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REVIEW ARTICLE

Synergistic technologies for a circular economy: upcycling waste plastics and biomass

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Abstract The urgent need for sustainable waste management has led to the exploration of upcycling waste plastics and biomass as viable solutions. In 2018, global plastic production reached 359 million tonnes, with an estimated 12000 million tonnes projected to be delivered and disposed of in landfills by 2050. Unfortunately, current waste management practices result in only 19.5% of plastics being recycled, while the rest is either landfilled (55%) or incinerated (25.5%). The improper disposal of plastics contributes to issues such as soil and groundwater contamination, air pollution, and wildlife disturbance. On the other hand, biomass has the potential to deliver around 240 exajoules of energy per year by 2060. However, its current utilization remains relatively small, with only approximately 9% of biomass-derived energy being consumed in Europe in 2017. This review explores various upcycling methods for waste plastics and biomass, including mechanical, chemical, biological, and thermal approaches. It also highlights the applications of upcycled plastics and biomass in sectors such as construction, packaging, energy generation, and chemicals. The environmental and economic benefits of upcycling are emphasized, including the reduction of plastic pollution, preservation of natural resources, carbon footprint reduction, and circular economy advancement.

Keywords waste management, plastic waste, biomass, upcycling, economic benefits, circular economy

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1 Introduction

The current world population of 7.9 billion is projected to increase to between 9 and 10 billion by 2050, which will, in turn, cause municipal solid waste (MSW) levels to rise from 2.01 billion tonnes in 2018 to 3.40 billion tonnes by 2050 [1]. This increase in waste generation emphasizes the urgent need for effective waste management strategies, as MSW consists largely of biomass and plastics [2,3]. Plastics have gained significant demand due to their desirable properties, with global production reaching 359 million tonnes in 2018, and an estimated 12000 million tonnes of plastics will be delivered and disposed of in landfills by 2050 [4]. Unfortunately, the

conventional disposal method of landfilling not only requires large amounts of space but also poses a risk of contaminating nearby soil and water sources. Statistics indicate that 55% of all produced plastics end up in landfills, 25.5% are incinerated, and only 19.5% are recycled. The improper disposal of plastics is a worldwide concern, with China and Europe (EU) being major contributors to plastic production [5]. In the United States, a significant portion of discarded plastics is sent to landfills, with 75.8% of the total plastic waste generated in 2017 ending up in landfills.

Similarly, India faces challenges in managing plastic waste, with a considerable amount remaining uncollected despite efforts to recycle a portion of it [6]. The demand for plastics spans various industries due to the widespread use of common types like polypropylene (PP), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polyvinylchloride (PVC), polyurethane (PU), poly(ethylene terephthalate) (PET), and polystyrene (PS) [7]. If current waste management practices persist, billions of metric tonnes of plastic waste are projected to be disposed of in landfills and bodies of water globally by 2050 [6,8].

The non-biodegradable nature of most plastics results in long degradation periods, causing significant disruption to ecosystems and leading to issues such as soil and groundwater contamination, air pollution, land usage inefficiency, wildlife disturbance, and greenhouse gas emissions [5,9]. Although incineration is a commonly used thermal processing technique to reduce the volume of waste plastics, it poses its own challenges due to the release of toxic pollutants during combustion [9,10]. Despite this, there is ongoing research to develop more efficient combustion and heat recovery systems that can harness energy from waste plastics and MSW incineration, providing a potential solution to mitigate the environmental impact of plastic waste.

Biomass, which includes a wide range of organic materials derived from plants or animals, has vast potential as a chemical and energy fuel source. It is estimated that by 2060, biomass could deliver around 240 exajoules of energy per year, which is equivalent to 1 exajoules = 24 million tonnes of oil [11]. Despite this potential, the current utilization of biomass-derived energy in industrial consumption remains relatively small, such as approximately 9% in the EU in 2017 [12]. Biomass and biowastes are formed through photosynthetic processes, utilizing solar energy to convert carbon dioxide and water into carbonaceous solids [13]. Due to its carbonaceous nature and fast production rate, biomass is considered carbon neutral when converted into versatile products. Various sources contribute to biomass resources, including wood or forest residues, agricultural grain residues, energy crops, food production or industry residues, animal farming waste, and human waste [4,14].

The circular economy is increasingly gaining global recognition, supported by the EU, China, Japan, Canada, Finland, and numerous businesses. The EU projects a potential annual increase of 600 billion euros for its manufacturing sector, while Finland expects 2.5 billion euros per year. Globally, the circular economy could yield 1 trillion USD annually. China, pioneering this model with a 2008 law, emphasizes circular economy as a sustainable alternative to the linear economic flow [15]. The principles of a circular economy revolve around the "5Rs"—reduce, reuse, reprocess, recover, and recycle—along with the use of renewable resources in daily domestic and industrial activities. The goal is to extend the lifespan of materials and resources while minimizing waste and environmental impact [16,17]. Upcycling, a related concept, involves converting waste materials into higher-value products, leading to practical, environmental, and economic advantages [18]. Unlike standard recycling, upcycling alters both the physical and chemical properties of materials, resulting in purer, value-added products [19]. The term "upcycling" was introduced by Reiner Pilz in a 1994 interview with journalist Kay [20] to describe transforming waste, by-products, or low-value resources into higher-value products or materials [21]. Pilz differentiated these practices from traditional recycling, which he referred to as "downcycling." Xu and Gu [22] further developed the concept in their book *Upcycling*. Subsequently, McDonough and Braungart helped popularize the idea in their book *Cradle to Cradle*: *Remaking the Way We Make Things* [23]. In recent years, academic and business interest in these concepts has surged, with an increase in publications and reports from firms like McKinsey, Accenture, EY, and Deloitte [24].

