



## Evaluating Recycled PET as an Alternative Material for the Construction Sector Towards Sustainability

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### Abstract

Addressing the environmental threat of Polyethylene Terephthalate (PET) waste is critical for sustainable development. Despite PET's prevalence in everyday products, its improper disposal endangers environmental health. This study targets a pivotal gap in current research. PET waste's potential as a sustainable building material will be thoroughly evaluated, focusing on whether recycling PET waste is feasible. In the construction industry, it can be a substitute for natural sand and an additive in cement. This study contributes to a dual-purpose solution: mitigating environmental pollution and innovating in construction material science. The systematic literature review (SLR) delves into existing studies, focusing on PET's impact on concrete properties when substituting natural sand at ratios of 5% to 20% and as a cement additive at 0.5% to 2% by weight. The findings revealed that up to a 10% PET replacement enhances compressive strength, highlighting a sustainable pathway for construction practices. However, replacements above 10% show a reduction in strength, indicating an optimal substitution threshold. Moreover, incorporating PET additives at 1% by cement weight optimizes flexural strength, underscoring the material's viability in enhancing structural integrity. This study sheds light on PET waste's application in reducing environmental impact and proposes a viable, eco-friendly alternative for construction materials. The recommendation for further research underscores the necessity to refine PET's application in construction, aiming to bridge the knowledge gap and encourage sustainable future innovations.

**Keywords:** PET Waste Utilization; Eco-friendly Building Materials; PET in Civil Engineering; Recycled Plastic Aggregate Innovation.

### 1. Introduction

For more than ten decades, rapid growth in the world population can be seen, leading to a very intense need for natural resources being utilized by industrial enterprises and the urban expansion of developing countries. For this reason, a massive burden on natural materials causes natural disasters. Recycling waste products has a lot of benefits for the sustainable development introduced by the Rio Earth Summit [1–3]. It helps reduce pollution, which can be induced in water, air, and soil. It helps save electricity and minimizes solid waste and greenhouse gases. Therefore, it is imperative to comprehend the factors that could positively impact the construction industry, particularly in relation to the utilization of waste and recycled materials [4–7]. This field has become an essential subject of study and has been explored by researchers. It primarily focuses on strategies for effectively utilizing suitable waste materials to enhance sustainability and the economy by emphasizing recycling and reutilization [8–11]. Within the construction industry, materials frequently recycled comprise crumb rubber, silica fumes, roofing shingles, palm fruit husks, citrus rinds, kiln dust cement, asphalt, flyash, foundry sand, glass, slag, and recycled aggregates derived from dismantled concrete infrastructures [12–15]. For this review article, PET waste as a substitute for natural construction material is selected for systematic review.

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Only the European Union (EU) recorded the data on plastic waste production and allowed access to the public, excluding Asian countries. The unprecedented worldwide rise of plastic output indicates its excessive usage and manhandling. If improperly handled, the end product of plastic waste is consumed in landfills, oceans, and seas. Estimations suggest that approximately 30% of total solid waste disposal could be reduced upon achieving an optimal solution for plastic waste management. Consequently, there is an urgent requirement for a sustainable strategy for the consumption and processing of plastic waste. The plastic material in concrete will significantly contribute towards more sustainable and holistic building materials for the construction industry. The long-term processing and environmental consequences of plastic residues in concrete are recommended for further study after their service life [16–19]. As presented in the overview by Padgelwar et al. [20], India ranks 5<sup>th</sup> globally for plastic product consumption. About 38 kg/person, followed by Brazil, China, Europe, and the USA, which have the highest, 109 kg/person. Some studies have shown plastic is used to replace aggregates in concrete, replace plastic fiber aggregate in concrete, and use plastic materials to construct flexible pavement. Furthermore, a comprehensive analysis concluded that polyethylene and PET are the most prevalent among the diverse forms of plastic waste [21–23].

The recyclability and potential of PET waste as a sustainable construction material are attracting significant research interest. PET waste's massive availability is estimated to be nearly 400 metric tons annually [21]. Due to its massive demand in the packaging industry and mineral water bottles, its disposal has become a serious matter of concern. As its consumption has grown faster, the waste landfill area required for PET products' disposal is also increasing rapidly [20, 21]. The production and disposal of plastic in large amounts have created a colossal level. Hence, recycling is a critical matter that must be resolved shortly. In the past few years, we have come across many recycling techniques that are financially and technically feasible while keeping ecological health under consideration [24, 25]. Many research studies studying lightweight concrete have successfully examined PET waste products' impact as aggregate particles [26–28].

The consideration of recycled plastic as input for the construction and plastic recycling industries has become significant. Considering the numerous benefits of recycling plastic, the most substantial one is maintaining ecological balance, which blesses nature with immense relief. As a researcher, it becomes a huge responsibility to emerge with such techniques and ideas for recycling that are cost-effective, reliable, practically feasible, and durable for a longer period of time.

