearing applications.

A. Tensile Properties

Comparative evaluation of tensile properties across the reviewed literature reveals that recycled polyethylene (HDPE, LDPE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET) commonly exhibit reductions in tensile strength and elastic modulus following mechanical recycling. Moderate to significant reductions relative to virgin polymers have been reported, depending on recycling intensity and processing history [6], [7].

Despite these limitations, tensile performance can be substantially enhanced through reinforcement strategies. Fiber-reinforced recycled polymer composites incorporating glass fibers, carbon fibers, or natural fibers exhibit significant improvements due to improved load transfer and stress distribution [9]–[11].

Reported improvements include 50–150% increases in tensile strength and 200–500% increases in elastic modulus, particularly in recycled PET and polypropylene composite systems [12], [13].

Nanofiller-modified recycled polymers further demonstrate 10–40% improvements in tensile properties at optimized filler concentrations, attributed to restricted polymer chain mobility and enhanced interfacial interactions [14], [15]. These findings indicate that tensile degradation in recycled plastics can be effectively mitigated through engineered composite design.

B. Compressive and Flexural Properties

Analysis of compressive and flexural behavior indicates that load-bearing performance is strongly governed by reinforcement type, plastic content, and interfacial bonding quality. Fiber-reinforced recycled polymer composites exhibit notable improvements in flexural strength and stiffness due to crack-bridging mechanisms and enhanced matrix–reinforcement adhesion [16], [17].

Several studies report substantial flexural performance enhancement in reinforced recycled polymer systems [9], [18].

In contrast, cementitious systems incorporating waste plastic aggregates consistently show reductions in compressive strength with increasing plastic content [19]–[21].

However, improved ductility, crack resistance, and post-cracking behavior under flexural loading have been reported at low replacement levels, indicating suitability for non-load-bearing and semi-structural applications [22], [23].

C. Impact Resistance and Toughness

The impact resistance of recycled plastics is highly sensitive to recycling-induced embrittlement and microstructural heterogeneity [6], [7].

To counteract this behavior, elastomer modification, fiber reinforcement, and hybrid composite approaches have been explored. Reinforced recycled polymer composites exhibit 15–70% improvement in impact resistance through mechanisms such as fiber pull-out, crack deflection, and interfacial debonding [24]–[26].

D. Fatigue and Creep Behavior

Long-term performance studies indicate that unreinforced recycled polymers exhibit reduced fatigue life and increased creep deformation compared with virgin materials, particularly under cyclic and sustained loading conditions. Molecular degradation and processing-induced defects are identified as dominant factors [27], [28].

Reinforcement strategies significantly improve long-term performance, with fiber-reinforced and nanocomposite recycled polymer systems demonstrating 2–4× improvement in fatigue life and 30–70% reduction in creep strain under sustained loading [29], [26].

TABLE II REPRESENTATIVE INDUSTRIAL APPLICATIONS OF WASTE PLASTIC–DERIVED MATERIALS AND OBSERVED MECHANICAL PERFORMANCE TRENDS

Industrial Sector	Application Area	Waste Plastic–Derived Material Used	Key Mechanical Requirement	Observed Performance Trend	Representative References
Construction & Infrastructure	Concrete blocks, pavements, asphalt	Recycled PE and PET aggregates	Compressive and flexural strength	Reduction in compressive strength with improved ductility and crack resistance	[13–16]
Construction & Infrastructure	Roofing sheets, panels	Recycled PE and PET aggregates	Flexural stiffness and impact resistance	Increase in flexural strength by approximately 20–80%	[6–8]
Automotive & Transportation	Interior panels, trims	Recycled PP composites	Weight reduction and impact resistance	Weight reduction of approximately 10–30% with improved impact resistance	[23–25]
Automotive & Transportation	Under-the-hood components	Glass fiber–reinforced recycled polymers	Thermal stability and fatigue resistance	Fatigue life improvement by approximately 2–4 times	[21,19,22]
Packaging & Consumer Goods	Containers, crates	Recycled HDPE and PET	Tensile strength and toughness	Tensile strength reduction of approximately 10–30%	[26–28]
Energy & Environmental	Cable insulation, casings	Recycled polymer blends	Electrical insulation and creep resistance	Reduction in creep strain by approximately 30–60%	[11,12,21]
Public Utilities (PSU-relevant)	Drainage pipes, utility covers	Recycled plastic composites	Load-bearing capacity and long-term durability	Improved long-term durability and service life	[14,16,22]

E. Overall Mechanical Performance Trends

A synthesis of approximately fifty peer-reviewed studies highlights recurring mechanical performance trends for waste plastic–derived materials, reflecting the combined effects of recycling history, reinforcement strategy, and material formulation. Fiber-reinforced, hybrid, and nanofiller-modified recycled polymer composites exhibit substantial improvements in stiffness, strength, toughness, and long-term durability. In cementitious systems, waste plastic aggregates reduce compressive strength but enhance ductility and energy absorption when used at controlled replacement levels. These trends indicate that reinforcement strategy and material design play a more critical role than recycling history alone in determining the mechanical viability of waste plastic–derived materials.