A sustainable solution to the problems associated with the management of plastic waste is plastic upcycling. It entails taking plastic waste and turning it back into its monomers or using certain reaction conditions to synthesize other valuable materials to produce high-value products. Different plastics have varying chemical functionalities in their polymeric chains, which influence their upcycling efficiency. Plastics with a variety of functional groups, such as PET, PVC, and polylactic acid, are relatively easier to upcycle compared to those with fewer or no functionalities, such as polyolefins or PS [19]. On the other hand, upcycling biomass is a crucial goal in sustainable chemistry, aiming to convert these materials into valuable products through resource-efficient chemical transformations. This approach aligns with the principles of a circular economy, which seeks to minimize waste, maximize resource efficiency, and reduce the environmental impact of production and disposal [25,26]. By upcycling biomass and plastic waste, significant waste reduction can be achieved, promoting sustainable resource management. This approach contrasts with the linear economy model of "take-make-dispose," offering a more environmentally friendly and resource-efficient alternative [26].

This review aims to comprehensively analyze synergistic technologies for upcycling waste plastics and biomass within a circular economy framework. It covers the types, sources, composition, and properties of these materials, focusing on environmental impacts. Various upcycling methods, including mechanical, chemical, biological, and thermal approaches, are explored. Applications in construction, packaging, energy, and chemicals are discussed, emphasizing environmental and economic benefits like pollution reduction and resource conservation. Challenges such as technical limitations and policy considerations are addressed, along with future perspectives. Overall, the review stresses the importance of upcycling for sustainability and suggests advancements in technology and policy for a circular economy.

2 Characterization of waste plastics and biomass

Plastic waste is a serious worldwide problem that must be addressed. If waste management practices are not improved, an estimated 1.2×10^{12} tonnes of waste could accumulate in city landfills or persist in other environmental contexts by 2050 [27]. Plastic waste releases a lot of microplastics into the environment as a result of physical, chemical, and biological changes over time [28]. The persistent nature of plastic and its high rates of environmental pollution make plastic pollution one of the most critical challenges of our time.

At the same time, biomass comprises lignocellulosic and herbaceous bioenergy crops (classified as primary sources of biomass), agricultural and forest leftovers (generally classified as secondary sources of biomass) and wastes from industry and urbanization. The sustainable utilization of biomass for energy is increasing steadily [29]. However, primary biomass raises sustainability concerns due to potential competition with other land uses, such as food production, and the expected need for extensive irrigation and fertilization [30]. Despite their differences, waste plastics and biomass share potential as energy sources and can be reclaimed through various synergistic technologies [31]. This intersection offers a promising avenue for managing both types of waste while sustainably producing energy.

2.1 Types and sources of waste plastics

Waste plastics encompass a variety of types, reflecting their widespread applications in modern society. Understanding these types and their sources is essential for effective waste management and recycling initiatives. Petroleum-based plastics, including PE, PP, PS, and PET, are extensively utilized in the production of shopping bags, textiles, and food packaging due to their resistance to corrosion, flexibility, durability, lightweight nature, and cost-effectiveness [32]. The categorization of various types of plastic waste is outlined in Table 1.

As the fuel market expands and global populations increase, the demand for plastic is also on the rise, driven by higher consumption levels. This trend causes a considerable quantity of plastic debris to accumulate, which poses a serious threat to the environment [32]. The correct disposal of plastic waste has emerged as a main worldwide issue that affects both human health and environmental stability. Table 2 offers a detailed examination of the different sources of plastic debris.

Research in the field of plastic pollution is both dynamic and crucial for gaining a comprehensive understanding of this pressing environmental issue. Addressing plastic pollution necessitates collaborative

Table 1 Types of waste plastics

Types	Sources	Ref.
PE	Primarily used in packaging materials, plastic bags, and containers	[27,32,33]
PP	Extensively found in packaging, textiles, and consumer goods	[32−34]
PVC	Frequently used in pipes, cables, construction materials, and packaging	[35]
PET	Used in beverage bottles, food packaging, and textiles	[32,33,36]
PS	It is found in disposable foam products, packaging, and food containers	[32,33,37]
Polyamide (nylon)	Employed in textiles, fishing gear, and industrial applications	[28,31,38]
PU	Found in foam products, cushions, mattresses, and automotive parts	[28]

Table 2 Waste plastic sources

Sources	Example	Ref.
Packaging	Bottles, containers, and wraps: plastic packaging materials from food, beverages, and consumer products	[39]
Single-use plastics	Bags, straws, and cutlery: disposable plastic items used in daily life	[40]
Construction and demolition	PVC pipes, insulation, and sheet materials: plastic materials used in construction and building	[41,42]
Consumer goods	Electronic components and appliances: plastics from discarded electronic devices and appliances	[43,44]
Automotive sector	Interior and exterior components: plastic parts from vehicles	[27]
Textiles	Synthetic fibers and clothing: microplastic shedding from textiles	[45]
Medical waste	Disposable medical items: plastic products used in healthcare	[46]
Fishing gear	Nets, lines, and traps: abandoned or lost fishing gear made of plastic	[47]

efforts to reduce reliance on single-use plastics, promote recycling programs, and innovate alternative materials.