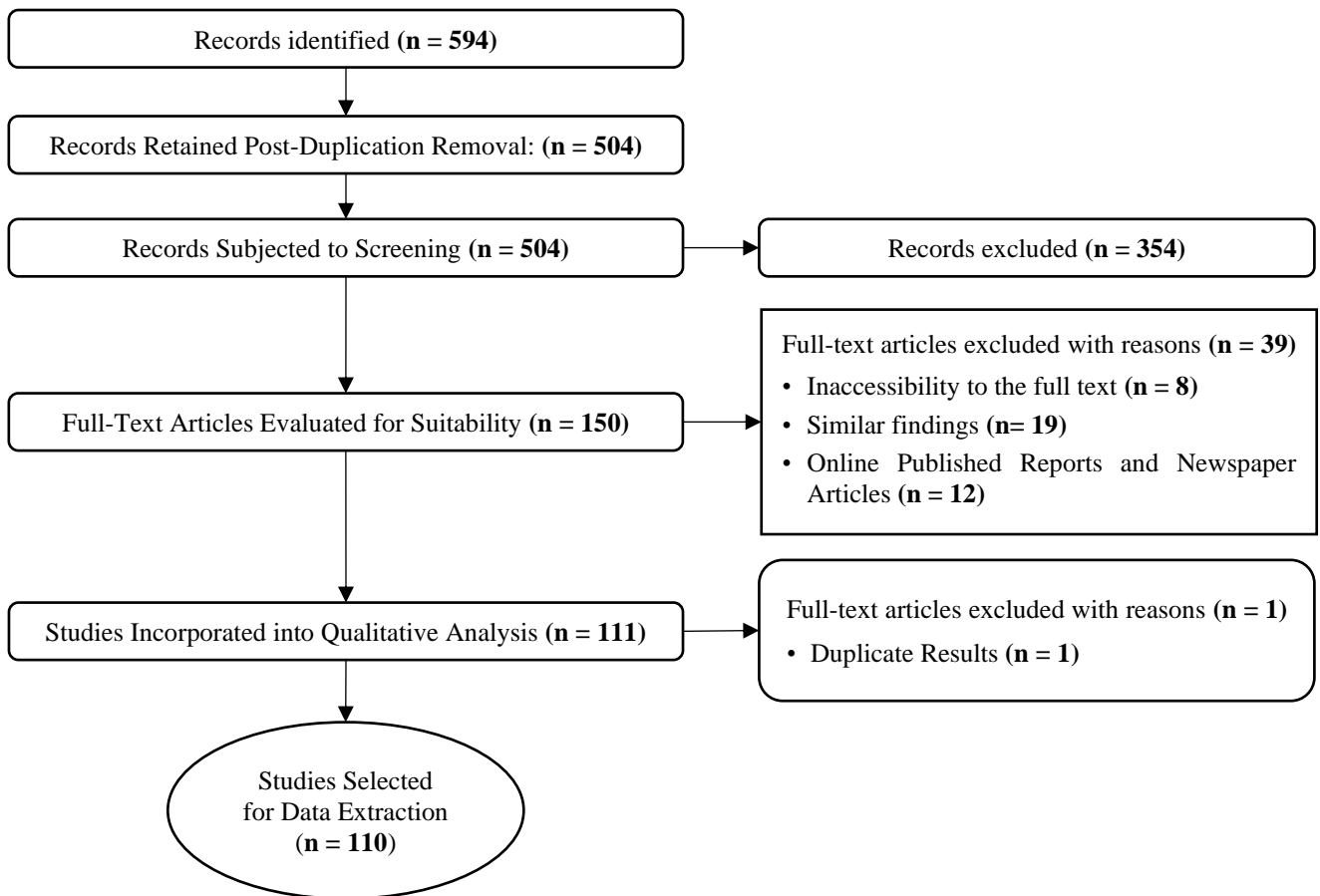
While there is considerable research on PET recycling methods, such as mechanical recycling and chemical depolymerization, less attention has been devoted to the integration of PET waste in construction materials. Studies have focused on the potential of various waste materials in construction to promote sustainability; however, the utilization of PET waste, particularly in concrete, remains underexplored. This gap highlights a critical area for investigation, given the dual benefits of reducing environmental pollution and addressing the construction industry's demand for sustainable materials.

In light of the identified gaps, this study explores the feasibility of using recycled PET waste as an alternative construction material. Specifically, it investigates the mechanical properties of concrete integrated with PET aggregates, offering insights into the potential of PET waste to replace conventional materials. This research contributes to the body of knowledge by comprehensively evaluating PET's viability in construction applications by conducting a systematic review coupled with experimental analysis. Moreover, it proposes a sustainable pathway for managing PET waste, aligning with global sustainability goals.

## 2. Research Methodology

This research was meticulously planned to explore the potential of PET waste as an alternative to natural construction materials. The study began with a comprehensive literature review to identify gaps in the current understanding and opportunities for innovation in using PET waste in construction. The objective was to assess PET waste's environmental impact and utility as a sustainable construction resource. Following this, a systematic methodology was set to evaluate the performance of PET waste when used as a substitute for natural sand and as an additive in cement in various proportions. This approach allowed for a controlled investigation into the effects of PET waste on concrete properties, enabling us to draw comparisons and identify optimal configurations for its use in the construction industry.

The method employed for this critical article is the Systematic Literature Review (SLR) approach, formulated by Moher et al. [29]. This methodological approach is depicted in Figure 1, which outlines the data selection procedure. The research methodology involved an extensive search across multiple databases (e.g., Web of Science, Science Direct, Google Scholar, and Scopus) alongside various published online technical reports. This search was broad-ranging, encompassing a wide array of relevant references, all of which were considered for inclusion in this study. Key subject terms such as "polyethylene terephthalate (PET)," "recycled plastic waste," "PET waste in concrete," "PET waste as construction material," and "replacement of PET in concrete as sand" were systematically employed in the SLR to ensure a thorough investigation of relevant literature.



**Figure 1. Methodology for the data selection**

The search focused on construction materials based on PET, particularly those replacing natural substances. Any articles from irrelevant sources were excluded from consideration, leading to the removal of 354 items. For this review, 110 publications were carefully chosen for an in-depth subject matter analysis. This study incorporates data from various sources, including research papers, reports (practical and theoretical), comprehensive reviews, and proceedings from relevant conferences.

The data collected from the literature review was systematically analyzed to draw meaningful insights into using recycled PET waste in construction. Additionally, a meta-analysis of the gathered literature was performed to contextualize our experimental results within the broader scope of existing research.

### 3. PET as a Non-Bio-Degradable Waste

The escalation in global population, pervasive urbanization, and enhanced living standards, accompanied by the extensive utilization of polymers, have led to the generation of non-biodegradable polymeric waste. This phenomenon poses a persistent global environmental challenge. Concurrently, the escalating energy demands of modern society represent a significant concern. In contemporary times, polymeric materials are integral to everyday life, attributed to their broad spectrum of applications across diverse sectors. Consequently, the management of polymer waste and its global production have witnessed a substantial increase in recent decades. Notably, these polymeric wastes are more voluminous than other organic residues and are characterized by their non-degradable nature. Therefore, the accumulation of debris in landfills contributes to environmental hazards, and massive space consumption may lead to the continuous demand for this non-biodegradable waste [30-33]. Polymeric waste materials predominantly consist of a composite of various polymers, including but not limited to Polyethylene Terephthalate (PET), High-Density Polyethylene (HDPE), Low-Density Polyethylene (LDPE), Polypropylene (PP), Polystyrene (PS), Polyvinyl Chloride (PVC), and Polyamide (PA) [34-37].

In academic literature, Polyethylene Terephthalate (PET) is recognized by commercial trade names such as Decron, Mylar, Recron, and Terylene. It is characterized by a notable crystalline melting point of approximately 260°C. The molecular structure of PET contributes to its increased mechanical strength, fatigue resistance, particularly efficacious till 150-170°C, and substantial toughness. Additionally, PET exhibits commendable resistance to chemicals, solvents, and hydrolysis. Their exceptional crease and abrasion resistance distinguish the fibers derived from PET.

Furthermore, these fibers can undergo treatment with specific cross-linking resins, enhancing their durability with permanent wear and wash characteristics [38–40]. These fibers can be blended with cellulosic fibers and other cotton

materials to give moisture permeation. Thus, these fibers find diverse applications, including in upholstery, wearing apparel, thread, curtains, industrial fibers, tire cord filaments, and fabrics used for industrial filtration. PET finds extensive application in engineering plastics, where it serves as a substitute for metals such as aluminum and steel. Precision moldings that involve substitution are commonly used in various applications, including but not limited to electronics, appliances, and automotive components. The semi-crystalline polymer Polyethylene Terephthalate (PET) has garnered significant attention for its remarkable versatility and potential for sustainable applications across diverse industries. This thermoplastic polymer is highly favored for its exceptional chemical resistance, spinnability, and mobility.

