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The Holistic Approach of Plastic Waste Recycling for Sustainable Development

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Abstract: The rapid increase in plastic production has led scientists and researchers to seek innovative and sustainable approaches for reusing and recycling plastic waste, aiming to mitigate its adverse environmental impact. Plastic waste is finding applications in various sectors, including construction materials, fuel conversion, household goods, fabric, and clothing, offering viable alternatives. Particularly, the utilization of plastic waste in construction materials has gained significant attention. This practice serves a dual purpose: it reduces plastic waste going to landfills or becoming litter and diminishes the reliance on mined construction resources, thus mitigating the construction industry's environmental footprint. This paper provides an overview of developments in utilizing plastic waste as a component of construction materials. Its incorporation as a binder, aggregate, fine aggregate, modifier, or substitute for cement and sand in the production of bricks, tiles, concrete, and roads is comprehensively examined. The impacts of adding plastic waste on properties such as strength, water absorption, and durability are thoroughly explored. The review classifies research studies depending on whether they relate to the incorporation of plastic waste in bricks and tiles or its inclusion in concrete for road construction. The utilization of plastic waste within construction materials emerges as a pivotal locus where environmental, industrial, and social concerns coalesce, propelling us toward a future that champions resource efficiency, ecological harmony, and sustainable prosperity. This paper serves as an illuminating guidepost within this trajectory, celebrating the metamorphosis of a burgeoning idea into a tangible, transformative reality within the larger narrative of sustainable development.

Keywords: Plastic Recycling, Waste Management, Plastic Waste, Sustainable Development, Environmental Impact

1. Introduction

The rapid and unplanned growth of urban areas often leads municipalities to struggle with the collection and disposal of escalating volumes of waste [1]. Within this context, effective municipal solid waste management remains an overlooked aspect of urban development, prompting the need for sustainable solutions. Among the various waste types, plastic solid wastes (PSW) stand out as a significant challenge. The pervasive use of plastics is due to their versatile characteristics, including low density, strength, durability, design flexibility, and cost-effectiveness. This has led to their utilization not only in packaging but also across automotive and industrial sectors. Notably, plastics play a substantial role in preserving and distributing food, which contributes to the presence of considerable PSW in the municipal solid waste (MSW) stream. While plastics are present across numerous MSW categories, it's imperative to understand the factors influencing effective waste management practices. Despite their favorable attributes, plastics also pose challenges within waste management systems. Recycling, positioned as a prime option in the solid waste management hierarchy, offers a means to mitigate the impacts of end-of-life (EoL) and end-of-use (EoU) post-consumer packaging plastic waste. Beyond aiding municipal solid waste management by diverting valuable materials from the primary waste stream and thereby reducing the overall waste volume to be collected and disposed of, as highlighted by Matter *et al.* (2013) as well as Troschinetz and Mihelcic (2009) [2, 3], recycling provides a platform to transform recovered plastics into new products [4, 5]. This approach enables reclaimed polymers to transition through multiple life stages, thus contributing to sustainable manufacturing practices. Recycling holds the distinction of being widely acknowledged as the "most environmentally sound" strategy for addressing MSW, second only to source reduction and reuse in its ecological benefits [6, 7]. Renbi *et al.* underscore recycling as the most positively received form of solid waste management practice and a crucial element of sound waste management [8]. In fact, recycling not only embodies a waste management strategy but also serves as an example of implementing the principles of industrial ecology, akin to natural ecosystems where there are no wastes, only resources [9]. In developing economies, the challenges of effectively managing municipal solid waste, particularly the recovery of post-consumer packaging plastic waste (PSW) for recycling, persist as a significant issue. While numerous studies have delved into plastic recycling, a substantial portion of these investigations have employed life cycle assessment (LCA) to assess the environmental, economic, and societal impacts along the processing and recycling chain [10, 11]. Some studies have explored solutions to mitigate the impact of critical phases during the production of recycled polyethylene terephthalate (RPET) fiber-based panels for building heat insulation [12]. Additionally, comparative assessments of diverse recycling technologies, along with evaluations of reprocessing methods for reclaimed polyethylene terephthalate (PET) resins (e. g. converting bottles to fibers), have been conducted [13, 10]. These inquiries have been instrumental in identifying sustainable technologies and enhancing the efficiency of reprocessing reclaimed resins. In contrast, limited research has been dedicated to analyzing the factors driving sustainable post-consumer packaging PSW recycling. A review conducted by Hopewell *et al.* (2009) focused on the challenges and opportunities within plastics recycling. This research underscored recycling as a pivotal strategy for managing end-of-life (EoL) waste stemming from plastic products [14]. Moreover, Al-Salem *et al.* conducted a comprehensive literature review centered on recycling and recovery pathways for plastic solid waste [15]. Their review emphasized the significance of incorporating recycling and energy recovery techniques within plastic manufacturing and conversion facilities. Both Hopewell *et al.* and Al-Salem *et al.* offered insights into plastic recycling by elucidating the intricacies of recycling processes and highlighting the associated challenges and opportunities [14, 15]. Nevertheless, Al-Salem *et al.* highlighted the imperative of integrating recycling methods into plastic manufacturing and conversion facilities [15].

Plastics have seamlessly integrated into our daily lives, making it imperative to pursue the most sustainable avenue to curtail plastic pollution - namely, amplifying recycling and re-utilization efforts. Opportunities abound across various sectors to harness waste plastic's potential, ranging from repurposing it for construction materials to converting it into fuel, household items, fabric, clothing, shoe soles, and more. This study seeks to offer an all-encompassing assessment of how plastic waste finds application as a construction material. The paper extensively reviews diverse research approaches that leverage plastic waste as a binding agent, aggregate, fine aggregate, modifier, or substitute for cement and sand in the production of bricks, tiles, and concrete.

2. Literature Review

Recently, a multitude of reviews have emerged, centering on the exploration of diverse waste materials' applications in the realm of construction. In 2016, Tiwari *et al.* conducted a comprehensive review focusing on industrial waste products like bottom ash, waste foundry sand, copper slag, plastic waste, recycled rubber waste, and crushed glass aggregate. Their study evaluated these materials as potential substitutes for fine aggregates in concrete [16]. Gu and Ozbakkaloglu offered a summarization of studies pertaining to plastic waste recycling techniques and their influence on concrete characteristics and morphology [17].

