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A Critical Review on the Feasibility of Recycled Polyethylene Terephthalate (PET) In the Production of Plastic Lumber

Elijah Oluwatimilehin Awojulu
Department of Environmental Engineering
Faculty of Engineering & Technology, JAIN (Deemed to be University), India

Abstract — The Global upsurge in plastic waste generation, which accounts for more than 8 billion metric tonnes, calls for innovative recycling solutions. Recently, the construction industry has been searching for durable, low-maintenance, eco-friendly, and sustainable alternatives to traditional materials such as wood, which is subject to decay and leads to deforestation. This review synthesizes the existing literature to critically evaluate the feasibility of using recycled PET (rPET) as a feedstock for producing structural-grade plastic lumber. This can provide a dual-benefit approach to waste management and the green economy. Although plastic lumber utilizes high-density polyethylene (HDPE), rPET possesses superior mechanical properties, such as higher tensile strength and flexural modulus. This study thoroughly examines the material characteristics of rPET, prevailing recycling processes, and the performance of rPET-based composites in comparison with incumbent materials. This highlights that rPET lumber demonstrates significant promise but faces challenges related to impact resistance, long-term durability, and a lack of standardized structural design guidelines. This review also identifies critical research gaps, such as the need for long-term creep and fatigue data, optimization of hybrid composites, and site-specific life cycle assessments, particularly in the Indian context. The findings indicate that with targeted research and development, rPET plastic lumber can transition from a niche, non-structural product to a reliable, high-performance construction material, thereby advancing the principles of a circular economy.

Keywords: Recycled PET (rPET), Plastic Lumber, Sustainable Construction, Polymer Recycling, Mechanical Properties, Circular Economy, Waste Management, and Structural Composites

I. INTRODUCTION

The production and consumption of plastics, along with the accumulation of plastic waste over the past three decades, has resulted in substantial environmental challenges. The use of various types of plastic products has become an indispensable part of our lifestyle, and large amounts of plastic waste are being generated throughout the world on a daily basis, resulting in the overstretching of waste management facilities, which has led to the inability of concerned waste management authorities to cope with the volume of solid waste generated. Plastics are one of the most widely used materials in the world today. This is due to their distinctive and unique characteristics, such as being lightweight, inexpensive, and versatile. These features have led to a rapid increase in their usage in the past half a century, and the prevision is for the next 20 years to duplicate (MacArthur, 2016). Polyethylene Terephthalate (PET) plastics, commonly used in packaging water, beverages, and soda, account for one of the largest fractions of global waste streams because of their large-scale use and short life cycle (Geyer et al., 2017). Although PET possesses excellent mechanical and chemical properties, such as high tensile strength, stiffness, and thermal stability, only a limited percentage of its waste is recycled into value-added products (Ritchie and Roser, 2018). This is why most countries, including India, find it extremely difficult to manage the upsurge of post-consumer PET waste, leading to voluminous and uncontrolled landfills, microplastic formation, river pollution, and greenhouse gas emissions during incineration.

Due to the catastrophic consequences of the production and consumption of plastics, the world has now shifted its focus to sustainable materials and how we can reduce, reuse, and recycle our materials to encourage a green economy, reduce pollution, and promote a sustainable world. As part of this global shift, recycled PET (rPET) is a promising feedstock for civil and environmental engineering applications owing to its recyclability, mechanical resilience, and energy reprocessing capabilities (Al-Salem et al., 2017). One of the emerging engineering applications is the manufacture of plastic lumber, an engineered product intended to replace conventional wood in structural and non-structural applications. According to the American Society for Testing and Materials (ASTM), the term plastic lumber applies to products made primarily from plastic (with or without additives), with a rectangular cross-section and size typical of wood products used for construction. However, plastic lumber products can also take the form of a circular cross-section and other shapes, with applications such as furniture and farming, among others. (ASTM, 2017, 2018).