PET is produced through a multi-step process that involves melt phase polymerization, which results in resins with an inherent viscosity varying from 0.5 to 0.7 dL/g. The synthesized PET is then subjected to a solid-state polymerization process to create high-molecular-weight polymers. During this process, a low-molecular-weight melt phase polymer solid is heated to a temperature exceeding its Glass Transition Temperature ( $T_g$ ) yet below its boiling point. The outstanding mechanical properties imparted by this process establish PET as a preferred material for various applications, including manufacturing robust bottles, flexible films, and durable fibers [41–43]. The repeating units of the PET polymer, each ~1.09 nm in length and with a molecular weight of approximately 200, covalently connect to form its extended chain structure. These polymers are formed through the interaction between terephthalic acid and ethane 1, 2 diol, resulting in a structure capped with -OH on the right side and H on the left, as depicted in Figure 2. The polymerization process is marked by the creation of water, which is subsequently eliminated under vacuum conditions and at elevated temperatures. It is crucial to note that the presence of water can rapidly depolymerize the structure in its molten state. Therefore, it is essential to thoroughly dry the polymer before the melt-spinning process for fiber production. The molecule's rigidity can be attributed to incorporating an aromatic ring conjoined with a short aliphatic chain.

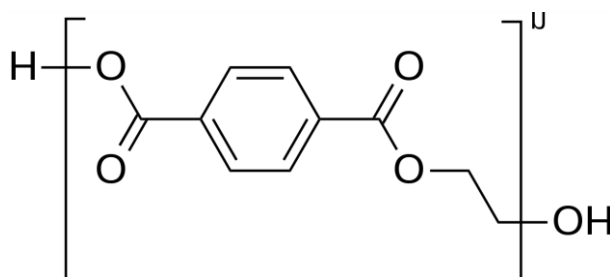


Figure 2. Structure of PET

Non-biodegradable polymers do not break down in environmental and naturally safe conditions by biological processes. Most plastics are non-biodegradable because they are widely used for their low cost, durability, and versatility. This durability is based on the benign, uncommon plastic target of bacteria, making it non-biodegradable. However, some chemical plastics can be biodegradable by breaking the polymer structure. PET has the properties of strength, toughness, heat resistance, and moisture and gas barriers. It has applications in soft drink bottles, beer bottles, water bottles, dressing containers, ovenable film, and trays. Plastics are used because they have many long-lasting applications, but unfortunately, they create a huge pollution problem. Plastic is very cheap, so it gets easily discarded, and its persistence can harm the environment significantly over decades [44].

### 3.1. Recycling Methods

Polymer plastics have become increasingly popular over the last decade due to their exceptional properties, including corrosion resistance, user-friendly design, low density, and many other unique characteristics. Consequently, recycling has become a critical process to mitigate environmental effects and illustrates one of the most critical sectors in the contemporary plastics industry. The degradation of polymer plastics occurs through four primary environmental mechanisms: photodegradation, hydrolytic degradation, biodegradation (facilitated by microorganisms), and thermo-oxidative degradation. With photodegradation, polymer plastic's natural degradation process begins due to the sunlight, giving the activation energy required to incorporate oxygen atoms into the plastic polymer. After the natural degradation, the thermo-oxidative degradation begins with incorporating oxygen atoms into a polymer, where the plastic converts into a brittle form and starts breaking into smaller pieces. Microorganisms now convert carbon from the polymer chain into carbon dioxide or incorporate it into bio-molecules. It will take considerable time, as discussed by Francis [45]. Therefore, recycling is one of the solutions to these problems. Here are some recycling methods that have been used to solve these problems.

#### 3.1.1. Primary Recycling

The recycling approach is a method known for its simplicity and cost-effectiveness. It involves repurposing products in their original form, which means the materials are used again without significant processing or alteration.

This approach has advantages, such as being inexpensive to implement compared to more complex recycling methods. A key sustainability challenge associated with these materials lies in their finite reusability. Their performance deteriorates after a specific number of cycles, ultimately rendering them unsuitable for further use. Therefore, it is essential to consider alternative recycling methods to ensure that we can maximize the use of our resources while minimizing waste [46-48].

### 3.1.2. Mechanical Recycling (Secondary Recycling)

This technique applies exclusively to thermoplastic polymers, which can be remelted and reshaped into final products. It is a physical process where waste plastic is transformed into granulated pellets or flakes through shredding and cutting, which is suitable for manufacturing. These prepared samples are then melted and extruded to create new products. Tailoring the final material's properties might involve incorporating virgin material alongside the reprocessed component, following established blending protocols. Plastic waste will be reduced dramatically after all these processes, as shown in Figure 3. A drawback of this recycling technique is the multifariousness of solid waste and the deterioration of product property in each cycle [45, 46].



Figure 3. Mechanical recycling process

### 3.1.3. Chemical Recycling (Feedstock Recycling)

Beyond mechanical recycling, a distinct avenue for polymer valorization lies in chemical reactions that induce their chemical depolymerization, yielding either reconstituted monomers or lower-molecular-weight oligomers. This approach deconstructs the original polymer chains at the molecular level. Subsequently, these monomers can be repurposed in new polymerization reactions to fabricate the original or related polymeric products [49]. The main chemical reactions used to decompose polymers into monomers are shown in Figure 4 [50-52].

There are various methods to break down Polyethylene terephthalate (PET), including water, acids, alcohols, or glycols. Each method utilizes different reagents and generates different products. Hydrolysis, for instance, involves the reaction of PET with water in acidic, alkaline, or neutral environments to break it down entirely into monomers. On the other hand, glycolysis involves inserting ethylene glycol into PET chains to produce (hydroxyethyl) terephthalate (BHET) [53, 54]. While methanolysis employs methanol at elevated temperatures and pressures (180-280°C, 2-4 MPa) to depolymerize PET into primary products like ethylene glycol (EG) and dimethyl terephthalate (DMT), pyrolysis offers an alternative route by thermally decomposing polymeric materials in the absence of oxygen [55].