The year 2018 saw Toghroli *et al.* undertake a review spotlighting the incorporation of recycled waste materials in pavement concrete. Their analysis encompassed recycled crushed glass, steel slag, steel fiber, tires, plastics, and recycled asphalt [18]. Babafemi *et al.* presented an examination of concrete properties when integrated with recycled waste plastic. This review underscored the impact of recycled waste plastic on mechanical attributes and durability [19]. Similarly, a detailed assessment of mortar and concrete composites containing recycled plastic was conducted by Mercante *et al.* [20].

Polyethylene terephthalate (PET) and marble dust's utilization in construction composites underwent a critical review by Singh *et al.* [21]. PET plastic bricks employed for the Rohingya refugee camp were the subject of another review [22]. Progress in bricks reinforced with fibers sourced from waste materials was reviewed by Salih *et al.* [23]. Lightweight concrete's utilization of various waste materials, including fly ash, blast furnace slag, fumed silica, tire waste, plastics, and agro waste, was explored in a review by Bejan *et al.* [24].

The utilization of plastic waste as a constituent in cement composites was extensively examined by Awoyera and Adesina, who also delved into limitations and future possibilities [25]. Li *et al.* conducted a thorough study on the ramifications of adding rubber and plastic waste as aggregates in concrete [26]. Another recent review scrutinized the utilization of plastic waste as construction material aggregates, particularly focusing on their effects on mechanical and durability properties [27].

Vishnu and Singh contributed a review focused on the appropriateness of diverse waste materials for bituminous pavements [28]. Ogundairo *et al.* conducted a review covering plastic's application in bitumen modification, soil stabilization, and its reinforcement role in bricks [29]. In light of these discussions, it's apparent that some researchers have extensively explored plastic waste within their studies, while others have addressed it partially. Despite the existing reviews, a comprehensive examination of plastic waste's integration into various aspects of construction materials remains absent. An opportunity exists to delve deeply into the varied types of plastic waste employed across multiple construction sectors, including bricks, tiles, blocks, concrete, and road construction. Recognizing this void, we present an exhaustive review encompassing an array of plastic waste materials, such as polyethylene, polypropylene (PP), polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polyvinyl chloride (PVC). This review comprehensively explores their suitability for incorporation into the production of bricks, tiles, construction blocks, and concrete for road construction. Additionally, this paper outlines the impact of plastic waste on the strength and durability of the final products.

3. Overview of Plastic

3.1. What Is Plastic

Plastic is characterized as a substance comprising a fundamental element - an organic compound with a substantial molecular weight. Plastics encompass a diverse array of synthetic or partially synthetic substances that employ polymers as their primary constituents. The malleability inherent in plastics enables them to be shaped through processes like molding, extrusion, or compression into solid forms of varying geometries. This inherent versatility, coupled with a wide spectrum of other attributes like low weight, resilience, pliability, and cost-effectiveness in production, has resulted in their extensive adoption. The creation of plastics is typically a product of human industrial systems. Although a majority of contemporary plastics originate from petroleum or natural gas-based chemicals, innovative manufacturing techniques have emerged, utilizing alternatives sourced from renewable materials such as derivatives of corn or cotton [30].

3.2. Composition of Plastic: Unraveling the Components and Structures

The composition of plastic, a complex amalgamation of elements and compounds, is the cornerstone of its diverse properties and wide-ranging applications. Plastics are predominantly composed of carbon, hydrogen, and oxygen, with varying proportions of other elements such as nitrogen, sulfur, chlorine, and fluorine. These elements are intricately combined to form the polymer chains that constitute the backbone of plastics. The presence and arrangement of these elements, along with the specific polymerization processes, influence the resulting properties and behaviors of the plastic material.

The structure of plastic polymers is defined by the arrangement of monomer units along the polymer chains. Linear polymers have a straightforward arrangement, while branched polymers feature side chains extending from the main chain. Cross-linked polymers have chemical bonds between different polymer chains, resulting in a three-dimensional network. The molecular weight—the size of polymer chains—also greatly impacts plastic properties, with longer chains often translating to higher strength and viscosity.

The diversity of plastic materials arises from different types of polymers. For instance, polyethylene (PE) consists of repeating ethylene units and is known for its flexibility and excellent resistance to chemicals. Polypropylene (PP) shares similar characteristics but exhibits higher heat resistance. Polyvinyl chloride (PVC) combines chlorine with ethylene units, resulting in a durable plastic used in construction and pipes. Polystyrene (PS) is characterized by its transparency and ease of processing, making it suitable for packaging and consumer goods.

The arrangement and bonding of elements in plastic molecules determine their properties. The presence of certain elements, such as chlorine, can make plastics flame-retardant or resistant to chemicals. The molecular structure and weight impact mechanical properties like strength, flexibility, and elasticity. Furthermore, the degree of crystallinity, dictated by the arrangement of polymer chains, affects properties like transparency, thermal resistance, and tensile strength.

Understanding the composition of plastics is crucial for assessing their environmental impact. Petrochemical-based plastics contribute to greenhouse gas emissions and the depletion of fossil fuels. Bioplastics, derived from renewable resources, offer a more sustainable alternative. However, even bioplastics can pose challenges in terms of end-of-life management and resource availability. Advances in polymer science are driving innovations in plastic composition. Bio-based polymers, derived from sources like corn starch or sugarcane, are gaining traction as eco-friendly alternatives. Additionally, research is focused on creating polymers with specific properties for applications such as biodegradable packaging, flexible electronics, and medical implants. The composition of plastic materials is a complex interplay of elemental constituents, molecular structures, and polymer types. This intricate arrangement underpins the remarkable versatility of plastics and governs their multifaceted properties and behaviors. Understanding plastic composition is pivotal for developing sustainable practices, optimizing material choices, and navigating the path toward a more environmentally conscious use of plastic materials.