2.2 Composition and properties of waste plastics

Waste plastics are diverse materials with varying compositions and properties, depending on the type of polymer, additives, and processing methods used during their manufacture [27,32,33,36]. Figure 1 provides an analysis and summary of the typical composition of waste plastic.

The composition and properties of waste plastics play a crucial role in their recyclability, environmental impact, and potential for various applications. Innovations in plastic design and recycling technologies aim to mitigate the environmental repercussions of plastic waste. Plastic packaging, typically a blend of polymers along with metals, halogens, paper, and organic waste, presents challenges for recycling due to its complex makeup [33]. There's a growing recognition that product design, with a focus on recyclability, is fundamental for significant improvements in plastic recycling, surpassing the importance of mere waste collection, sorting, or recycling processes [33]. Figure 2 summarizes some key properties governing the reusability of waste plastics, which are critical factors influencing their separability and suitability for incorporation into new materials or products.

Plastic density serves as a valuable parameter for sorting and separating different types of plastic materials, facilitating efficient recycling and upcycling processes. Moreover, understanding the melting point is crucial for determining the appropriate processing conditions and compatibility with various plastics, ensuring a uniform and effective blending process. Conversely, knowledge of mechanical properties, including strength, durability, and flexibility, enables the customization of materials to meet specific application requirements for upcycled plastics. Additionally, elucidating the plastic's thermal conductivity is essential for selecting suitable processing techniques, particularly in applications necessitating precise heating or cooling, where plastics with high heat resistance are preferable to ensure material stability at elevated temperatures. Furthermore, chemical resistance ensures the durability and longevity of upcycled materials under challenging conditions, minimizing significant degradation over time.

Moreover, biodegradable plastics can naturally decompose into environmentally benign components, reducing the impact on ecosystems and addressing concerns related to plastic pollution. While physical appearance, transparency, and surface finish may not directly impact the mechanical or chemical properties of

Fig. 1 Plastic waste composition. Plastic waste is composed of a variety of materials, including different types of polymers such as PE, PP, PVC, PET, PS, polycarbonate, PU, PE naphthalate, polytetrafluoroethylene, polyamide, acrylonitrile butadiene styrene, and polymethyl methacrylate (PMMA). Additionally, plastic waste contains various additives like plasticizers, stabilizers, colorants, and flame retardants. Fillers and reinforcements, such as glass fibers, minerals, and carbon black, are also present. Processing aids, including processing oil and lubricants, may be found in plastic waste, as well as residuals and contaminants like residual monomers and other impurities.

Fig. 2 Properties of waste plastics. Waste plastics exhibit a range of properties, including physical, mechanical, and thermal characteristics. They also possess chemical resistance, impact the environment in various ways, and have distinct appearances.

the plastic, they are important considerations for the marketability and acceptance of upcycled products. Striking a balance between aesthetic appeal and other functional properties ensures that upcycled plastics can find applications in a broad spectrum of industries and consumer preferences.

Understanding the composition and properties of waste plastics is crucial for effective recycling, waste management, and developing sustainable alternatives. Technology and materials science advances continue to influence the development of more environmentally friendly plastics and improve recycling processes.

2.3 Types and sources of biomass

Biomass is a diverse and renewable energy source derived from organic materials. The types and sources of biomass are wide-ranging, encompassing various organic materials from plants, animals, and microorganisms. An overview of different types of biomasses and their sources is provided in Table 3.

2.4 Composition and properties of biomass

Biomass, a non-fossil organic-inorganic solid product, is generated through both natural and man-made (technogenic) processes. It consists of two main components: (1) natural constituents obtained from photosynthesis in vegetation on land and water or from the breakdown of food consumed by humans and animals, and (2) technogenic products resulting from the processing of these natural elements [61]. Organic substances, including cellulose, hemicellulose, lignin, proteins, lipids, and carbohydrates, make up the majority of biomass. Its moisture content can vary, impacting its energy content and storage requirements [61].

The composition and properties of biomass offer numerous significant benefits. These include high concentrations of volatile matter, hydrogen content, structural organic components, extractives, and reactivity. Alkaline earth elements and water-soluble nutrition components are also present in biomass, which affects pH. Moreover, it exhibits low concentrations of fixed carbon, ash yield, C, N, S, and Si, as well as low initial ignition and combustion temperatures. Additionally, biomass contains low levels of a variety of trace elements, including hazardous ones [62]. Figure 3 illustrates the vital properties of biomass that are instrumental in determining the success and efficiency of the upcycling process.

The physical property of biomass, such as density, is a critical factor affecting the associated transportation costs and storage demands. Reduced value may mandate the implementation of densification methodologies, exemplified by palletization, to optimize both handling procedures and logistical considerations. On the other

Table 3 Types and sources of biomass

Types	Sources	Ref.
Wood biomass	Trees, branches, wood chips, and sawdust	[48]
Crop residues	Agricultural residues such as corn stover, wheat straw, and rice husks	[49–51]
Dedicated energy crops	Specifically grown crops for energy production, e.g., switchgrass and miscanthus	[52,53]
Animal waste	Livestock manure, poultry litter, and other agricultural by-products	[51,52]
Aquatic biomass	Algae and aquatic plants	[54]
MSW	Organic components of household waste	[55,56]
Food waste	Discarded food materials from households, restaurants, and food-processing industries	[52,55,57,58]
Forest residues	Debris, bark, and other residues from forestry operations	[59,60]