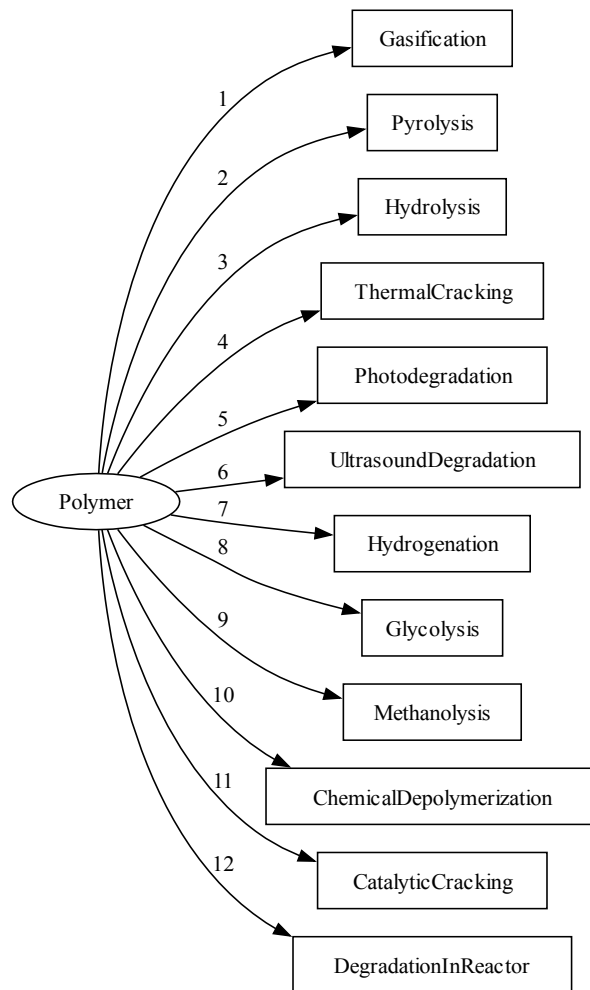


Figure 4. Various chemical reactions that decompose polymers [51]

### 3.1.4. Quaternary Recycling (Energy Recovery)

This method focuses on harnessing the energy content inherent in plastics. Incineration is recognized as an efficient approach for reducing the volume of organic materials. Chemical recycling presents a promising avenue for advancing sustainable development due to its ability to deconstruct polymers and recover valuable feedstocks for reuse, potentially complementing and enhancing existing mechanical recycling methods. This method gives rise to monomer formation from which the polymeric material is made [46, 56-58]. The challenges and advantages of recycling methods are represented in Table 1.

Table 1. Overview of recycling methods discussed

Techniques	Limitations	Benefits	Sources
Mechanical Recycling	Property deterioration, the necessity for pre-treatment	Cost-effectiveness, established familiarity, high efficiency	[49, 59]
Chemical Recycling	Primarily suitable for condensation polymers	Simplified process, effectively applicable to PET	[49, 52, 60]
Energy Recovery	Ecological acceptability concerns	Significant energy generation from polymers	[45, 61]

### 3.2. Characterization of PET Waste-Based Concrete

The analysis of concrete microstructure often employs a Scanning Electron Microscope (SEM). It has been observed that concrete containing Polyethylene Terephthalate (PET) exhibits a relatively asymmetrical morphology, which is conducive to the formation of pores ranging in size from 2 to 4  $\mu\text{m}$ . The connection between PET fibers and the matrix is strengthened by many brilliant inclusions (cement formations) ringed by hydrating chemicals on the surface. The contact between the cement matrix and PET particles in concrete containing PET is significantly denser. A further benefit of PET fiber is reducing micro-cracks [46].

Fourier Transform Infrared (FTIR) studies can be conducted to identify the functional group characterization of PET waste. The obtained peaks at 1740 and 750  $\text{cm}^{-1}$  indicate the presence of C=O—O stretching, and at 1250  $\text{cm}^{-1}$ , indicate C—O—C stretching. The phthalate ester group present in PET makes it flexible, enhancing PET-based concrete's flexural property [62]. Pereira et al. (2017) presented a study on a composite from PET waste with geopolymer concrete waste

(GCW) in the varied ratio (PET/GCW) 80/20, 60/40, and 50/50 (wt %). They characterized the composite by FTIR, FEG-SEM, X-ray fluorescence, and thermogravimetric analysis (TGA). Geopolymer concrete waste was used to create composites in its untreated state (U-GCW) and after oleic acid (T-GCW) treatment. To verify the composition of these materials, an analytical assessment was performed on both the geopolymer concrete waste and Polyethylene Terephthalate (PET) using techniques like X-ray Fluorescence and Fourier Transform Infrared (FT-IR) Spectroscopy, which established the geopolymer structure.

The thermal stability of the polymer composites was thoroughly investigated using Thermogravimetric analysis (TGA). This technique revealed a trend of increasing stability with higher filler content. Field Emission Gun Scanning Electron Microscopy (FEG-SEM) was employed to elucidate the observed behavior further and delve into the adhesion characteristics between the fillers and polymer matrix in the treated composites. The findings suggested that oleic acid on the surfaces of geopolymer concrete waste played a crucial role in promoting strong adhesion. Mechanical testing demonstrated the robust performance was consistent across all composite samples, with further improvement achieved through compatibilization [63].

Further bolstering the case for utilizing PET waste in construction, a meticulous study on the stability and morphological characteristics of high-strength PWBs was conducted, offering valuable data on their structural integrity and microstructural features. These were created by combining foundry sand (FS) with PET waste (PW) in varying ratios (PW: FS) of 20%, 30%, and 40% relative to the dry mass of FS. In this study, when compared to burnt clay bricks, the developed PWBs were tested for tensile and compressive strength, durability, and load-bearing capability. Scanning electron microscopy (SEM) examinations were used to further examine the morphological structure of the bricks. This study shows that utilizing plastic waste and different amounts of foundry sand can be an innovative solution for brick masonry. This approach can improve the load-bearing capacity and the tensile and compressive strength of the resulting product compared to the traditional burned clay brick.

The SEM study confirmed the formation of a stable foundry sand matrix framework within the PET waste bricks, evidenced by its thorough integration with the surface and interior sections. Additionally, the presence of viscous floccules suggests further strengthening mechanisms. The PWB morphology had stronger inter-cluster bonds on the surface than clay bricks. The SEM demonstrated that the microstructure of PWB developed with lesser porosity; thus, the plastic waste bricks do not require wetting before masonry building. The results showed a practical methodological strategy for producing high-strength masonry bricks from a blend of PET waste and used foundry sands [64]. Lee et al. [65] presented a study on chemically treated PET and PP concrete at 10%, 20%, and 30% incorporation of PET and PP waste by weight of cement. This work examines the impact of treating PET wastes with calcium hypochlorite and hydrogen peroxide solutions before using them as replacements for coarse aggregate in concrete.

Analysis of SEM provided revealing insights into the interfacial bonding between the cementitious matrix and PET aggregates. The control mix exhibited suboptimal adhesion, characterized by sizable gaps visible in the SEM images. However, a significant improvement was observed in concrete mixes containing  $\text{Ca}(\text{ClO})_2$ -modified PET aggregates and  $\text{H}_2\text{O}_2$ -treated PE aggregates. These treated mixes displayed markedly reduced gaps between the matrix and aggregates, signifying enhanced bonding. The chemical treatments applied to the plastic aggregates were found to augment the binding strength and diminish the gap at the interfacial transition zone (ITZ). Such improvements in the microstructure contributed to a decrease in permeability and porosity, simultaneously enhancing the compressive strength of the material [65]. Expanding upon understanding of recycled PET waste in concrete, Kangavar et al. [66] investigated its performance as a partial replacement for fine aggregate (0%, 10%, 30%, and 50%). This work evaluated some properties of PET-containing concrete, such as compressive strength, workability (slump), elastic modulus, density, tensile strength, crack mouth opening displacement, and flexural strength. The SEM analysis characterized the microstructure study of the PET-contained concrete. PET waste granules improved the durability and mechanical properties of the PET-modified concrete in this study. SEM imaging demonstrated an even dispersion of PET granules within the concrete mix at replacement levels of up to 10%. However, increasing the substitution ratio to 30% and 50% led to a more uneven distribution and pronounced demarcation between the PET granules and the cement matrix, attributed to increased porosity. These studies' compressive, tensile, and flexural strength tests revealed significantly enhanced performance, especially in concrete samples containing 10% PET particles [66].