3.3. Types of Plastic

Plastics are a diverse group of synthetic materials. They can be classified into various types based on their chemical composition, properties, and uses. Following are five prevalent varieties of plastics:

3.3.1. Polyethylene (PE)

Polyethylene is one of the most widely used plastics and comes in different forms, including high-density polyethylene (HDPE) and low-density polyethylene (LDPE). PE is composed of ethylene monomers (C_2H_4), which are made up of two carbon atoms and four hydrogen atoms. HDPE has a linear structure with relatively high density, making it strong and rigid, while LDPE has a branched structure and lower density, resulting in flexibility and lower tensile strength.

3.3.2. Polypropylene (PP)

Polypropylene is another versatile plastic commonly used for packaging, textiles, automotive parts, and more. It is composed of propylene monomers (C_3H_6), containing three carbon atoms and six hydrogen atoms. PP has a linear structure and offers good chemical resistance, high melting point, and excellent durability.

3.3.3. Polyvinyl Chloride (PVC)

PVC is widely used in construction, electrical wiring, and various consumer products. It is composed of vinyl chloride monomers (C2H3Cl), consisting of two carbon atoms, three hydrogen atoms, and one chlorine atom. PVC can be rigid or flexible depending on the addition of plasticizers. It's important to note that PVC production involves the use of chlorine gas, which has environmental considerations.

3.3.4. Polystyrene (PS)

Polystyrene is used in packaging, insulation, and disposable cutlery. It is composed of styrene monomers (C8H8), containing eight carbon atoms and eight hydrogen atoms. PS can be produced in various forms, including expanded polystyrene (EPS) for insulation and extruded polystyrene (XPS) for rigid foam applications.

3.3.5. Polyethylene Terephthalate (PET)

PET is commonly used for beverage bottles, food containers, and synthetic fibers. It is composed of terephthalic acid and ethylene glycol units. The chemical structure of PET includes ester linkages (CO-O) between these units. PET is known for its transparency, high tensile strength, and resistance to moisture and chemicals.

It's important to note that these are just a few examples of the many types of plastics available. Each type of plastic has its own unique properties and applications, and their compositions can vary based on manufacturing processes and specific additives used. Figure 1 shows different types of plastic.

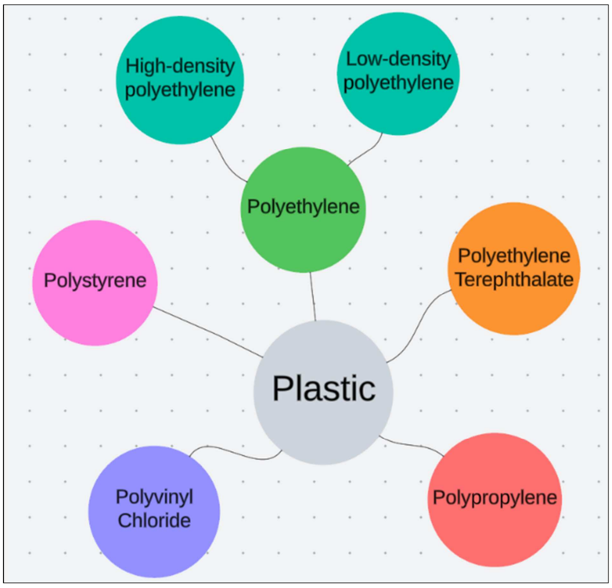

Figure 1. *Types of plastic.*

3.4. Plastic Manufacturing Process

The manufacturing of plastic materials involves intricate processes that transform raw materials into a wide range of plastic products. This section provides a detailed overview of the plastic manufacturing process, highlighting key stages, materials, and technologies involved.

Plastics originate from petrochemicals, primarily sourced from crude oil and natural gas. These hydrocarbons serve as the foundational feedstock for plastic production. Through refining and chemical processes, the hydrocarbons are broken down into simpler compounds, such as ethylene and propylene, which are the building blocks for various types of plastics. Polymerization is the process of linking these smaller molecules (monomers) together to form long chains, known as polymers. This is achieved through chemical reactions, often involving catalysts, heat, and pressure. The specific polymerization method depends on the type of plastic being produced. For example, polyethylene is produced through a high-pressure polymerization process, while polyethylene terephthalate (PET) is synthesized through a condensation polymerization process. Upon polymer synthesis, a sequence of processing stages shapes the polymers to meet specific properties and forms. Common techniques encompass extrusion, which involves melting polymers and forcing them through shaped dies to create continuous profiles like pipes, sheets, and films. Injection molding, another technique, injects molten plastic into mold cavities, where it cools and solidifies to craft products spanning toys to automotive components. Blow molding serves to fashion hollow objects like bottles by introducing heated plastic into molds, which then conform to the mold's shape through air pressure. Rotational molding involves rotating plastic-filled molds in multiple dimensions to uniformly coat the mold surface, resulting in the production of large, hollow items such as storage tanks and playground equipment. During polymer processing, various additives are incorporated to modify the plastic's properties. These include stabilizers to prevent degradation during processing and exposure, plasticizers to enhance flexibility, colorants for pigmentation, and flame retardants to increase fire resistance. The specific additives used depend on the intended application of the plastic product.

Throughout the manufacturing process, quality control measures are implemented to ensure consistency and meet industry standards. Tests for properties such as tensile strength, impact resistance, thermal stability, and dimensional accuracy are conducted. These tests help manufacturers optimize processes and maintain product quality.

The plastic manufacturing process generates waste materials such as trimmings, rejects, and off-spec products. These waste materials can be recycled within the production facility if feasible, reducing the overall environmental impact. However, some waste, particularly in the form of microplastics or non-recyclable byproducts, can pose challenges for waste management. In recent years, there has been a growing emphasis on the sustainability of plastic manufacturing. Manufacturers are exploring methods to reduce the environmental impact by adopting more efficient processes, incorporating recycled content, and developing bioplastics derived from renewable resources. Additionally, the concept of a circular economy aims to minimize waste through recycling, reuse, and extended product life cycles. As the awareness of plastic pollution and environmental concerns grows, there is an increasing focus on developing technologies that improve the efficiency and sustainability of plastic manufacturing. This includes the use of advanced catalysts for polymerization, innovations in processing techniques to reduce energy consumption, and the incorporation of smart materials that can enhance product functionality. The plastic manufacturing process is a complex series of steps that transform raw materials into a wide array of products. Understanding these processes is essential for addressing the challenges posed by plastic waste and for promoting sustainable practices throughout the plastic lifecycle. Steps involved in plastic manufacturing process are shown in Figure 2.