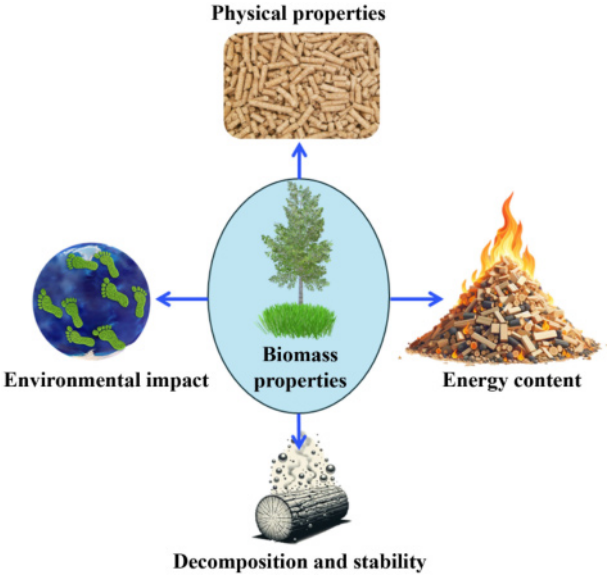

Fig. 3 Various biomass properties. The properties of biomass encompass several key aspects: physical properties, such as density and particle size; energy content, including calorific value; decomposition and stability, such as biodegradability and overall stability; environmental impact, particularly its carbon neutrality and renewability.

hand, the dimensions and configuration of biomass particles play a crucial role in influencing the reachability of enzymes or catalysts in the context of upcycling procedures. The calorific value of biomass also stands as a pivotal parameter in assessing its viability since the primary purpose of upcycling is often to extract the energy content. Additionally, the energy content also influences the efficiency of the conversion process during upcycling. For upcycling applications, especially those focusing on sustainable practices, biodegradability and environmental impact are of utmost importance. Biodegradable biomass can be more environmentally friendly as it tends to decompose into natural substances without leaving persistent pollutants. Utilizing carbon-neutral biomass can help upcycling projects comply with regulations, avoid potential legal issues, and demonstrate a commitment to environmentally responsible practices. On the other hand, stability and renewability are crucial for ensuring that the biomass remains suitable for upcycling throughout its life cycle with minimal degradation and environmental impacts.

Researchers investigated experiments to understand the impact of the physical properties of the biomass and how they interact with the handling and storage apparatus. According to the test results, wood chips and torrefied pellets had the best flowability among the other biomass sources. Given that the partially composted wood chips are more brittle, one of the explanations for their flowability characteristics is their high moisture content [63].

2.5 Comparison between waste plastics and biomass

Waste plastics and biomass have distinct characteristics related to their chemical composition, physical properties, mechanical behavior, environmental impact, and usability. Understanding these characteristics is essential for effective waste management, recycling, and biomass utilization for energy production. Promoting using biomass-derived materials as an alternative to traditional plastics can reduce the demand for fossil fuel-based plastics and mitigate plastic pollution [64].

Using biomass in the context of plastic waste represents a sustainable and circular approach to materials management. It involves reducing the reliance on fossil fuel-based plastics and offering solutions that align with the principles of a circular economy. However, it is essential to consider the entire life cycle of these materials to ensure that they contribute to environmental sustainability.

3 Upcycling methods for waste plastics and biomass

3.1 Upcycling methods for waste plastics

Upcycling strategies for waste plastics encompass a range of innovative techniques aimed at converting discarded plastic materials into higher-value products, thereby minimizing environmental impact and promoting sustainable resource utilization. The different upcycling strategies, as depicted in Fig. 4, are further discussed in the subsequent subsections.

3.1.1 Mechanical upcycling approaches

Mechanical upcycling involves a range of techniques that use physical methods to effectively transform plastic waste into new, higher-value products or materials [65]. These techniques include but are not limited to, shredding or grinding plastic waste, primarily PET and HDPE, into small pieces, which are then melted and molded into new products [66]. Melted plastic waste can undergo several processes to transform it into usable forms. It may be extruded through a die to form continuous shapes, injected into a mold cavity to create solid plastic parts, or compressed in a heated molding cavity until it solidifies into the desired shape. Extrusion is frequently used to produce plastic pellets or sheets for diverse manufacturing needs. Injection molding, on the other hand, is the method of choice for manufacturing items such as automotive parts and toys. Compression molding finds its niche in handling thermosetting plastics like PU and phenolic resins.

Recently, Zabihi et al. [67] investigated an efficient

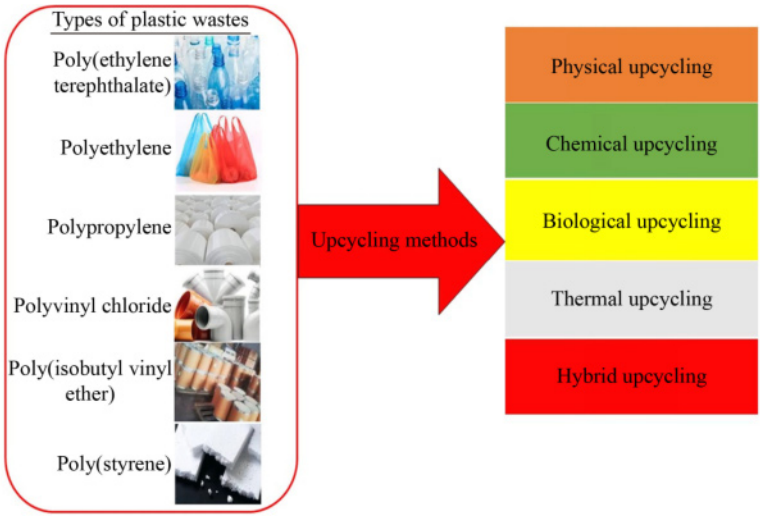

Fig. 4 Strategies for upcycling of waste plastics.