### 3.3. Applications of PET Waste

After the recycling and recovery methods of plastics, various applications of recycled plastics are summarized in Table 2. The PET production rate is projected to increase by 30 million tonnes by 2020. In India, nearly 900 kilo-tonnes of PET were utilized during 2015-2016 [67]. Over the past sixteen years, there has been a significant increase in the usage of PET for manufacturing drinking bottles. In 2000, the global consumption rate stood at 300 billion, which soared to 480 billion by 2016. This growth trend is expected to continue, and the consumption rate is forecasted to reach a staggering 583 billion by 2021 [68]. The National Chemical Laboratory (NCL) and the PET Packaging Association for Clean Environment (PACE) [67] indicate that India achieves a PET recycling rate of 90%, exceeding those of Japan at 72.1%, Europe at 48.3%, and the United States at 31%. Within India, PET waste recycling is segmented across various sectors, with the organized sector responsible for 65% of recycling activities, the unorganized sector contributing 15%, and the remaining 10% repurposed domestically, forming a substantial part of the overall recycling process [67].

**Table 2. Utilization of recycled plastics applications**

Product Identification Code	Plastic	Applications	References
PETE	PET	Detergent bottles, drinking bottles, carpet fiber, clear film for packaging	[69]
HDPE	HDPE	Mobile components, detergent bottles, agricultural pipes, pallets, toys	[69, 70]
V	PVC	Textile, drinking bottles, packaging for food, medical materials	[71]
PP	PP	Kerb side recycling crates, compost bins	[46]
PS	PS	Disposable cutlery	[72]
LDPE	LDPE	Plastic tubes, bottles, food packaging	
OTHER	Other materials, such as Polylactic Acid, Nylon, Acrylonitrile Butadiene Styrene, and Polycarbonate	Containers	[73]

#### 4. PET Waste in the Construction Industry

PET recycling research was undertaken for construction materials over the past decade (2010 to 2020). The present section aims to investigate research articles that have been reviewed for using PET in different sustainable construction materials. This has been an activity of interest for a considerable period, from the early decade [74, 75]. 2012, global plastic production was estimated to be approximately 280 million tonnes. Of this, around 130 million tonnes were either landfilled or recycled. On an annual basis, the worldwide processing of plastics reaches nearly 300 million metric tonnes, serving various industries [48]. Within this context, India specifically recovers about 6.5 to 8.5 million tonnes of plastic annually as waste, predominantly collected from municipal sources [76]. A sustainable solution suggested by Padgelwar et al. [20] is recycling plastic waste to reduce environmental haggard. Recycling plastic waste as a value-added component in concrete presents a promising avenue for alternative use of plastic waste [77]. After carefully reviewing the available research articles in the mentioned period, it is noticed that not much research has been done on this topic. It was observed that this area of research has fascinated researchers for the last decade. This waste material gives new research opportunities for civil engineering construction industry researchers [75, 78-82]. Table 3 provides the construction sector's critical findings on waste PET recycling.

**Table 3. Wastes PET recycling for construction sectors**

References	LWM	OMM	MI	Significant Remarks
[83]	PET	Portland cement	Cementitious mortar	Incorporating PET plastic aggregates into cement-based materials has opened new doors for creating robust and energy-absorbing substances. These materials have displayed exceptional characteristics for engineering purposes, especially for structures that require resistance to dynamic or impact events. Research has yielded promising results, showing PET-based cementitious materials can withstand high-stress loads without cracking or breaking. This discovery presents a significant breakthrough in the construction field and provides a sustainable solution for recycling PET waste.
[84]	PET	blasting sand	Thermoplastic composites	The study prepared composite materials to be used as floor tiles, paving slabs, or bricks in the construction industry, with good structural performance.
[85]	PET	Aggregate, bitumen, and Portland cement	Stone mastic asphalt (SMA)	The study results indicate that integrating PET waste into mixtures (e.g., Stone Mastic Asphalt) significantly impacts the resulting mixture's properties. This inclusion has the potential to improve the sustainability of road construction by promoting the reuse and recycling of waste materials. Moreover, it can enhance the mixture's ability to resist permanent deformations and increase its stiffness while reducing binder drainage. Roads constructed with SMA mixtures containing waste PET can potentially last longer and require less maintenance, leading to cost savings and environmental benefits.
[86]	PET	Natural river sand and limestone powder	Cementitious Mortar	This study used recycled PET bottles to produce plastic mortar. Critical parameters such as compressive strength, gradation, the ratio of sand to PET, curing conditions, and temperature exposure were methodically examined. It was observed that the plastic sand mortar exhibited superior compressive strength at specific gradation levels. The ideal proportion of sand to PET was identified as 3:1; remarkably, the mortar accomplished over 90% of the projected seven-day strength by a mere 3 hours. Furthermore, when subjected to higher curing temperatures, the mortar displayed enhanced compressive strength.
[87]	PET	Crushed basalt aggregate and asphalt	Roadway pavement	This study explored the potential of incorporating reclaimed PET bottle waste into asphalt and asphalt mixtures. The results demonstrated that newly developed additive products derived from PET waste enhanced the performance of these materials and provided a sustainable and advantageous option for diverting this ecologically harmful waste stream. This approach offers a promising avenue for promoting environmental responsibility and improved infrastructure performance.