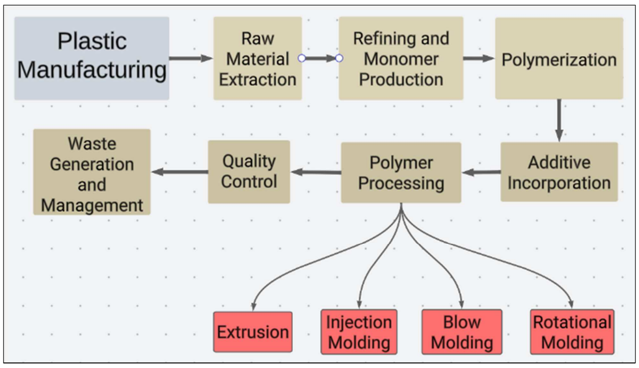

Figure 2. *Plastic manufacturing process.*

3.5. Plastic Components and Their Relevance in Recycling: Exploring Scope and Opportunities

The ubiquity of plastic components in modern society has transformed industries and consumer goods, but it has also led to a growing concern about plastic waste and environmental impact. Plastic components are integral to a wide range of products across industries such as automotive, electronics, packaging, and consumer goods. They offer benefits like lightweighting, durability, and cost-effectiveness, driving innovation and functionality in diverse applications. However, the rampant use of single-use plastics and inefficient disposal practices have resulted in a staggering volume of plastic waste, which presents environmental and resource challenges. The diverse types of plastic polymers and the presence of additives in plastic components make recycling a complex process. Sorting and separating these plastics are critical for effective recycling, as different polymers have distinct properties and recycling capabilities. Contamination, lack of infrastructure, and consumer behavior further complicate recycling efforts, leading to substantial amounts of plastic ending up in landfills, oceans, and other ecosystems.

Despite the challenges, plastic recycling holds immense promise for addressing the plastic waste crisis. Advancements in sorting technologies, such as spectroscopy and artificial intelligence-based systems, are improving the accuracy of plastic identification and sorting. Additionally, the growing consumer demand for sustainable products and increasing regulatory pressures are pushing industries to adopt circular economy principles, encouraging them to incorporate recycled plastic into their products. Innovation in Material Recovery, involving inventive methods like solvent-based techniques or smart sorting systems, stands to elevate recycling rates by curbing contamination and elevating recovered material quality. Concurrently, progress in Technological Advancements, particularly chemical recycling breaking plastics into original monomers, offers promise for recycling conventionally tough-to-process plastics. Collaborative Initiatives linking governments, industries, and non-profits can galvanize plastic recycling awareness, education, and infrastructure, fostering a more efficient waste management system. Simultaneously, Design for Recycling by manufacturers, focusing on product recyclability through component separability and minimal waste packaging made from recycled materials, assumes a pivotal role. The adoption of Circular Economy models further encourages closed-loop systems in businesses, diminishing virgin plastic demand by reusing, repurposing, and recycling plastic components.

3.6. Why Is Plastic Recycling Important

Plastic recycling holds multifaceted significance due to its environmental, economic, and social benefits. By conserving finite petroleum-based resources, recycling minimizes the demand for new plastic production and lessens the strain on fossil fuel reserves. Moreover, it curtails the enduring decomposition of plastics in landfills, which not only accumulates waste but also releases harmful substances into the environment. Recycling consumes less energy than virgin plastic production, reducing greenhouse gas emissions and contributing to climate change mitigation. Mitigating pollution, particularly in aquatic ecosystems, is another vital outcome, as recycling prevents plastic waste from polluting rivers, oceans, and landscapes, safeguarding wildlife and habitats. Additionally, plastic recycling aligns with circular economy principles, fostering resource sustainability through reuse and repurposing. Job creation, public awareness, and innovation in recycling technologies further underscore its importance, while its role in reducing ocean plastic pollution and ensuring long-term environmental sustainability makes plastic recycling a cornerstone in addressing the challenges posed by plastic waste.

4. Different Approaches of Recycling Plastic

4.1. Integration of Plastic Waste into Construction Bricks, Tiles, and Blocks

The utilization of plastic waste in the production of construction bricks, tiles, and blocks has gained significant attention in recent years due to its potential to address two critical environmental issues simultaneously: plastic waste management and sustainable construction materials. This innovative approach involves incorporating plastic waste, often in the form of shredded or melted plastic, into traditional construction materials like bricks, tiles, and blocks.

This not only helps in reducing the burden on overflowing landfills and oceans but also reduces the demand for virgin raw materials like clay and sand, which are commonly used in these products.

Plastic waste incorporation in construction materials offers various advantages. Firstly, it enhances the thermal insulation properties of the products, potentially leading to energy savings in buildings. Secondly, it can improve the durability and flexibility of the materials, making them more resilient to impacts and structural stress. Additionally, by diverting plastic waste from landfills and oceans, this approach contributes to mitigating environmental pollution and conserving natural resources. The utilization of plastic waste in construction materials has the potential to revolutionize the construction industry, promoting a circular economy where waste materials are given new life as valuable resources.

In a research study, discarded polyethylene terephthalate (PET) plastic waste (SPW) and foundry sand (FS) were innovatively employed to create environmentally friendly bricks. By blending FS and SPW at different proportions, namely 80: 20, 70: 30, and 60: 40 based on dry mass, novel bricks were fabricated. To gauge durability, the bricks underwent acid and water immersion tests, while their strength was assessed through compressive and tensile strength evaluations. The outcome of the study revealed that bricks formulated with a composition of 70% foundry sand and 30% plastic waste exhibited remarkable performance. Specifically, these bricks demonstrated exceptional compressive strength at 38.14 MPa and an impressive tensile strength of 9.51 MPa [31]. Another research report indicated that incorporating recycled crushed glass (RCG) alongside PET plastic waste (PPW) in varying ratios of 80: 20, 70: 30, and 60: 40 led to substantial enhancements in both tensile and compressive strengths. These improvements amounted to 70.15% and 54.85%, respectively, when compared to the strength of traditional clay bricks. Notably, the average compressive strength and tensile strength recorded were 42.01 MPa and 9.89 MPa, respectively. Moreover, these innovative bricks displayed minimal water absorption, registering only 2.7%. Importantly, due to their strong hydrophobic properties, the masonry bricks made from foundry sand and crushed glass exhibited remarkable water resistance. This attribute translated to enhanced resistance against chemical deterioration and reduced deformation when subjected to strain stress, distinguishing them from conventional fired clay bricks [32].