Plastic lumber offers benefits such as resistance to moisture, biological decay, insects, and chemical attack, making it a durable alternative for outdoor structures, pedestrian walkways, marine environment,s and low-loaded bearing structural elements (Kibria & Sannasiraj, 2020). Although most commercially available plastic lumber is manufactured using low-density polyethylene (LDPE), high-density polyethylene (HDPE), and polypropylene (PP), these polymers possess lower tensile and flexural strengths than virgin PET and most often require reinforcement agents to meet structural requirements (Hopewell et al., 2009).

Despite PET's superior mechanical performance compared to other commonly used plastics, its use in the production of plastic lumber is limited. This is due to its higher melting point, susceptibility to hydrolytic degradation during thermal processing, and viscosity during extrusion (Awaja & Pavel, 2005). However, advances in controlled washing, drying, and high-temperature extrusion technologies have made PET recycling feasible for structural materials. Recent research has shown that rPET lumber can provide significantly higher stiffness and load-carrying capacity than HDPE lumber while reducing deflection and creep (Osswald & Baur, 2015). These research and developments promise the great potential of rPET lumber to bridge the gap between conventional plastic lumber and timber.

II. LITERATURE REVIEW

Polymers are long-chain molecules composed of repeating structural units known as monomers, which are linked predominantly through covalent bonds (Strong, 2006). Their distinctive mechanical, chemical, and thermal properties are derived from variations in molecular weight, chain orientation, crystallinity, and intermolecular forces. Over the past century, polymers have become indispensable owing to their low cost, versatility, and processability. This has resulted in the large-scale production of polymers, leading to large-scale plastic waste generation (PlasticsEurope, 2022). All plastics are polymers, but not all polymers are plastics.

Plastic waste has become a defining environmental challenge in the 21st century. It is estimated that global plastic production surpassed 390 million tonnes in 2022 (PlasticsEurope, 2023). A large percentage of this production becomes waste within a few months, generating major environmental, social, and economic challenges for rapidly urbanizing countries. However, PET bottles constitute nearly 14% of global municipal solid waste (UNEP, 2021) and are particularly problematic because of their slow biodegradation, leaching potential, and ubiquitous accumulation in drainage, water bodies, and dumpsites. In engineering applications, the performance of polymeric materials is determined by their structural and chemical configurations. Due to this variety, plastics are categorized into thermoplastics, thermosets and elastomers. Thermoplastics such as PET, PE, PP, and PVC are the most relevant to plastic lumber production because they can be melted and reprocessed repeatedly without significant chemical alteration (Rosen & Kutz, 2012).

India generates approximately 3.4 million tonnes of PET waste annually, accounting for nearly 10% of the national plastic waste (CPCB, 2022). Despite India’s comparatively high recycling rate (~70–75%), large volumes remain unmanaged in rural and sub-urban regions due to infrastructural and behavioral gaps (Chauhan & Singh, 2021). When PET waste is openly dumped or burned, it contributes to microplastic formation, soil degradation, groundwater contamination, and greenhouse gas emissions, making its sustainable reuse highly important. The concept of repurposing PET into value-added engineering materials, such as plastic lumber, is increasingly recognized as both a waste mitigation and materials innovation strategy. Recycling PET into construction materials helps divert waste from informal dumpsites, reduces virgin plastic demand, and supports circular economy transitions in developing nations (Shrivastava and Bansal, 2020).

Fig. 1: Plastic wastes

III. THE BIG SIX PLASTICS

A. High Density Polyethylene (HDPE)

HDPE is characterized by a linear polymer chain with minimal branching, resulting in high stiffness, chemical resistance, and moderate tensile strength (Fleming, 2017). They are opaque. Common applications of HDPE include milk jugs, detergent bottles, pipes, and most commercially manufactured plastic lumber.