F. Engineering and Industrial Applications

Advancements in recycling technologies and composite engineering have expanded the industrial applicability of waste plastic–derived materials. In construction and infrastructure, recycled plastic composites are increasingly used in paving blocks, roofing sheets, wall panels, drainage pipes, and modular components [19]–[21]. In automotive applications, recycled polymer composites are used in interior panels, trims, and insulation components, contributing to weight reduction and improved fuel efficiency [30], [31]. Public utility applications further highlight the suitability of recycled plastic composites for durable, low-maintenance infrastructure components. Table II summarizes major industrial application sectors, associated waste plastic–derived material systems, key mechanical performance requirements, and experimentally observed behavior reported in the literature. Tables I and II collectively highlight that although unreinforced recycled plastics often exhibit reduced mechanical properties compared to virgin polymers, appropriately engineered waste plastic–derived composites can achieve performance levels suitable for a wide range of industrial applications. The tabulated data further demonstrate that reinforcement strategies, material hybridization, and optimized processing play a critical role in enabling the use of recycled plastics in the construction, automotive, consumer goods, and public utility sectors.

V. CHALLENGES AND LIMITATIONS

Despite increasing research interest and the promising mechanical performance trends observed for waste plastic–derived materials, several challenges and limitations continue to hinder their widespread adoption in structural and non-structural engineering applications. These limitations are multidimensional in nature, encompassing technical inconsistencies, economic feasibility issues, regulatory constraints, and sustainability considerations. A comprehensive understanding of these challenges is essential for the effective integration of waste plastic–based materials into engineering systems.

A. Technical Challenges

One of the most critical technical challenges associated with waste plastic–derived materials is the inherent variability of plastic waste streams. Post-consumer plastic waste often consists of mixed polymer types, such as polyethylene, polypropylene, polystyrene, and polyethylene terephthalate, along with contaminants including pigments, fillers, labels, and residual chemicals. This heterogeneity leads to inconsistent material behavior, resulting in unpredictable mechanical properties such as tensile strength, impact resistance, and fatigue life. Mechanical recycling processes further exacerbate these challenges. Repeated thermal and mechanical processing cycles can induce polymer chain scission, oxidation, and molecular weight reduction, all of which deteriorate mechanical performance. These degradation mechanisms often result in reduced ductility, increased brittleness, and diminished load-bearing capacity in recycled polymers when compared to their virgin counterparts.

In composite systems, interfacial compatibility between recycled polymer matrices and reinforcing fibers or fillers presents a significant limitation. Poor interfacial bonding can lead to inefficient stress transfer, fiber pull-out, and premature failure under mechanical loading. This challenge is particularly prominent in natural fiber–reinforced recycled composites, where moisture sensitivity and surface incompatibility adversely affect long-term durability. For construction and infrastructure applications, especially plastic-modified concrete and asphalt, weak bonding between plastic aggregates and cementitious matrices remains a major technical barrier. This typically results in reduced compressive strength and stiffness, restricting the use of such materials in structural or load-bearing applications. Additionally, the absence of optimized mix-design methodologies limits the repeatability and reliability of experimental outcomes reported in the literature.

B. Economic Considerations

Economic viability is a key determinant for large-scale industrial adoption of waste plastic–derived materials. While recycled plastics are often assumed to be cost-effective alternatives to virgin materials, overall processing costs can be substantial. Collection, segregation, cleaning, shredding, and reprocessing of plastic waste require significant infrastructure, energy input, and labor, which may offset the perceived economic benefits. Advanced recycling techniques-such as chemical recycling or composite manufacturing involving fiber reinforcement and surface treatments-further increase production costs. These additional expenses may reduce the competitiveness of recycled plastic materials, particularly in markets where low-cost virgin polymers remain readily available.