Numerous research studies have highlighted the utilization of HDPE and PET polymer waste as enhancers for unfired clay bricks, aiming to optimize their performance. To explore this, different additives with grain sizes ranging from 1 to 3 mm and 3 to 6 mm were investigated. These additives were incorporated at varying percentages—0%, 1%, 3%, 7%, 15%, and 20% by weight. The results of the investigation showcased that the most favorable enhancement in brick efficiency was achieved when using the smallest polymeric grain additive, measuring 1 mm in size. Notably, the bricks exhibited a bulk density of less than 1.75 g/cm³, indicating their lightweight nature. Moreover, there was an approximately 17% rise in the water absorption coefficient, coupled with a significant 28% enhancement in compressive strength [33, 34].

Low-density polyethylene (LDPE) water sachets have been innovatively repurposed to create LDPE sand bricks. This process involves melting the LDPE water sachets and subsequently blending them with sand. The resulting properties of the bricks, including density, compressive strength, and water absorption, are contingent upon the particle size of the sand and the ratio of sand to plastic. Furthermore, the best-performing samples underwent assessment for flexural strength and thermal conductivity. Under optimized processing conditions, it was observed that LDPE-bonded sand yielded robust and enduring materials, boasting an impressive compressive strength of up to 27 MPa. Notably, the thermal conductivity was determined to be approximately 1.72 W/mK. In addition, the bricks displayed specific thermal properties: a thermal diffusivity of 0.86 mm²/s and a specific heat value of 2.0 MJ/m³K [35].

Diverse waste thermoplastics, encompassing polycarbonates (PC), polystyrenes (PS), and mixed plastic, were combined with sand, ash, and regular Portland cement in varying proportions to fashion bricks. The thermoplastic content ranged from 0% to 10% by weight, while sand constituted 60% to 70% by weight. Concurrently, the blend featured a 15% proportion of fly ash and Portland cement. The resultant bricks exhibited characteristics of porosity, lightweight nature, and thermal resilience. Remarkably, these bricks boasted compressive strength surpassing 17 MPa, with a maximum water absorption value of 14.18%. Additionally, the bulk density decreased from 2.06 to 1.60 g/cm³ upon the inclusion of waste materials [36]. In an alternative approach, rice husks and discarded expanded polystyrene, together with styrene as a binding agent, were employed to produce rice husks-plastic composite building materials. This production method employed hot press molding. The resulting composites underwent testing for apparent density, water absorption, thickness expansion, and both dry and wet flexural strength. The apparent density of these composites ranged from 0.80 to 1.60 g/cm³. Regardless of the filler-binder ratio, higher binder content led to reduced water absorption in the composites. Moreover, dry and wet flexural strengths of the composites exhibited enhancement with improved filler-binder ratios, with the optimal outcome achieved at a 30% binder content [37]. Contrastingly, bricks constructed from waste plastics such as polyethylene, high-density compound (nylon 66), and polyethylene terephthalate, in combination with red soil, river sand, and crushed stone, displayed compelling attributes. Across various compositions, these plastic-infused bricks demonstrated a remarkable absence of water absorption, and when river sand was integrated with plastic waste, they showcased a commendable maximum compressive strength of 15.50 kN. This brick variant exhibited substantial durability and hardness, with no indications of defects during soundness testing [38].

In contemporary times, the utilization of ash derived from thermal power plants has extended to the creation of construction materials, including bricks. Building on the advantages of ash bricks, researchers are exploring its compatibility with waste plastic. In the context of brick production, Low-Density Polyethylene (LDPE) is being combined with materials like bottom ash, copper slag, and ceramic in various proportions. Notably, a notable approach involves blending LDPE with bottom ash at a ratio of 3: 1, yielding a commendable compressive strength of approximately 16 MPa and a water absorption rate of 4.2%. These values align with standard specifications, barring the ASTM average. Additionally, when LDPE is paired with ceramic aggregates in a 3: 1 ratio, supplemented by 10% oil, it attains a peak compressive strength of around 22 MPa and a water absorption rate of 4.9%. Practically, any mixture featuring ceramic aggregates achieves a threshold beyond 15 MPa and meets typical specifications except the ASTM norm, particularly in challenging weather conditions. Further exploration involved combining LDPE with copper slag at a 2: 1 ratio, facilitated by a coupling agent. This concoction yielded the highest compressive strength, approximately 21.4 MPa, and a water absorption value of 4.5%. Moreover, a blend of plastic and ceramic waste at a 3: 1 ratio was found to produce optimal blocks [39]. Meanwhile, in the realm of paver blocks, varying proportions of LDPE waste were mixed with granite dust, sand, and clay. The mix ratio of 50:50 (plastic melt-granite dust) exhibited the highest compressive strength, measuring 15.0 N/mm² according to compression test results. In contrast, the ratio of 70:30 (sand-plastic melt) achieved the highest flexural strength, recording 14.28 kN in the flexural test [40].

The research focused on constructing bricks and paver blocks using plastic waste (HDPE and PE) combined with sand at varying ratios of 1:2, 1:3, 1:4, 1:5, and 1:6. The resulting materials underwent evaluation based on compressive strength, water absorption, efflorescence, hardness, and resistance to fire. By conducting a comparative analysis involving ash bricks, plastic sand bricks, and conventional bricks, the study revealed notable findings. Among these materials, plastic sand bricks exhibited the highest compressive strength, measuring 5.12 N/mm², while paver blocks achieved a compressive strength of 9.19 N/mm². The water absorption capacity of plastic sand bricks registered at 1.10%, with plastic paver blocks showing a similar value of 1.082%. Notably, the structural properties of both bricks and blocks remained largely consistent up to temperatures of 180°C. These results collectively indicated that plastic sand bricks and paver blocks surpassed the quality of ash bricks and traditional clay bricks [41].