[88]	PET	Portland-limestone blended cement, lime, and hydraulic lime	Lightweight Plaster	The research demonstrated that environmentally sustainable plasters can be formulated by substituting virgin materials with 100% PET waste components. These plasters, characterized by their low thermal conductivity and notable lightness, have exhibited energy efficiency. Based on the outcomes of sensitivity tests concerning sulfate reactions in hydraulic binders, these plasters show potential applicability in restoring ancient masonry.
[89]	PET	Asphalt cement 60/70, sand, granite chippings, and stone dust	Bituminous asphaltic concrete	This study stands out in developing a sustainable method tailored for the 21st century, focusing on recycling PET waste plastic bottles into bituminous asphaltic concrete (BAC) in North Central Nigeria. This approach is primarily driven by the dual benefits of environmental conservation, through the diversion of multiple million tons of PET waste from landfills, and economic advantages, including extended service life of highways, efficient management of natural resources, and potential revenue generation from handling such waste.
[90]	PET	Portland cement and water	Plastic cement	Polyethylene packages, including bottles and food crates in the 10 to 80% range, were used experimentally in the temporary reinforcement structure. The study results show positive findings for producing plastic cement from polyethylene waste. Results emphasize that their density has decreased, flexibility has increased, and workability has improved, resulting in light materials.
[91]	PET	Fine & coarse aggregate and cement	Structural concrete	In India, a significant portion of waste plastic, approximately 40%, is not reused. This research involved testing eleven concrete mixtures, where plastic was utilized as a partial substitution for sand. The utilization of sand-graded PET fragments was capped at a 10% substitution ratio. The findings of this study suggest that replacing waste plastic with sand could potentially conserve 820 million tons of sand annually.
[92]	PET	Recycled concrete aggregate (RCA), crushed brick (CB.)	Construction materials	When combined with Recycled Concrete Aggregate (RCA) and Crushed Brick (CB), the PET mixture underwent testing to evaluate its crucial geotechnical properties. This assessment also included the geo-environmental parameters of PET, RCA, and CB following specified standards. It was found that all blends met the California Bearing Ratio (CBR) requirement of 80%, rendering them suitable for use in pavement applications.
[93]	PET	Asphalt cement, crushed aggregates, hot mix asphalt (HMA)	Fiber-Modified Asphalt	The cost-advantage analysis has shown that fibers can be a dependable way of improving typical asphalt mixtures' efficiency at a reasonable cost for transportation agencies. The next step of this research is a microscopic study to ensure that fiber is well spread into the asphalt mix. The fiber length impacts the mixing characteristics and the fatigue life determination for fiber-modified asphalt mixes.
[64]	PET	Waste and Foundry Sand	PET waste-based bricks	PET waste bricks were fabricated using varying ratios of PET waste to foundry sand, specifically 20%, 30%, and 40% of the total dry weight of the foundry sand. The study evaluated these PET waste bricks' durability, compressive, and tensile strength. Additionally, their load-bearing capacities under tension and compression were analyzed and compared with those of traditional heated clay bricks.
[87]	PET	Asphalt and hot mix asphalt (HMA)	PET-Modified Asphalt	This research explores the effectiveness of two PET waste-derived additives, Viscous Polyol PET (VPP) and Thin Liquid Polyol PET (TLPP), in modifying asphalt and HMA mixtures. The results demonstrated that TLPP and VPP effectively improve the asphalt's cold weather flexibility, resistance to fatigue cracking, and HMA's resistance to moisture damage and mechanical deformation.

LWM = leading waste materials, OMM = Other mixing materials, MI = Materials invented

## 4.1. Engineering Properties

The engineering properties of any material are a prime concern for practical utilization in any construction industry. Any recycled material can be replaced as a filling or supplementary cementitious materials (SCM) because its compressive and flexural strength are the two most essential parameters for the approval of any construction material [94, 95]. The comparative strengths were determined by calculating the materials' design strength ratio in comparison to the reference design strength of the concrete. Documentation of the incorporation ratio of PET in sustainable construction materials is extensively reported in the literature, as referenced in surveys [96, 97].

### 4.1.1. Comparative Analysis of Compressive Strength

The following Figure 5 compares the relative compressive strength and the percentages of PET as reported in various published studies. The compressive strength variation of construction material by incorporating 1-20% PET is presented by SLR for this review article.