Market acceptance also poses a considerable challenge. Industries may exhibit reluctance to adopt waste plastic–derived materials due to concerns regarding long-term performance, durability, and quality consistency. The lack of demonstrated large-scale industrial success further contributes to hesitation among manufacturers and end-users. Moreover, production scalability remains limited, particularly for high-performance recycled composite systems that require controlled processing conditions and specialized equipment.

C. Regulatory and Standardization Issues

The absence of comprehensive regulatory frameworks and standardized testing procedures represents a significant obstacle to the widespread use of waste plastic–derived materials. Existing standards are predominantly tailored for virgin polymers or conventional composite materials and often fail to address the unique characteristics and performance variability associated with recycled plastics. Inconsistencies in testing methodologies, specimen preparation techniques, and performance evaluation criteria make it difficult to compare results across different studies. This lack of standardization reduces confidence among engineers, designers, and policymakers, particularly for safety-critical applications such as construction, transportation, and public utility infrastructure. Furthermore, regulatory uncertainty regarding the use of recycled plastics in structural components, automotive systems, and public infrastructure limits their acceptance in these sectors. The development of harmonized design guidelines, material specifications, and certification procedures is therefore essential to facilitate broader industrial implementation.

D. Environmental and Sustainability Limitations

Although waste plastic–derived materials offer clear advantages in terms of waste reduction and resource conservation, their overall environmental benefits must be critically evaluated. Certain recycling processes are energy-intensive and may generate emissions that partially offset the sustainability gains associated with plastic waste diversion. Transportation of waste materials and the use of chemical additives can further contribute to environmental impacts. Another important limitation relates to end-of-life management. Composite materials containing recycled plastics-particularly multi-material systems-are often difficult to recycle further. This raises concerns regarding long-term circularity and may result in downcycling or disposal at the end of service life. Designing waste plastic–derived materials with recyclability and reuse in mind remains a significant challenge for achieving circular economy objectives.

E. Research and Implementation Gaps

Despite extensive laboratory-scale research, the transition of waste plastic–derived materials from experimental studies to real-world engineering applications remains limited. Many studies focus on short-term mechanical performance without adequately addressing long-term durability, environmental exposure effects, and field performance. Additionally, limited collaboration among academia, industry, and policymakers has slowed the translation of research findings into practical solutions. Bridging these gaps requires integrated research approaches that combine material science, mechanical engineering, environmental assessment, and policy development. Without such coordinated efforts, the full potential of waste plastic–derived materials may remain unrealized. A summary of the key challenges, their impact on material performance, and corresponding research opportunities is presented in Table III. Addressing these challenges through technological innovation, policy development, and sustainable design strategies will be critical for enabling broader adoption of waste plastic–derived materials, as discussed in the following section.

TABLE III KEY CHALLENGES, PERFORMANCE IMPACTS, AND RESEARCH OPPORTUNITIES FOR WASTE PLASTIC–DERIVED MATERIALS

Identified Challenge	Impact on Performance	Research Opportunity
Mixed plastic waste streams	Property inconsistency	Advanced sorting and compatibilization
Weak fiber–matrix bonding	Premature failure	Surface treatment and coupling agents
Reduced fatigue and creep life	Durability concerns	Hybrid composites and nanofiller incorporation
Lack of standards	Limited industrial adoption	Standardized, performance-based testing frameworks
End-of-life recyclability	Sustainability concerns	Design-for-recycling and circular design approaches

VI. FUTURE PERSPECTIVES AND RESEARCH DIRECTIONS

The future advancement of waste plastic–derived materials is closely linked to technological innovation, improved material design strategies, and the integration of sustainability principles into engineering practice. As global concern regarding plastic waste management intensifies, research efforts are increasingly directed toward transforming waste plastics into value-added engineering materials. This section discusses emerging trends, research priorities, and future directions that can facilitate the large-scale adoption of waste plastic–based materials across industrial sectors.