In addition to bricks and paver blocks, plastic waste has found application in the creation of various types of tiles. An example is the development of roof tiles using recycled high-density polyethylene (RHDPE) in combination with sand. The composition ratios of RHDPE ranged from 30% to 80% by weight. Comprehensive testing encompassing density, flexural breaking load, and impermeability were conducted on these tiles. The findings indicated that with an increase in the percentage of plastic waste, the density of the tiles decreased from 1.8 to 1.379 kg/m³. Concurrently, impermeability decreased while flexural strength exhibited enhancement [42]. Furthermore, the utilization of waste plastic and broken glass has been documented for crafting roof tiles, hollow blocks, and floor tiles. In these applications, plastic waste partially replaced cement, while broken glass substituted for a portion of river sand. The composition of hollow blocks comprised 33% plastic waste, 11.2% fine glass, and 44.6% fine sand. For roof tiles, a blend of 30% plastic waste and 70% glass was employed. Similarly, floor tiles comprised 32% plastic and 68% glass. Remarkably, these efforts yielded an optimal compressive strength of 27 MPa. For roof tiles, the average breaking strength measured was 2356 N [43].

The utilization of plastic waste in the production of construction bricks, tiles, and blocks presents a promising avenue for addressing plastic pollution while promoting sustainability in the construction sector. Continued research, technological advancements, and collaboration among researchers, manufacturers, policymakers, and environmental agencies are essential to fully realize the benefits of this approach and address any associated challenges.

4.2. Incorporating Plastic Waste in Concrete and Road Construction

In various regions worldwide, the enhancement of concrete for road construction through the incorporation of plastic materials has become a prevalent practice. Researchers have extensively explored diverse plastic admixtures, considering both partial and complete replacements for conventional aggregates.

A study documented the creation of recycled plastic-bounded concretes (RPBCs) utilizing 100% waste plastic without the inclusion of asphalt binder or Portland cement. This investigation delved into mechanical properties, crack recovery, and the thermal and moisture sensitivities of recycled plastic-bounded concrete. The study involved two types of recycled plastic waste: recycled high-density polyethylene (RHDPE) and recycled polypropylene (RPP). The compressive strength of the recycled polypropylene-bounded concrete reached 30 MPa, nearly tripling that of asphalt binder concrete. Recycled PP exhibited threefold the bending strength of plain cement concrete (PCC) and fivefold the bending strength of asphalt concrete (ACs). Impressively, the crack healing capability of RPBCs stood at around 92%. RPBCs showcased heightened resistance to moisture exposure. In comparison, the strength of recycled PP endured a mere 5% reduction, whereas asphalt concrete's strength declined by 17%. Whereas asphalt concrete (ACs) exhibited a bending capacity of up to 10%, the structural integrity of concrete bound with recycled HDPE and recycled PP maintained its strength remarkably, with a retention of 85% and 99% respectively. The study inferred that recycled HDPE was less effective than recycled PP due to its inability to adequately confine aggregates within the concrete. Notably, since cement production entails substantial CO2 emissions and significant oil consumption, the substitution of waste plastic for cement emerged as an environmentally friendly alternative [44].

In certain studies, PET obtained from drinking water bottles was employed as a substitute for sand in the concrete formulation. Varied volumetric proportions of sand—2%, 5%, 10%, 15%, 20%, 30%, 50%, 70%, and 100%—were replaced by an equivalent volumetric amount of recycled PET aggregate. Notably, as the aggregate volume ranged from 0% to 30%, the bulk density remained modest. However, nearing the 50% aggregate volume, a decrease in bulk density was observed, reaching a minimum value of 1000 kg/m³. Furthermore, augmenting the aggregate amount from 0% to 50% led to a 15.7% reduction in compressive strength compared to the reference mortar. Remarkably, when sand volume was entirely replaced by PET, compressive strength exceeding 3.5 MPa was achieved. Notably, high compactness persisted up to the 50% replacement threshold, while beyond this point, the arrangement displayed a more spacious configuration [45].

Another investigation focused on the mechanical attributes of concrete augmented with polyethylene terephthalate (PET) fibers of varying lengths—10 mm, 15 mm, and 20 mm—at volumetric proportions of 0%, 0.05%, 0.18%, and 0.30%. Incorporating PET fibers led to a decline in concrete's slump value from 100 mm to 50 mm. After 28 days, the highest flexural strength recorded was 4.47 MPa, and this value held steady at 4.48 MPa after 150 days with a 0.30% fiber volume. Correspondingly, at the 0.30% fiber volume, the maximum compressive strength reached 29.52 MPa after 28 days and 29.69 MPa after 150 days. Furthermore, after 150 days of curing, the highest modulus of elasticity attained was 27.31 GPa [46].

Dombe *et al.* undertook the formulation of bituminous mixtures incorporating both E-waste and plastic waste. Plastic waste served as a substitution for bitumen, ranging from 4.5% to 6% of the overall bitumen quantity employed. Meanwhile, shredded electronic waste was utilized to partially replace aggregates in proportions of 7.5%, 10%, 12.5%, and 15% by volume of the mold. The inclusion of plastic heightened the bitumen's melting point, maintaining asphalt flexibility during colder months, and shredded plastic waste contributed to road longevity. Following the introduction of 6.5% waste plastic, the penetration value of bitumen witnessed a 6.68% decline, yet the softening point improved by 8.60%. The remaining bitumen properties remained unaltered. Moreover, when applying a 7% waste plastic coating on aggregate, the specific gravity surged by 2.88%, while the crushing value, effect value, and loss abrasion value saw reductions ranging from 3% to 4% [47].

Similarly, electronic plastic waste was incorporated into concrete, replacing aggregates in varying degrees from 0% to 20% concerning M20 grade strength criteria. The optimal combination yielding concrete hardness and durability involved a 10% E-plastic addition to cement. Over a 28-day testing period, compressive strength saw a decline from 18.55 N/mm² to 10.72 N/mm² with waste inclusion ranging from 0% to 20%. The flexural strength experienced a decline, going from 3.14 N/mm² to 2.74 N/mm², while the split tensile strength witnessed a reduction from 2.137 N/mm² to 1.91 N/mm². Authors emphasized that employing E-plastic in concrete could curtail the need for traditional fine aggregates, thereby conserving natural resources [48]. Additionally, the inclusion of E-waste ranging from 0% to 21.5% (specifically, 7.5%, 14%, and 21.5%) in M30 concrete strength criteria led to a substantial 52.98% reduction in compressive strength, particularly when fine aggregates were replaced by 21.5% E-waste [49].