Fig. 2: HDPE

B. Polyvinyl Chloride (PVC)

PVC is a widely used thermoplastic owing to its durability, fire resistance (due to chlorine content), and weathering stability. It is commonly used in pipes, window frames and cable insulation (Titow, 2012). However, the release of chlorine during incineration remains a major environmental concern.

Fig. 3: PVC

C. Low Density Polyethylene (LDPE)

LDPE has a highly branched polymer structure, which imparts flexibility, toughness, and transparency. Applications include plastic bags, squeeze bottles and films. Although abundant in municipal waste streams, LDPE is less commonly used in structural composites because of its low stiffness (Mohee et al., 2015).

Fig. 4: LDPE

D. Polypropylene (PP)

PP is semi-crystalline, lightweight, heat-resistant, and exhibits excellent fatigue performance. It is widely used in automotive parts, household goods and laboratory equipment (Brydson, 1999).

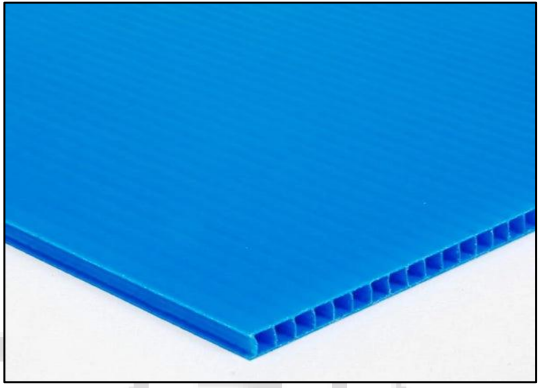


Fig. 5: PP

E. Polystyrene (PS)

Polystyrene is rigid and brittle, and is used in disposable cutlery, toys, and insulation foam. However, its low impact resistance and environmental persistence render it unsuitable for structural products (Hopewell et al., 2009).

Fig. 6: PS

F. Polyethylene Terephthalate (PET)

Polyethylene Terephthalate (PET) is a semi-crystalline polyester known for its high tensile strength, dimensional stability, and excellent barrier properties against water vapor and gases (Eagan & Baer, 2014). PET is formed through a polycondensation reaction between terephthalic acid (TPA) and ethylene glycol (EG), producing a semi-crystalline polymer with both amorphous and crystalline regions (Awaja & Pavel 2005). PET is highly transparent and strong, with extremely high resistance to acids and bases, and zero diffusion of gases. They are used in soft drink/soda bottles with screw tops. All kinds of clear and tough food containers, such as mayonnaise, warehouse-sized nuts, and peanut butter containers, along with many others. They can also be used as fibers in various clothing products (polyester), fleece-type fabrics, carpets, and fiber-fill insulation. Globally, PET accounts for 18% of all plastic packaging (Ellen MacArthur Foundation, 2017), making it one of the most widely consumed and discarded plastics.

Fig. 7: PET

G. *Plastic Lumber*

Plastic lumber refers to structural or semi-structural sections manufactured from recycled or virgin plastics, and is often used as a substitute for timber in various applications, such as decking, fencing, walkway planks, signposts, and formwork. Compared to natural timber, plastic lumber offers the following advantages:

- resistance to moisture, rot and insect attack
- longer service life in outdoor applications
- low maintenance requirements
- consistent material quality
- reduced demand for deforestation-based wood supply

According to the American Society for Testing and Materials (ASTM D6108, 2018), plastic lumber is evaluated based on its density, tensile strength, flexural strength, creep resistance, impact behavior, and environmental durability. PET-based lumber, in particular, is an emerging class of material known for its superior strength compared to polyethylene- or polypropylene-based lumber (Leng & Cernansky 2020).

PET's higher density (1.34–1.37 g/cm³) and crystalline structure give PET lumber with enhanced stiffness and flexural strength, making it suitable for load-bearing applications where other plastics may deform under sustained loading (Balaji & Karthikeyan, 2021).