A. Advancements in Recycling and Processing Technologies

TABLE IV COMPARISON OF RECYCLING AND UPCYCLING ROUTES FOR WASTE PLASTIC–DERIVED MATERIALS

Recycling Route	Description	Effect on Mechanical Properties	Key Advantages	Key Limitations	Representative References
Mechanical recycling	Re-melting and reprocessing of sorted plastic waste through extrusion, injection molding, or compression molding	Moderate reduction in strength and ductility due to polymer chain degradation during repeated processing	Cost-effective, industrially scalable, well-established	Property degradation, limited tolerance to mixed plastic streams	[1–3]
Chemical recycling	Depolymerization of plastics into monomers or fuel-like products via solvolysis, pyrolysis, or gasification	Properties comparable to virgin polymers after repolymerization	High material quality, feedstock flexibility	High cost, energy-intensive processes	[4–6]
Energy recovery	Conversion of plastic waste into thermal or electrical energy through incineration or co-processing	No material reuse	Reduction in waste volume, energy generation	Non-circular route, loss of material value	[7–8]
Composite upcycling	Utilization of waste plastics as matrices in fiber- or filler-reinforced composite systems	Substantial improvement in stiffness, strength, and load-bearing capacity	High-value engineering applications	Processing complexity, interfacial compatibility challenges	[9–11]

Significant advancements in recycling and processing technologies are anticipated to improve the consistency and mechanical performance of waste plastic–derived materials. Enhanced mechanical recycling methods incorporating advanced sorting techniques, such as near-infrared (NIR) spectroscopy and automated separation systems, can significantly reduce contamination and improve feedstock purity. Improved control over processing parameters, including temperature, shear rate, and residence time, can further minimize polymer degradation during recycling.

Chemical recycling and upcycling approaches offer promising alternatives to conventional mechanical recycling. Techniques such as depolymerization, solvolysis, and pyrolysis enable the conversion of waste plastics into monomers or fuel-like products, which can be repurposed for high-quality material production. These methods provide opportunities to recover materials with properties comparable to virgin polymers, thereby expanding the application potential of waste plastic–derived materials in high-performance engineering systems. Recent advances in chemical recycling and composite upcycling further support the transition toward high-performance circular materials for engineering applications [32], [35], [36]. Innovations in composite processing, including reactive extrusion, surface treatment of reinforcements, and compatibilizer-assisted blending, are expected to enhance interfacial bonding between recycled polymer matrices and fillers or fibers. The incorporation of nanotechnology, such as nanoclays, carbon nanotubes, and graphene-based fillers, also presents opportunities to improve mechanical strength, thermal stability, and barrier properties. A comparison of recycling and upcycling routes for waste plastic–derived materials and their associated mechanical performance implications is presented in Table IV. Among the reviewed routes, composite upcycling currently offers the most balanced combination of mechanical performance enhancement and circular economy alignment for engineering applications.

B. Material Design, Optimization, and Performance Enhancement

Future research should focus on the systematic design and optimization of waste plastic–derived materials tailored to specific engineering applications. Material formulation strategies that optimize reinforcement type, geometry, orientation, and volume fraction can significantly improve tensile, flexural, impact, fatigue, and creep performance. Hybrid composite systems that combine natural fibers with synthetic fibers or mineral fillers offer a promising balance between mechanical performance, cost efficiency, and environmental sustainability.

Advanced computational modeling and simulation techniques can play a crucial role in predicting the mechanical behavior of recycled plastic composites under various loading conditions. Multi-scale modeling approaches that account for microstructural features, interfacial interactions, and damage mechanisms can reduce experimental costs and accelerate material development. Additionally, data-driven approaches and machine learning techniques may support the rapid optimization of material formulations based on performance and sustainability criteria.

C. Expansion of Industrial and PSU-Oriented Applications

The scope of applications for waste plastic–derived materials is expected to expand significantly in the coming years, particularly in sectors aligned with public sector undertakings (PSUs). In construction and infrastructure, recycled plastic composites can be increasingly used for non-structural components such as drainage systems, manhole covers, cable trays, utility ducts, noise barriers, and modular building elements. These applications demand durability, corrosion resistance, and cost-effectiveness-properties that waste plastic–based materials can offer when properly engineered. In the automotive and transportation sectors, future developments may focus on lightweight recycled composite components that contribute to fuel efficiency and emission reduction. Interior panels, underbody shields, and insulation components represent potential application areas where recycled plastics can meet performance requirements while supporting sustainability goals. Similarly, in the energy and environmental sectors, waste plastic–derived materials may find applications in insulation systems, energy storage casings, water treatment infrastructure, and renewable energy installations.

D. Sustainability, Circular Economy, and Life Cycle Considerations

To fully realize the environmental benefits of waste plastic–derived materials, future research must incorporate circular economy principles into material design and application. Designing recycled plastic composites for recyclability, disassembly, or secondary use can significantly enhance material circularity. Life cycle assessment studies should be expanded to quantify environmental impacts across the entire material life cycle, including raw material acquisition, processing, usage, and end-of-life management.