approach for upcycling discarded single-use face masks (W-PP). The upcycled plastic was subsequently blended with varying percentages of vegetable oil, creating a material with improved tensile strength and modulus for versatile applications. The upcycled W-PP was further utilized in fabricating glass fiber-reinforced composites. Using dissolution, spin-coating, and annealing techniques, Saleem et al. [68] upcycled polyolefin-based plastic waste via conversion into a bimodal super oleophilic sorbent. This process yields a sorbent with an extensive network of pores and cavities, exhibiting sponge-like behavior and the ability to recover sorbed oil through mechanical or manual squeezing.

Similarly, Topuz et al. [66] investigated the valorization of PET waste via dissolution in trifluoroacetic acid or a trifluoroacetic acid/dichloromethane binary solvent system to produce nanofibrous adsorptive membranes for oil removal. According to the authors, this technique is a sustainable approach to the management of waste plastic and oil pollution.

In summary, physical upcycling involves various techniques to convert plastic waste into new products or materials with higher value. These techniques include shredding or grinding plastic waste into small pieces, melting them, and forming them into new products through processes like extrusion, injection molding, or compression molding. Recent studies have explored innovative approaches to upcycle specific types of plastic waste, such as PP from single-use face masks and PET.

3.1.2 Chemical upcycling approaches

Chemical upcycling represents a transformative approach to managing waste plastic materials, utilizing advanced depolymerization technologies. Through depolymerization, the intricate polymeric structures of waste plastics undergo breakdown into simpler molecules, facilitated by either catalytic or non-catalytic conversion steps. Here are several examples of chemical upcycling techniques utilized for waste plastics.

3.1.2.1 Catalyst-free technique

Catalyst-free chemical upcycling involves transforming waste materials or low-value feedstocks into high-value products without relying on catalysts. This strategy is quite significant as it eliminates the requirement for expensive or environmentally detrimental catalysts, thereby cutting down on both the cost and environmental impact of the upcycling process. During the upcycling of chlorine-contaminated PP, Kots et al. [69] utilized a magnesia-alumina mixed oxide to trap chlorine from the polyolefin melt. Using ruthenium-based catalysts, this method guaranteed the subsequent upcycling of plastic waste into lubricants with a maximum PVC concentration of 10%. According to the authors, this strategy lowered the impact of chlorine impurities on the hydrocracking and hydrogenolysis catalysts while mitigating the emissions of hydrochloric acid, potentially fostering advancements in plastics upcycling.

Obando et al. [70] directly converted crosslinked PE foams into porous carbon materials in the absence of catalysts. This process, facilitated by sulfonation-based crosslinking, efficiently converted PE into valuable carbon precursors while preserving the high porosity characteristic of the foam precursors. Through sulfonation and subsequent carbonization steps, the resulting carbons exhibited significant surface area and a sulfur-doped framework, enhancing carbon dioxide sorption capacity and CO_2/N_2 selectivity. The authors stressed that this upcycling approach offered a promising solution to address the substantial environmental challenges posed by plastic waste and greenhouse gas emissions on a large scale. Using terpenoids and waste sulfur, Derr et al. [71] successfully recycled PET into composites. This technique proceeded with the transesterification of post-

consumer PET into low-molecular PET oligomers using terpenoid alcohol. The resulting alkenes in the PET oligomer then served as reaction sites for inverse vulcanization to yield composite materials.

Gao et al. [72] documented a groundbreaking transformation of discarded PET (dPET) into a high-performance material. Through a streamlined one-pot process, the soft and hard segments of thermoplastic polyester elastomeric (TPEE) molecules were cross-linked with dPET, resulting in the generation of two key polymers: $(C_8H_4O_4)_n$ and $((C_{16}H_{18}O_4)_{0.76}\cdot(C_4H_8O)_{0.24})_n$. This chemical reaction between TPEE and dPET led to the formation of unique product characteristics and chemical bond-crossing structures. The resulting material exhibited high tensile strength (34.21 MPa) and impact resistance, attributed to the anchoring effect of dPET particles or multiple TPEE particles due to its high viscosity. Adipic acid and microwave irradiation were used. Similarly, Hoang et al. [73] suggested a technique of upcycling PET bottles that had been used after the date of consumption. As a consequence, several materials are isolated, including terephthalic acid, excess adipic acid, and a new oligo(ethylene adipate-co-terephthalate) (OEAT) containing carboxylic end groups. This upcycling process demonstrated high atom efficiency and a high yield reaction, with recovered adipic acid and terephthalic acid serving as feedstock materials and OEAT utilized for curing diglycidyl ether of bisphenol-A resin.

Moreover, recent reports highlight innovative approaches toward PET upcycling for composite synthesis. Lopez and Smith [74] employed a three-stage route involving glycolysis and trans/esterification to produce high-compressive strength composites. Maladeniya et al. [75] introduced a single-stage process where PET, heated with geraniol and elemental sulfur, formed a highly crosslinked sulfur-PET-geraniol network composite. Similarly, Wijeyatunga et al. [76] reported on the upcycling of PMMA via transesterification with terpenoid and geraniol, resulting in a durable composite, PGMA-S, with mechanical properties competitive with legacy building materials. Beyond PET, Ng et al. [77] demonstrated the efficient upcycling of mixed plastic waste and the production of vitrimer processable PET from recovered PET oligomers. This approach, utilizing glycerol as a cleaving agent, yielded crosslinked yet reprocessable vitrimers suitable for various applications, showcasing the potential for sustainable plastic waste management.