Fig. 8: plastic lumber

IV. MECHANICAL PROPERTIES AND APPLICATIONS OF PET PLASTIC LUMBER

The mechanical behavior is essential for determining the suitability of rPET lumber for load-bearing or structural applications. The mechanical strength of PET lumber depends on the processing conditions, melt homogeneity, degree of crystallinity, and impurities in the recycled feedstock (Rahimi & García, 2017).

A. *Water absorption*

PET is hydrophobic and absorbs <0.5% water by weight, giving PET lumber excellent outdoor durability. In comparison, natural timber may absorb 10–25% water, leading to swelling, decay, and reduced life span (ASTM D7031, 2018).

B. *Tensile strength*

Studies indicate that rPET lumber typically has tensile strength between 25–45 MPa, depending on molding parameters and PET grade (Balaji & Karthikeyan, 2021). Virgin PET can reach 50–75 MPa, meaning recycled PET exhibits a controlled but acceptable reduction due to thermal degradation.

C. *Flexural strength*

Flexural strength is a critical indicator for decking, flooring, and structural plank applications. According to Dawes et al. (2018), rPET lumber achieves flexural strengths of 40–70 MPa, surpassing polyethylene-based lumber which averages 10–25 MPa.

D. *Density and dimensional stability*

PET lumber's density typically ranges from 1.20–1.40 g/cm³, significantly higher than HDPE lumber (~0.95 g/cm³), resulting in superior stiffness and lower creep deformation under sustained loading.

E. *Impact resistance*

The impact performance depends on crystallinity and cooling rate. Controlled cooling during compression molding helps maintain adequate impact resistance while preserving stiffness (Welle, 2011).

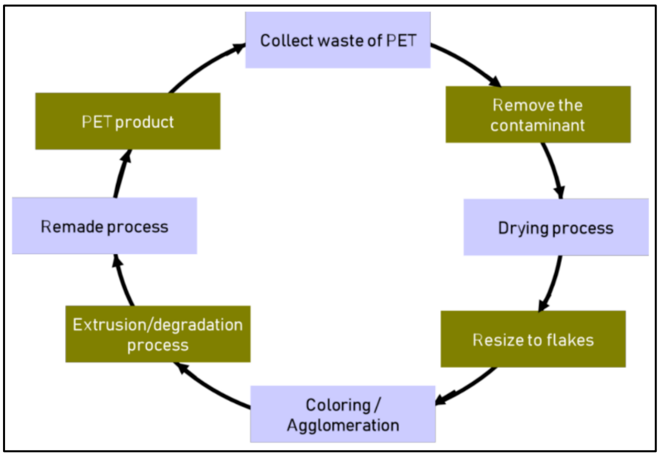
V. PET RECYCLING PROCESSES

A. *Collection and sorting*

PET waste is collected through informal waste pickers, municipal handling facilities, and material recovery facilities (MRFs). Sorting involves:

- manual sorting based on color and contamination
- automated sorting using near-infrared (NIR) spectrometry
- magnetic/eddy current separation for metals

Accurate sorting is essential because impurities such as PVC cause severe degradation of PET during melting (Al-Salem et al., 2009).



B. *Size Reduction*

The sorted bottles are shredded into 8–12 mm flakes using rotary or granulator cutters.

C. *Washing and Separation*

Flakes undergo a rigorous hot caustic wash to remove contaminants like labels, adhesives, and food residues. A sink-float tank is used to separate PET (which sinks) from lighter plastics like PP and LDPE (which float), because PET has a density of 1.38 g/cm^3

D. *Drying*

The clean flakes are thoroughly dried to a moisture content below 0.02% to prevent hydrolytic degradation during subsequent melting. The dried flakes can then be melted and extruded into pellets or directly into new products.