The integration of waste plastic–derived materials into broader waste management and resource recovery systems can further improve sustainability outcomes. Closed-loop recycling systems, in which recycled materials are reintegrated into similar or higher-value applications, represent an important research direction. Additionally, the use of bio-based additives and environmentally benign processing aids can reduce the ecological footprint of recycled plastic materials.

E. Policy Support, Standardization, and Industry Collaboration

Policy interventions and regulatory support are expected to play a crucial role in accelerating the adoption of waste plastic–derived materials. Government incentives, procurement policies favoring recycled materials, and extended producer responsibility frameworks can encourage industries to invest in recycling and material innovation. Standardization efforts aimed at developing performance-based material specifications and testing protocols are also essential for building confidence among engineers and manufacturers. Collaboration between academia, industry, and public sector organizations can facilitate knowledge transfer and large-scale implementation. Pilot projects, demonstration studies, and field trials can provide valuable data on long-term performance and help bridge the gap between laboratory research and real-world applications.

F. Addressing Research Gaps and Future Priorities

Despite significant progress, several research gaps remain that warrant further investigation. Long-term durability studies under realistic environmental and loading conditions are limited and should be prioritized. The effects of aging, moisture exposure, ultraviolet radiation, and thermal cycling on recycled plastic composites require comprehensive evaluation. Additionally, further research is needed to develop cost-effective processing techniques that maintain material performance while minimizing environmental impact. Interdisciplinary research approaches that integrate material science, mechanical engineering, environmental assessment, and policy analysis can accelerate the development of robust and sustainable waste plastic–derived materials. Addressing these research gaps will be critical to unlocking the full potential of waste plastics as viable engineering materials. These future directions collectively provide a roadmap for transitioning waste plastic–derived materials from experimental research to reliable engineering applications.

VII. CONCLUSION

The growing accumulation of plastic waste presents a serious environmental challenge, while simultaneously offering an opportunity to develop sustainable, value-added engineering materials. This review has systematically examined the mechanical performance and industrial applicability of waste plastic–derived materials, with particular emphasis on their relevance to engineering systems and sustainable development goals. By synthesizing findings from a broad range of published studies, this paper provides a comprehensive understanding of the current state of research in this field.

The review highlights that unreinforced recycled plastics generally exhibit reductions in mechanical properties such as tensile strength, impact resistance, fatigue life, and creep performance when compared to virgin polymers, primarily due to polymer degradation and material heterogeneity. However, the findings clearly demonstrate that these limitations can be effectively addressed through appropriate material engineering strategies. Fiber reinforcement, hybrid composite design, nanofiller incorporation, and optimized processing techniques have been shown to significantly enhance the mechanical performance of waste plastic–derived materials, enabling their use in a wide range of functional applications. From an application perspective, waste plastic–derived materials show strong potential across multiple industrial sectors, including construction, automotive, consumer goods, energy, and public utility infrastructure. In particular, non-structural and semi-structural applications such as drainage systems, utility components, interior automotive parts, and modular construction elements present promising avenues for large-scale adoption. These application domains align well with the requirements of public sector undertakings, where durability, cost-effectiveness, corrosion resistance, and sustainability are critical considerations.

Despite these promising developments, several challenges continue to limit widespread industrial implementation. Technical issues related to material variability, interfacial bonding, and long-term durability, along with economic constraints, regulatory gaps, and sustainability concerns, remain significant barriers. Addressing these challenges requires coordinated efforts involving advanced recycling technologies, standardized testing methodologies, supportive policy frameworks, and stronger collaboration between academia, industry, and government agencies.

Overall, this review underscores that waste plastic–derived materials are no longer limited to low-value applications but can be engineered to meet functional performance requirements for demanding engineering systems. With continued research, technological innovation, and policy support, these materials have the potential to play a key role in promoting circular economy principles and reducing the environmental impact of plastic waste. The insights presented in this paper are expected to assist researchers, engineers, and policymakers in advancing the responsible development and utilization of waste plastic–based materials in sustainable engineering practice. From a mechanical engineering perspective, waste plastic–derived materials should not be viewed as direct replacements for conventional materials, but rather as functionally optimized alternatives for targeted applications. Their successful deployment depends less on material novelty and more on intelligent engineering design, standardization, and policy-driven adoption. It should be noted that this review is based on a qualitative synthesis of published literature, and the reported performance trends may vary depending on material composition, processing conditions, and application-specific requirements.

Declaration of Conflicting Interests
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ORCID
Abhinab Borah https://orcid.org/0009-0000-1618-3719

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