3.1.2.2 Catalytic upcycling technique

The catalytic upcycling technique represents a departure from conventional chemical methods, offering the simultaneous generation of valuable chemicals while reducing energy consumption. Different catalytic waste plastic upcycling approaches vary in their mechanisms and the energy sources employed to drive chemical reactions.

In electrocatalytic upcycling, external electrical potentials catalyze reactions by lowering activation energy requirements. Li et al. [78] investigated the use of electrocatalytic techniques to convert plastic waste into fuels and chemicals. Their study employed medium entropy cobalt spinel oxide compounds integrated with nanostructured nickel foam ($Ni_{0.5}Ce_{0.5}Co_2O_4$) as electrocatalysts tailored for selective oxidative upcycling of PET into potassium diformate and terephthalic acid, alongside hydrogen evolution at the cathode. The electrocatalyst exhibited superior oxidative activity compared to water, demonstrating 91.8% selectivity for formate conversion with a Faraday efficiency of 95%. The synergistic interplay between nickel and cerium in the ($Ni_{0.5}Ce_{0.5}Co_2O_4$) electrocatalyst facilitated ethylene glycol molecule and hydroxide ion adsorption, guiding directionally-oriented *OH to participate in ethylene glycol oxidation and thus enhancing hydrolyzed PET product oxidation.

Similarly, Zhang et al. [79] presented a photovoltaic-driven electrocatalytic strategy for PET upcycling into formic acid products and green hydrogen co-production. Their approach dissolved waste PET in potassium hydroxide and then pumped it into an electrochemical flow reactor comprising CuO nanowires anode and Pt/C 20% cathode, powered by commercial silicon photovoltaic panels. This strategy demonstrates the potential for utilizing renewable energy to produce chemicals and fuels from plastics.

In photocatalytic upcycling, chemical reactions are initiated or accelerated by light energy in the presence of a photocatalyst, often involving the activation of oxygen or other molecules by reactive oxygen species generated on the photocatalyst surface upon illumination. Meanwhile, studies have depicted carbon dots and nanodots as novel materials with excellent light absorption properties and rapid electron transfer capabilities [80]. Consequently, Han et al. [81] synthesized carbonized polymer dots-graphitic carbon nitride composites to serve as binary catalysts for PET upcycling coupled with photocatalytic hydrogen production. This process yielded ethylene glycol and other value-added products, along with high-purity terephthalic acid and hydrogen fuels. Qin et al. [82] combined carbon nanodots with a metal-organic framework (CDs/Zr-MOF) for photocatalytic upcycling of PVC. The investigation resulted in improved PVC conversion due to the generation of •OH radicals, which facilitate the cleavage of the C–Cl/C–C bond and reduce the energy barrier for hydroxylation reaction.

Furthermore, Langer et al. [83] investigated the upcycling of poly(isobutyl vinyl ether) (PIBVE) to small molecules using visible light-mediated methods. This technique involves the degradation of PIBVE to low molecular weight oligomers through photooxidative pro-

cesses, resulting in the production of alcohols, aldehydes, and carboxylic acids. According to mechanistic research, oxidative cleavages caused by hydrogen atom transfer from the side chain or backbone generate tiny molecules. Application of this upcycling approach to a copolymer of poly(methyl acrylate-co-isobutyl vinyl ether) demonstrates that it is especially efficient for polymers with more electron-rich C–H bonds.

3.1.3 Biological upcycling approaches

A viable method for handling plastic waste that offers a long-term solution to plastic pollution in the world is biological upcycling [84]. Unlike traditional methods such as landfilling and incineration, biological upcycling harnesses the potential of microorganisms to degrade plastic waste into environmentally friendly byproducts and, in some cases, valuable resources [85]. As elucidated by Jaiswal et al. [86], the microbial breakdown of plastics involves a series of sequential steps: biodeterioration, biofragmentation, assimilation, and mineralization. During the biodegradation phase, bacteria that break down plastic first adhere to the plastic surface to create biofilms. These microbial biofilms subsequently produce certain extracellular enzymes that help break down polymer long chains into oligomers, which are oxidized [87]. During the absorption stage, microorganisms absorb oligomers by a variety of *in vivo* metabolic processes, primarily the citric acid cycle and β-oxidation. At last, these oligomers go through a process called mineralization, which produces water, methane, and carbon dioxide [88].

Understanding the critical function that energy plays in natural systems and the limited supply of fossil fuels in addition to its harmful effects on the environment when burned, Jadhav et al. [89] emphasized the potential energy that microalgal biomass possesses. Because microalgal biomass is high in oil and lipids, it may be properly transesterified to produce biodiesel or fatty acid methyl ester, which presents a viable alternative energy source. Furthermore, the cultivation of freshwater or marine microalgae requires significant amounts of carbon dioxide. Therefore, the carbon dioxide generated from the complete biodegradation of plastics can serve as an effective carbon source for microalgal cultivation. Consequently, the bio-mitigation of plastics by microorganisms for carbon dioxide generation and the subsequent utilization of carbon dioxide for algal biomass generation was investigated. *Pseudomonas mendocina* ABF786 was employed as an efficient plastic-degrading bacterium, with the substantial carbon dioxide produced during plastic biodegradation being diverted to another container and solubilized as bicarbonate (HCO_3^-). Bicarbonate was then utilized in the production of algal biomass (*Chlorella vulgaris*), which relies on a continuous supply of carbon dioxide for growth [89].