Azhdarpour *et al.* highlighted the influence of incorporating plastic particles into freshly prepared concrete, impacting both its physical attributes and strength-related properties. As the proportion of plastic fragments increased, there was a noticeable decrease in physical characteristics such as density and ultrasonic velocity. When substituting 5-10% of the concrete's fine particles with an equivalent amount of polyethylene terephthalate (PET) fragments, there was an enhancement observed in the compressive, tensile, and flexural strengths of the specimens. However, the study underscored that replacing more than 10% led to a substantial decline across all concrete strength-related metrics. Consequently, it was proposed that the replacement of fine particles with PET fragments could yield positive effects on concrete strength characteristics, as long as the substitution ratio remained below 10%. Furthermore, the incorporation of plastic into the concrete mixture led to reductions in both fresh and dry densities, as evidenced by density measurements. Significantly, it was observed that samples incorporating 30% plastic particles experienced the most notable decrease in density, with a reduction of 9% [50].

Waste plastics such as polyethylene and polystyrene in sliced form were applied as a coating over aggregates and subsequently mixed with heated bitumen. An array of tests encompassing crushing strength, abrasion, Los Angeles abrasion, impact, softening point, and surface evaluations were conducted on both conventional aggregates and plastic-coated aggregates. The incorporation of plastic waste led to a reduction in the crushing value, diminishing from 23.22% to 14.22%. Notably, the softening point registered at 81.2°C, while the penetration value measured 67 mm. Additionally, the loss angle abrasion value decreased from 5.6% to 4.2% for plastic-coated hydrocarbon materials [51]. Across diverse plastic categories encompassing thermosets, elastomers, and thermoplastics, there were reports of elevated bitumen temperatures resulting in improved road longevity. The application of waste plastic coating to the mixture exhibited an enhancement in compressive strength, achieving 320 MPa, and bending strength of 390 MPa, notably by harnessing 40% waste plastic content [52].

For road construction purposes, waste plastic items such as bottles, cups, and caps were processed into a powdered form using a crusher. These powdered plastics were then heated and applied as a coating over a mixture of aggregates and bitumen. The aggregates used were sized between 10 to 20 mm, and two grades of bitumen, namely 60/70 and 80/100, were employed. With an increase in the percentage of plastic content, notable improvements were observed in properties such as softening point, flash point, and fire point. Conversely, the penetration value and ductility decreased. The utilization of polymer-coated aggregates combined with the bitumen mixture yielded several positive outcomes. These included enhanced strength, improved binding capabilities, greater stability, heightened wear resistance, and increased road durability. These findings were reported by Chada Jithendra Sai Raja *et al.* in 2020 [53].

In a study conducted by Kazmi and Rao in 2015, it was found that incorporating waste polythene ranging from 5 to 11% with bitumen of 60/70 grade yielded favorable results as a binding agent for road construction. Another research report explored the use of waste plastic sourced from municipal solid waste as a coated mixture in bituminous construction. This involved subjecting the plastic-coated aggregates to various tests including Marshall properties, impact assessment, abrasion resistance, water absorption, and soundness. The plastic-coated mixture demonstrated a maximum Marshall stability value of 2812.1 kg, achieved with a 4.7% bitumen content by weight [54]. This mixture exhibited improved characteristics in terms of water absorption, soundness, and temperature resistance, as reported by Dawale in 2016 [55]. Furthermore, waste plastic was employed as a modifier in the production of quasi-dense bituminous concrete. The process involved incorporating chopped plastic in the hot mixture using varying percentages of 6, 8, 10, 12, and 14% by weight of hydrocarbon. The results indicated that the highest Marshall stability value of 13.0 kg was achieved with 12% plastic content by weight of the bitumen. However, it should be noted that at this plastic content level, the soundness value was negatively impacted. The plastic-modified mixture also exhibited a maximum flow value of 4.0 mm, with 75.9% voids filled with bitumen (VFB) achieved when 14% waste plastic was added to the mixture, as reported by Rajput and Yadav in 2016 [56].

The utilization of plastic waste in concrete and road construction holds immense promise for sustainable infrastructure development. By transforming plastic waste into a valuable resource for enhancing construction materials, we can simultaneously tackle plastic pollution and promote more resilient and eco-friendly construction practices. Continued research, testing, and implementation will be key in harnessing the full potential of this approach while ensuring its environmental and structural integrity.

4.3. Integration of Waste Plastic with Waste Rubber in Concrete and Road Construction

The integration of waste plastic and waste rubber materials into concrete and road construction represents a notable stride toward sustainable and innovative infrastructure development. This approach involves combining discarded plastic and rubber waste, often in shredded or granulated form, into the production of concrete mixes and road construction materials. This practice holds the promise of addressing two significant environmental challenges simultaneously: plastic and rubber waste management, and enhancing the properties of construction materials.

Plastic waste and rubber waste have been combined to enhance the mechanical strength of both rubber and concrete materials. Particularly, the focus has been on elevating the chemical characteristics of crumb rubber-modified asphalt (CRMA) through the utilization of waste PET additives, which were obtained via an aminolysis process. The incorporation of these additives into CRMA yields numerous benefits. This includes heightened storage stability, improved resistance to rutting and fatigue, as well as an increase in the rotational viscosity (RV) of the modified binders. The introduction of bis (2-hydroxy ethylene) terephthalamide (BHETA) to the rubber binders leads to a reduction in penetration values. The addition of up to 3 to 5% BHETA results in minor changes in consistency; however, at a 7% BHETA content, a significant increase in consistency is observed. Notably, crumb rubber modified with BHETA demonstrates enhanced fatigue resistance. The inclusion of BHETA additives in CRMA contributes to increased stiffness and storage stability, as highlighted in a study conducted by Leng *et al.* in 2018 [57].