E. *Extrusion and post-processing*

Extrusion is the primary manufacturing technique for PET lumber. In this process:

- PET flakes are fed into a single or twin-screw extruder
- Material undergoes sequential heating zones (230–270°C)
- Melt is homogenized and conveyed to a shaping die
- Melt exiting the die is water- or air-cooled to solidify the profile

The extrusion process may incorporate the following:

- stabilizers (UV absorbers, antioxidants)
- fiber reinforcement (glass fiber, natural fibers such as jute/coir)
- impact modifiers (ethylene copolymers)
- compatibilizers (maleic anhydride grafted polymers)

Twin-screw extruders often provide superior mixing and dispersion of additives (Chaudhary et al., 2016). Proper melt filtration ensures that contaminants <200 microns are removed to maintain structural integrity.

VI. COMPARISON BETWEEN PET LUMBER AND CONVENTIONAL/NATURAL TIMBER

Below is a table of comparing the mechanical properties of PET plastic lumber to that of natural timber.

Property	PET Lumber	Timber
Water absorption	Very low	High
Durability	Very high	Moderate
Biological resistance	Excellent	Poor
Tensile strength	Comparable	moderate
Maintenance	Very low	High
Service life	25-40 years	10-15 years

VII. FEASIBILITY STUDIES ON PET PERFORMANCE OVER HDPE

A. *Technical and Performance Feasibility.*

- Higher strength and Stiffness; Vasquez & Majewski (2018) provide the most direct evidence, finding that plastic lumber produced from rPET exhibited approximately 25% higher flexural strength than lumber produced from HDPE. This is a critical finding, as flexural strength is paramount for applications like decking, boards, and load-bearing elements where sagging must be minimized. The inherent properties of PET include a high tensile strength and modulus (stiffness) compared to polyolefins like HDPE and PP (Awaja & Pavel, 2005). This suggests that rPET lumber is found to be less prone to creep (long-term deformation under load), a known disadvantage of some traditional plastic lumber.
- Durability and Environmental Resistance; Low water absorption; Siddique et al. (2008) highlighted that PET's low water absorption translates to excellent resistance to rot, decay, and fungal attack, outperforming wood and being comparable to other plastics in this regard. This makes Low Water Absorption a key benefit for PET plastic.
- Vulnerability to UV Degradation; All plastics, including PET, undergo photo-degradation when exposed to sunlight, leading to surface embrittlement, color fading, and loss of mechanical properties. This necessitates the use of additives like UV stabilizers and pigments (e.g., carbon black) for outdoor applications (Andrady, 2003). This proves that UV exposure on plastics poses a significant challenge.
- Material Degradation during Processing: Beg and Pickering (2008) showed that mechanical reprocessing (such as extrusion) of polypropylene can cause chain scission and reduce molecular weight, degrading polymer properties. This is highly relevant for rPET, which may undergo multiple heat histories, potentially weakening the final product if not carefully controlled during processing.
- Established Recycling Infrastructure: The pre-processing steps for rPET such as collection, sorting, shredding, washing, and drying, are well documented and commercially practiced (Hopewell et al., 2009). This solidifies the existence of supply chain for converting post-consumer PET bottles into rPET flakes.
- Compatibility with Extrusion: The successful production of rPET lumber profiles by Vasquez & Majewski (2018) and Nagavarapu & Saravanakumar (2021) proves that the manufacturing process, primarily extrusion is technically viable.

B. *Critical Processing Challenges:*

- The Need for Thorough Drying: Awaja & Pavel (2005) emphasize that PET is highly hygroscopic and prone to hydrolytic degradation. If rPET flakes contain even small amounts of moisture during the high-temperature extrusion process, the polymer chains break down, severely compromising the mechanical properties of the final lumber. This makes pre-drying an essential, non-negotiable, and energy-intensive step.

- Higher Processing Temperatures: PET processes at higher temperatures (~260-290°C) than the more commonly used HDPE, potentially leading to higher energy consumption during manufacturing.