Valenzuela-Ortega et al. [90] detailed a novel one-pot bio-upcycling of PET plastic waste utilizing an engineered strain of *Escherichia coli*. The significance of their work stems from the utilization of PET depolymerization byproducts, namely ethylene glycol and terephthalic acid, as substrates in the metabolic pathway for adipic acid production. Similarly, Kim et al. [91] showed how to use *Gluconobacter oxydans* to bioconvert $(CH_2OH)_2$ from PET into glycolic acid and how to use engineered *Escherichia coli* MG1655, to bioconvert terephthalic acid into vanillic acid, muconic acid, gallic acid, and pyrogallol, with yields ranging from 33% to 93%. Additionally, Werner et al. [92] achieved high-level bioproduction of β-ketoadipate from bis(2-hydroxyethyl) terephthalate using engineered *Pseudomonas putida* KT2440, with a yield of 76%. Sullivan et al. [93] developed a strategy for selectively converting mixed plastic waste into valuable chemical products. Their research involved metal-catalyzed autoxidation depolymerization of mixed plastic waste into oxygenated small molecules, which served as substrates for biological conversion. Engineered *Pseudomonas putida* was employed to channel these oxygenated compounds into either β-ketoadipate or polyhydroxyalkanoates, demonstrating the versatility of the approach. Vanillin, a highly sought-after flavoring molecule widely used in the food and cosmetic sectors, is produced directly from the PET-derived monomer terephthalic acid by an innovative metabolic route that Sadler and Wallace [94] developed using modified *Escherichia coli*. Through process optimization, the study achieved an impressive 79% conversion rate of terephthalic acid to vanillin. Additionally, Carniel et al. [95] successfully employed wild-type *Yarrowia lipolytica* IMUFRJ 50682 as a biocatalyst for PET depolymerization. This study also highlighted the biocatalyst's capability to oxidatively transform ethylene glycol, derived from PET depolymerization, into glycolic acid.

Ballerstedt et al. [96] focused on the research project MIX-UP, which aims to transform the conventional linear value chain of plastics into a sustainable and biodegradable one. The project addresses the global plastic waste issue by utilizing mixed microbial communities to biodegrade and upcycle mixed plastics. The project targets a variety of plastic polymers, including common fossil-based plastics such as PE, PU, PP, PET, and PS, as well as bioplastics like polyhydroxyalkanoate and polylactate. The plastic waste is subjected to regulated enzymatic and microbial breakdown, which is succeeded by microbial conversion via mixed cultures into polymers and compounds with added value. Through integrated protein engineering, the researchers hope to improve the stability, catalytic effectiveness, and binding capabilities of plastic-degrading enzymes under demanding circumstances. Additionally, the project focuses on discovering and isolating novel enzymes capable of degrading recalcitrant polymers. The consortium behind MIX-UP

consists of multidisciplinary experts and industry partners aiming to develop sustainable routes for valorizing plastic waste streams. The project's process turns plastic monomers into biomass, important building elements, and value-added goods, all of which support a circular (bio)plastic economy.

In summary, biological upcycling, a promising approach for tackling plastic waste, involves leveraging microorganisms to degrade plastics into environmentally friendly byproducts and valuable resources. This process, elucidated by various studies, encompasses biodeterioration, biofragmentation, assimilation, and mineralization stages. Notably, the carbon dioxide generated during plastic biodegradation can be utilized for microalgal biomass cultivation, offering a sustainable energy alternative. Recent research has also highlighted innovative strategies for upcycling specific types of plastic waste. For instance, engineered strains of *Escherichia coli* and *Pseudomonas putida* demonstrate the potential to convert PET waste into valuable compounds like ethylene glycol, terephthalic acid, glycolic acid, vanillic acid, and others. These studies showcase the versatility of biological approaches in transforming plastic waste into useful chemicals, contributing to the mitigation of plastic pollution while offering valuable resources for various industries.

3.1.4 Thermal upcycling approaches

The thermal/pyrolytic upcycling technique for waste plastics involves converting plastic waste into valuable products through heat application, typically in an oxygen-deprived environment. At high temperatures, waste plastics undergo thermal degradation and decompose into smaller molecules. These molecules are then processed further to produce fuels, chemicals, or other useful materials.

Kumari et al. [97] employed disposable syringes, gloves, and face masks as precursors to produce three distinct types of highly fluorescent carbon dots using a straightforward heating method. The carbon dots exhibited significant variations in optical and luminescence properties. Notably, the study operated within a temperature range exceeding 100 °C, effectively eliminating pathogens and mitigating the risk of transmission to living beings. In another study, Lee et al. [98] generated carbon material (PE-C) from PE using e-beam irradiation to facilitate linear chain conversion to cyclic ladder structures. This advancement led to increased carbonization yield compared to conventional methods. The resulting PE-C was subsequently integrated into a polyamide 6 (PA6) polymer matrix to produce composite materials (PE-C/PA6).