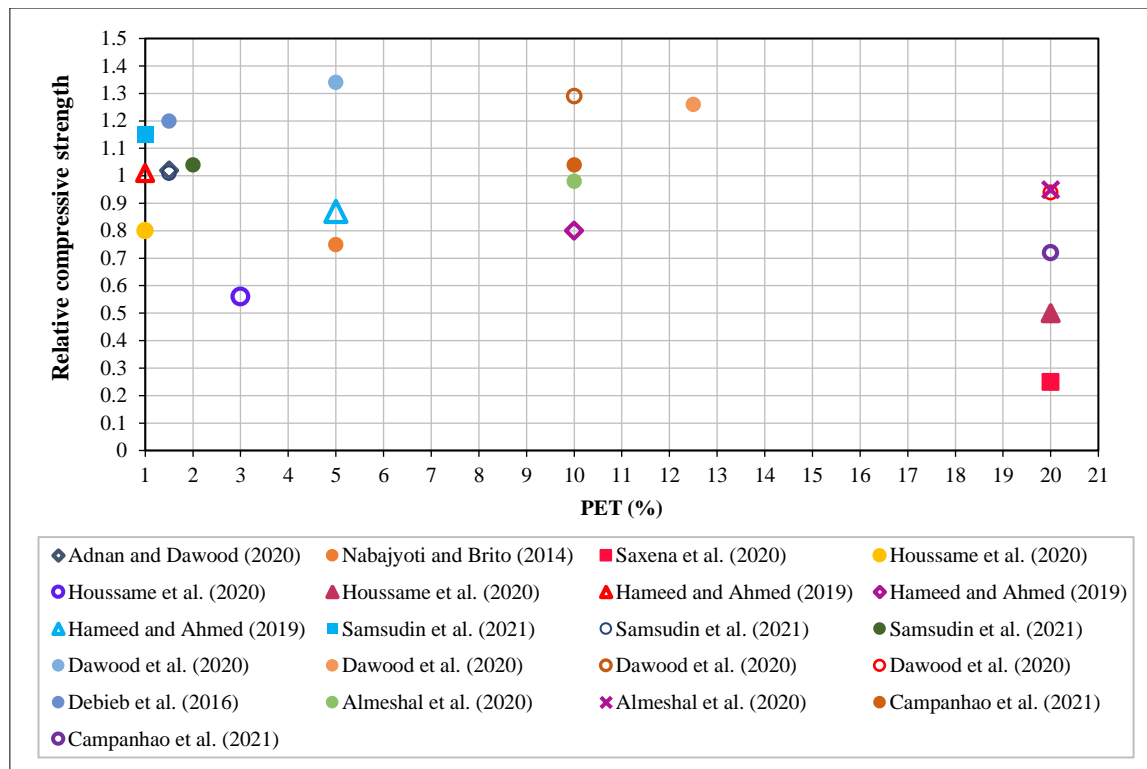


Figure 5. Relative compressive strength variation with PET percentage

Limami et al. [98] examined the efficacy of clay bricks enhanced with PET additives, focusing on their potential practical applications within the building industry. As seen in Figure 5, the relative strength is calculated from the ratio of material design strength to concrete design strength. An inverse correlation was seen between the strength and the increasing percentages of PET additives. Specifically, at PET additive levels of 1%, 3%, and 20%, there were corresponding reductions in compressive strength of approximately 20%, 40%, and 50%, respectively. The reason for reduced strength at higher PET replacement with clay is the incorporation of porosity in the sample due to PET additives compared to reference samples without PET. The more significant proportion and finer grain size in polymeric additives PET is the main reason for producing porous brick samples, ultimately reducing the compressive strength. Hameed & Ahmed [99] disclosed compressive strength results at 1%, 5%, and 10% of PET incorporation. The study observed a nuanced trend in compressive strength relative to PET percentages. A marginal increase of approximately 1% in compressive strength was noted at a 1% PET concentration, while PET levels at 5% and 10% resulted in compressive strength reductions of about 13% and 20%, respectively. This pattern indicates a clear correlation where PET percentage increases are associated with compressive strength decreases. Further, Samsudin et al. [100] evaluated the compressive strength of concrete with 1%, 1.5%, and 2% PET. Figure 7 illustrates the increase in compressive strength values by 15%, 1%, and 4% by adding 1%, 1.5%, and 2% PET to the concrete mixture. The study shows that 1% of PET fiber concrete mixture shows better fiber distribution than others. Therefore, the highest compressive strength was obtained at 1% PET fiber content. Dawood et al. [101] explored the efficacy of concrete made using PET waste, replacing natural river sand with 5%, 10%, 12.5%, and 20% PET waste. The findings revealed an increase in compressive strength between 5% and 12.5% PET incorporation, with noted enhancements of 34%, 29%, and 26% at 5%, 10%, and 12.5%, respectively. However, at a 20% substitution level, a notable decline in compressive strength was recorded, showing a 6% reduction compared to natural river sand. These results suggest that compressive strength improves with PET waste replacement up to 12.5%, but it diminishes at higher replacement ratios, especially at 20%. It leads to the conclusion that replacing natural river sand with PET waste up to a threshold of 12.5% benefits compressive strength.

The studies done by previous studies at 20% replacement of natural river sand with PET waste revealed a 75%, 5%, and 28% reduction in compressive strength [102-104]. However, the variation in strength was seen in different studies, and trends show precise observation of declining strength at a higher replacement ratio of up to 20%. Different design mixes and using numerous SCMs in the same concrete mix are the leading causes of strength differences at the same replacement ratio. The reduction in compressive strength is demonstrated by a replacement ratio of 20% PET waste. Studies have revealed that the results are more positive when the replacement ratios are between 1 and 12.5%. At a 10% replacement ratio, a threshold and ideal results were observed. The microstructure is demonstrated to become denser with smaller quantities of PET waste, increasing the material's compressive strength. Because it is so fine, PET trash will have a large surface area and establish a strong binding with the cement and sand. The right amount of PET trash will also offer compaction.

#### 4.1.2. Flexural Strength (Relative)

The relative flexural strength and PET proportions from published research are shown in Figure 6. The flexural strength variation of construction material by incorporating 0.5-20% PET is presented by SLR for this review article.

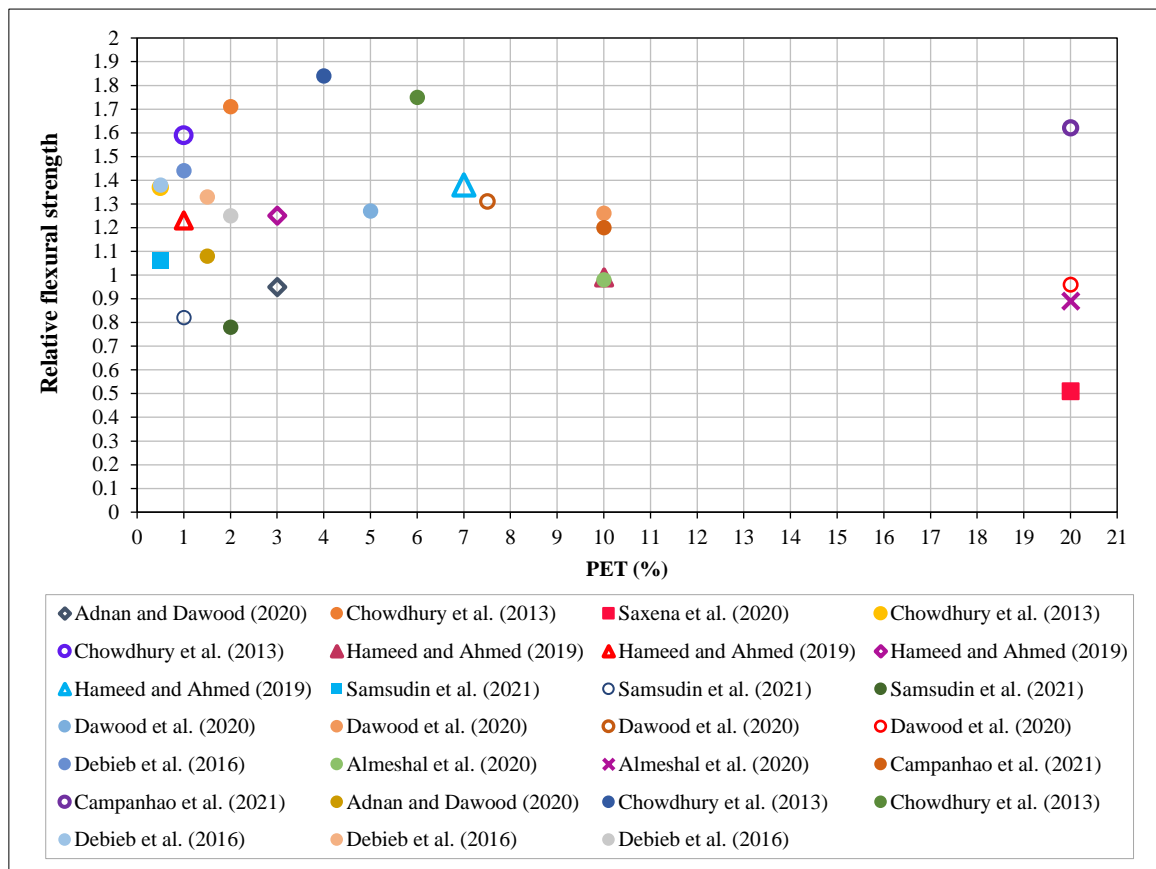


Figure 6. Relative flexural strength variation with PET percentage

Hameed & Ahmed [99] studied the performance of recycled plastic aggregate concrete by replacing 1%, 3%, 7%, and 10% PET waste with natural fine aggregate. Figure 6 shows flexural strength increased by 23%, 25%, and 38% at 1%, 3%, and 7% incorporation of PET aggregate. When the replacement ratio reached 10%, the strength was decreased by about 1% approximately. The interfacial shear strength of the inner layers and the compressive and tensile strengths of the top and bottom surface determine how resistant the material is to bending if it consists of layers of matrix and filler material. Incorporating PET aggregate in concrete structures slows growth and halts the propagation of fractures at particular percentages [105]. As a result, the ratings for flexural strength are improved when a small quantity of aggregate is added; nevertheless, this can also result in flaws in the concrete (such as voids), which lower the strength of the material when it reaches the optimum.