C. Economic and Market Feasibility.

- Raw Material Cost and Availability: Using post-consumer PET waste provides a low-cost feedstock and aligns with circular economy principles. However, the costs of collection, sorting, and cleaning to a high purity standard are significant (Hopewell et al., 2009).
- Value Proposition and Market Niche: The data from Vasquez & Majewski (2018) suggests that rPET lumber should not be seen as a direct, like-for-like replacement for HDPE lumber. Instead, its superior stiffness and strength create an opportunity for a premium, "structural-grade" plastic lumber for applications like load-bearing decking frames, pilings, and industrial flooring, where HDPE's creep is a limitation. This allows it to compete with pressure-treated timber on performance rather than just durability.
- Competition for Feedstock: PET is a valuable material for closed-loop recycling (back into bottles) and fiber production. The economic feasibility for lumber depends on it being a more lucrative outlet than these traditional recycling streams.

D. Environmental Feasibility

- Waste Diversion: The primary driver is addressing the global plastic waste crisis. Using rPET for lumber diverts significant waste from landfills and the environment, a problem starkly quantified by Geyer et al. (2017).
- Resource Conservation: It reduces pressure on forests by providing an alternative to timber and decreases the use of virgin, fossil-fuel-derived plastics.
- Lifecycle Considerations: While environmentally beneficial in terms of waste management, a full Life Cycle Assessment (LCA) would be needed to quantify the net environmental impact, factoring in the energy used for collection, transportation, washing, drying, and extrusion.

VIII. RESEARCH GAPS

Below are the research gaps that has been identified from the literature review

A. Limited Research on Pure Compression Molded RPET Lumber

Most available studies examine:

- HDPE or PP-based lumber
- PET composites (PET + fibers)
- mixed-waste plastic lumber

There is very little research on 100% recycled PET lumber produced via compression molding, especially with mechanical characterization based on ASTM standards.

B. Lack Of Standardized Mechanical Performance Data

Existing studies provide partial data on tensile or flexural strength but often:

- use non-standard sample dimensions
- use non-uniform waste sources
- do not compare with ASTM D6109 / D790 standards

Thus, comprehensive, standardized mechanical testing (tensile, flexural, density, water absorption) for rPET lumber remains scarce.

C. Insufficient Experimental Studies in Indian Context

Despite high PET waste generation, very few Indian studies:

- fabricate PET lumber
- characterize it using ASTM standards
- explore its engineering applications

This creates a significant regional knowledge gap.

D. Limited Understanding of Pet Lumber Durability

Long-term performance under tropical climatic conditions is inadequately documented, especially regarding:

- water absorption behavior
- UV resistance
- dimensional stability
- creep performance

These aspects are critical for real-world use in construction.

IX. FUTURE SCOPE

Based on the research gaps realized as regards the literature review, the following research directions are proposed.

- More research should be done with focus on rPET, how to explore its characteristics and mechanical properties in creating more structural grade products. This will massively reduce its waste generation
- Extensive, comprehensive and standardized mechanical testing (tensile, flexural, density, water absorption) for rPET lumber must be done
- Multiscale modeling can be made to expand the knowledge of rPET, enabling predictive analysis.

X. CONCLUSION

This review establishes that recycled PET possesses inherent material properties, notably high strength and stiffness, making it a technically viable and environmentally beneficial feedstock for high-performance plastic lumber. The literature confirms that rPET lumber outperforms conventional HDPE lumber in key mechanical metrics, opening a pathway for its use in structural applications. However, its journey from a promising laboratory material to a mainstream construction element is fraught with challenges, including its inherent brittleness, susceptibility to UV degradation, and significant lack of long-term performance data and structural design codes.

Addressing the identified research gaps through concerted efforts in materials science, structural engineering, and environmental analysis is imperative. Future work should focus on optimizing the material system, validating its long-term durability, and integrating it into the framework of structural design standards. Thus, the construction industry can leverage a problematic waste stream to create a new class of sustainable, durable, and structural-grade materials, firmly embedding the principles of the circular economy into the built environment.

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