Within a research endeavor, low-density polyethylene (LDPE), high-density polyethylene (HDPE), and crumb rubber (CR) were incorporated into a base bitumen matrix across different proportions (2%, 4%, 8%, and 10% by weight of bitumen). The study delved into the rheological characteristics of these binders under varying temperatures and frequencies, unveiling that the introduction of plastic components, namely LDPE, HDPE, and CR, led to an enhancement in the elastic behavior of the binder. This modification has the potential to extend the lifespan of road pavements by mitigating susceptibility to issues like rutting and cracking, as substantiated by Khan *et al.* in 2016 [58].

For modification purposes, admixtures of recycled plastic waste were introduced in proportions of 2%, 4%, 6%, 8%, and 10% to alter the properties of a 60/70 penetration grade asphalt binder using a wet method. Concurrently, mineral aggregates were customized with 1%, 2%, 3%, 4%, and 5% crumb rubber through a dry method. Notably, the addition of 2% crumb rubber and 4% LDPE yielded a Marshall stability value that surpassed the standard asphalt concrete mix by 30%. The utilization of LDPE-modified asphalt binder resulted in notable enhancements in viscosity, softening point, and overall stiffness of the binder, as observed in the study conducted by Onyango *et al.* in 2015 [59].

Within a research investigation, a bituminous mix was enriched with plastic and rubber waste to enhance its suitability for road construction. The resultant modified bituminous mix exhibited remarkable strength, surpassing the standard mix by 61%. This improvement was reflected in the Marshall quotient (MQ), which increased by 52% in comparison to the reference bituminous mix. This higher MQ indicated enhanced stiffness, enabling better load-bearing capacity and resistance to deformation, as outlined in the study by Islam *et al.* in 2016 [60]. Plastic waste, including items like carry luggage, cups, and tires, was employed to create coatings over aggregates. The use of polymer-coated aggregates showcased heightened strength. While the softening point was augmented, the penetration value and malleability decreased as the quantity of plastic waste increased. Polymer-coated aggregates demonstrated improved binding properties and reduced air voids, as reported by Barad in 2015 [61]. In a separate report, plastic waste and crumb rubber were incorporated as partial replacements for bitumen in the production of an enhanced binder for bituminous concrete mixes. Replicating real-world conditions, Marshall stability analysis indicated that the bitumen modified with plastic waste and crumb rubber in specific proportions exhibited superior characteristics, as noted by Bansal *et al.* in 2017 [62].

However, the utilization of waste plastic and rubber in concrete and road construction necessitates careful consideration of processing and compatibility. Proper treatment and preparation of the waste materials are crucial to ensure that they can effectively contribute to the desired properties of the construction materials.

4.4. Incorporating Biomedical Plastic Waste in Road Construction

The incorporation of biomedical plastic waste into road construction signifies an innovative stride toward sustainable infrastructure development. This novel approach involves integrating discarded biomedical plastic materials, which might include items like single-use medical devices and packaging, into the production of road construction materials. This practice offers a dual advantage by not only addressing the challenges posed by biomedical plastic waste disposal but also by enhancing the performance and properties of road construction components.

The inclusion of biomedical plastic waste in road construction materials can contribute to improved road durability and performance. These plastics can act as modifiers, enhancing the properties of asphalt mixes and other road components. Their characteristics, such as flexibility and strength, can augment the resilience of road surfaces against wear and tear caused by traffic and environmental factors. This could potentially lead to longer-lasting roads, reducing maintenance requirements and extending the overall lifespan of the infrastructure.

Considerable volumes of plastic waste are generated daily within the medical sector, encompassing items such as syringes, medicine packaging, tubing, gloves, medicine bottles, and bags. Consequently, there exists a pressing necessity to recycle this medical plastic waste. Several studies have investigated the incorporation of items like aldohexose bottles and syringes into bituminous mixtures for construction purposes. The resulting bituminous mix, derived from pharmaceutical plastic waste, was compared to conventional bituminous blends. The research involved the creation of twelve modified mix specimens, with plastic content ranging from 6% to 12% by weight of bitumen. Mix designs were established using the Marshall methodology. Diverse Marshall parameters, including stability value, flow value, and air voids, were assessed. Notably, the maximum flow value measured was 3.2 mm, achieved with a 12% plastic content. Through experimentation, the optimal plastic proportion was determined to be 9.33%. The highest stability value, amounting to 24.77 kN, was observed with a 10% plastic content, as outlined in a study conducted by Sunny in 2018 [63].

The utilization of biomedical plastic waste in road construction offers a promising avenue for sustainable infrastructure development. By repurposing discarded medical plastics, we can address waste management challenges while simultaneously improving the quality and longevity of roadways. Through careful research, development, and collaboration, this approach has the potential to reshape the construction industry and contribute to a more environmentally conscious and resilient infrastructure network.

5. Conclusion

The exploration of plastic waste recycling within the context of sustainable development underscores the critical intersection of environmental responsibility and societal progress. The challenges posed by the escalating volume of plastic waste demand innovative solutions that not only alleviate environmental strain but also contribute to the advancement of society at large. The strategies discussed in this paper, ranging from the utilization of plastic waste in construction to its integration in various industries, exemplify the potential of a circular economy approach. Through the adoption of recycling technologies and the promotion of responsible consumption patterns, plastic waste can be transformed from a liability into a valuable resource. The multifaceted benefits of plastic waste recycling, including waste reduction, resource conservation, reduced carbon footprint, and enhanced economic opportunities, reflect the synergistic relationship between environmental preservation and sustainable development. Nevertheless, the journey toward effective plastic waste recycling and sustainable development necessitates concerted efforts from individuals, industries, governments, and international organizations. Comprehensive waste management infrastructure, technological innovation, policy frameworks, and public awareness campaigns are all essential components of a holistic strategy. It is imperative to recognize that the pursuit of sustainable development goes hand in hand with the responsible stewardship of our natural resources and the mitigation of ecological impact. In a world where the implications of plastic waste transcend geographical boundaries, the success of plastic waste recycling is emblematic of our commitment to a more harmonious coexistence with the planet. As we collectively navigate the path forward, the integration of plastic waste recycling into the ethos of sustainable development serves as a testament to our capacity to reshape our relationship with the environment and forge a future defined by ingenuity, responsibility, and prosperity for generations to come.

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