Dawood et al. [101] investigated PET waste concrete's strength (flexural) performance when incorporating 5%, 7.5%, 10%, and 20% PET waste aggregate in place of natural river sand. The study results show an increment in flexural strength from 5-10% PET waste aggregate. The increments in flexural strength of 27%, 31%, and 26% at 5%, 7.5%, and 10% incorporation of PET waste have been observed. At a 20% substitution ratio, a sudden fall in flexural strength was noted. A 4% decline in strength (compressive) at 20% replacement of PET waste with natural river sand was seen. The results showed that the flexural strength parameter declined at a higher replacement ratio of up to 20%. This study concluded that up to 10% of the replacement of natural river sand with PET waste positively affects flexural strength.

Guendouz et al. [106] have researched incorporating 0.5%, 1%, 1.5%, and 2% PET waste fiber in new concrete. Experimental results revealed the enhancement in flexural strength value by 38%, 44%, 33%, and 25% at 0.5%, 1%, 1.5%, and 2% addition of PET waste fiber by weight of cement. The ability to use leftover PET fiber to create concrete that behaves more ductility is a desirable consequence. Pereira De Oliveira & Castro-Gomes [107] found that 1.5% of PET fibers at 28 days increased the flexural strength of mortar by around 30%. In their study, Ochi et al. [108] explored various techniques for reinforcing fibers extracted from recycled PET waste bottles. They also evaluated the flexibility of concrete specimens subjected to these reinforced fibers. The findings of their study were comparable to previously reported results.

Samsudin et al. [100] presented a study on PET fiber concrete at 0.5%, 1%, and 2% incorporation of PET fiber by weight of cement. The study proved that flexural strength value increased by 6% at 0.5% of PET fiber. Further increasing the PET fiber percentage revealed a reduction in flexural strength. It has been noticed that flexural strength was reduced at 1% and 2% PET fiber, approximately 18% and 22% compared to reference concrete. It has been proven that PET fibers perform effectively with other components in concrete at an optimum 0.5% compared to regular concrete.

In previous studies [109, 110], the replacement of natural sand by PET fiber incorporation at 0.5%, 1%, 2%, 4%, and 6% in new concrete. The study showed that replacing waste PET fiber in new concrete significantly improved flexural strength. The results showed a continuous increment of about 37%, 59%, 71%, and 84% at 0.5%, 1%, 2%, and 4% waste PET fiber content addition. With an increase in replacement percentage, the flexural strength of samples containing PET fiber as fine aggregate gradually rises; however, as it is already between 4 and 6%, it may fall for further replacement percentage.

## 5. Conclusions

This critical review has systematically explored the innovative application of PET waste as a sustainable alternative in the construction industry, particularly as a replacement for natural sand and an additive in cement. Through a comprehensive analysis of over 110 peer-reviewed publications, this study has illuminated the significant theoretical and practical contributions of incorporating recycled PET waste into construction materials. The study's investigation reveals that optimal utilization of PET waste enhances construction materials' compressive and flexural strengths and alleviates environmental pollution attributed to PET waste accumulation.

Additionally, this study underscores the imperative for a paradigm shift towards sustainable construction methodologies, advocating for a transition that encompasses the academic and research communities, policymakers, industry stakeholders, and civil engineering practitioners. The conclusions drawn are based on data extracted from 110 peer-reviewed articles.

- Past experimental studies disclosed that PET waste can be recycled using chemical and mechanical methods to form precursor material for sustainable development.
- Past experimental studies disclosed that recycled PET waste-based concrete can be characterized by the SEM, TGA, FTIR, and EDX, which could examine the microstructure of the concrete, thermal stability, and chemical composition.
- Past experimental studies disclosed that PET waste could be successfully replaced as a leading waste material to replace natural materials in the construction industry.
- Based on previous experimental studies, it has been observed that replacing natural sand with PET waste is in the range of 5-20%. Most studies' compressive strength threshold reached a 10% replacement ratio. If 10% of natural river sand is replaced with PET waste, it can positively affect compressive strength. However, it is essential to note that beyond this point, a reduction in compressive strength is observed, and a significant drop in strength is noted at 20% replacement. These findings suggest that while PET waste can be a valuable substitute for natural sand, there are limitations to the amount that can be used to maintain the desired level of compressive strength.
- For flexural strength, adding 0.5%, 1%, 1.5%, and 2% PET waste powder in new concrete was studied by the weight of the cement. Experimental results revealed the enhancement in flexural strength value by 38%, 44%, 33%, and 25% at 0.5%, 1%, 1.5%, and 2% addition of PET waste powder. However, all replacement ratios show an increment in flexural strength, its optimum value observed at 1% addition. Furthermore, it also affected the concrete specimens' flexibility and bending.

In light of the findings and the potential impact on sustainable development, this conclusion serves as a catalyst, urging the academic community to engage in further research that bridges the gap between theoretical exploration and practical application. It is incumbent upon the collective expertise of researchers, engineers, and industry professionals to innovate.

### 5.1. Recommendation for Future Research

The SLR on PET waste-based construction materials is discussed in this review study. As demonstrated by the SLR, numerous researchers have successfully produced fresh concrete using recycled PET waste. There isn't much research on substituting recycled PET waste for natural sand. It has also been emphasized that little is known about the resilience of PET waste-derived concrete. Uncertainty exists over the effects of PET waste; recycled fine aggregate and desert sand can be added to PET waste in new concrete to make it more sustainable. An in-depth study was done on the selected studies for this review article. Prior studies have shown that using up to 12.5% recycled PET waste as sand and 1% recycled PET waste powder by weight of cement is the best option for maintaining engineering properties. The implications of substituting natural sand in new concrete with recycled PET waste and other sustainable fine aggregate alternatives remain uncertain. Given the findings and current research, further investigations are warranted. Based on these insights, the following recommendations are proposed:

- It is advisable to experiment with incorporating recycled PET waste into the concrete design mix, particularly at an elevated replacement ratio of 20%. It should be done in conjunction with completely substituting river sand with recycled fine aggregate and desert sand.
- A thorough understanding of the strength and durability parameters of the concrete mixture is essential, especially after observing the collective effects of adding recycled fine aggregate and desert sand in higher proportions.

Developing a sustainability measurement model using AI and machine learning tools is also suggested. This model would specifically evaluate scenarios where recycled PET waste is amalgamated with 100% alternative sustainable sources of fine aggregates to replace natural sand.

## 6. Declarations

### 6.1. Author Contributions

Conceptualization, M.N.A. and O.A.; methodology, M.N.A.; validation, O.A. and M.N.A.; formal analysis, M.N.A.; investigation, O.A.; resources, O.A.; data curation, M.N.A.; writing—original draft preparation, M.N.A.; writing—review and editing, O.A.; visualization, O.A.; supervision, M.N.A.; funding acquisition, O.A. All authors have read and agreed to the published version of the manuscript.

### 6.2. Data Availability Statement

Data presented in this study is available in the article.

### 6.3. Funding

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### 6.4. Conflicts of Interest

The authors declare no conflict of interest.

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