Another heat-related method for upcycling waste plastic is thermochemical conversion, which integrates thermal and catalytic processes. This technology operates at high temperatures, initiating the thermal decomposition of waste plastics to produce hydrocarbons, with the presence of a catalyst playing a crucial role in determining the composition and distribution of products. Excellent C–C bond activation breaking ability, high carbon solubility, and improved hydrocarbon diffusion on their surfaces have been discovered as catalysts for iron metal and zeolite [99]. These qualities make them useful for accelerating the transformation of waste polymers into valuable carbon compounds. Pal et al. [100] conducted research on the non-catalytic and zeolite-catalyzed fast pyrolysis of multilayer plastic packaging, primarily composed of PE and PET. Their research revealed that although zeolite-catalyzed rapid pyrolysis produced mono-aromatic hydrocarbons including benzene and xylene, non-catalytic fast pyrolysis mostly produced a combination of aliphatic and alicyclic hydrocarbons.

Due to the significant energy requirements associated with both catalyzed and noncatalyzed thermal upcycling techniques, Alali et al. [101] proposed a controlled partial depolymerization plant capable of transforming PE into value-added products at temperatures below 400 °C, with or without the presence of a catalyst. The process entails preheating PE in a furnace, followed by an aromatization reaction, where long-chain alkyl aromatics and hydrocarbons are formed at 280 °C over 24 h. After cooling, the resultant gaseous mixture is subjected to distillation in order to separate the components toluene and methane. Additionally, an adsorption column is used to separate the liquid waxes created in the reactor. This is followed by a succession of distillation columns to further separate the various alkyl aromatic compounds.

Other researchers have presented that plastic waste can only be converted into gaseous and solid value-added products exclusively, without generating a liquid product. Li et al. [99] used Fe/ZSM-5 catalysts in a two-stage fixed-bed reactor to catalytically pyrolyze PE, producing hydrogen and carbon nanotubes concurrently at different Fe catalyst loadings. The findings showed that when iron loading increases, the output of hydrogen and carbon nanotubes first rises and then falls. Wang et al. [102] synthesized porous chromium carbide via a chemical reaction between metallic chromium and waste PE, utilizing molten metallic magnesium as a reaction medium. The experimental setup involved mixing a specific mass of metallic chromium, waste PE, and metallic magnesium, charging them into a 20-mL stainless steel autoclave operated at 700 °C for 10 h at a heating rate of 5 °C·min^{-1}. After the autoclave cooled to 25 °C, the black product was removed and repeatedly cleaned to get rid of byproducts using distilled water, diluted hydrochloric acid, and alcohol. It was then vacuum-dried in an oven at 70 °C. Zhou et al. [103] similarly upcycled mixed plastic waste into carbon black and natural gas exclusively. The resulting pyrolysis gas exhibited high methane content and heat value, while the

solid product contained carbon spheres with a semicrystalline graphitic structure. Zhou et al. [104] successfully reclaimed carbon materials, pyrolysis gas and chlorides via PVC upcycling. The process involved dechlorination using Cl^- fixatives, carbonization of dechlorinated products, and further modification into carbon materials. Notably, the main components of the pyrolysis gas are methane and hydrogen (81.87–99.34 vol % of pyrolysis gas), and the process achieved up to 83.13% conversion of the precursor into carbon materials. Similarly, Wyss et al. [105] produced high-purity turbostratic flash graphene from cheap pyrolysis ash derived from plastic waste, which may be utilized to improve Portland cement and polyvinyl alcohol composites.

3.1.5 Hybrid upcycling approaches

Hybrid upcycling techniques merge multiple processes or technologies to optimize the conversion of plastic materials into valuable products. These methods typically integrate various physical, chemical, and biological approaches to enhance efficiency, increase product yields, and minimize environmental impact. Numerous authors have explored different hybrid upcycling techniques. For instance, Chang et al. [106] reported on the mechanochemical upcycling of waste PS and elucidated the associated kinetic phenomena. This mechanochemical method produces styrene at a constant rate and selectivity along with minor products like benzaldehyde by solid-state depolymerization at ambient temperatures in a ball-mill reactor. The authors stress that in order to prevent repolymerization, continuous monomer removal is essential throughout reactor operation. Moreover, molecular oxygen and iron surfaces are used during the process to produce reaction-boosting effects.

Mohd Abdah et al. [107] successfully converted PP waste from used centrifuge tubes into activated PP carbon of a well-organized three-dimensional (3D) structure, while Zhao et al. [108] achieved the conversion of LDPE plastic waste into hydrogen and carbon nanotubes using microwave-assisted pyrolysis. According to Zhao et al. [108], the hydrogen yield is as high as 63.5 $mmol \cdot g^{-1}$ plastic, with a high selectivity of 83.7 vol %.

To improve mechanical qualities, Nam et al. [109] upcycled post-consumer acrylonitrile-butadiene-styrene by combining it with styrene-butadiene-styrene using plasma-assisted mechanochemistry. Mechanochemical processes can be aided by plasma in the presence of high-energy plasma gases. This method improves impact strength by mitigating phase separation between acrylonitrile, butadiene, styrene, and additives and resolves thermo-oxidative deterioration of the butadiene phase.

Xu et al. [110] showcased the feasibility of producing carbon-based high-performance supercapacitors from waste materials using a solvothermal method. In their study, used PET bottles were transformed into a MOF known as MIL-53(Al). This material was subsequently carbonized to create a nitrogen-doped hierarchical porous carbon framework with a remarkable specific surface area of 1324 $m^2 \cdot g^{-1}$ and well-defined porosity. These findings suggest promising applications for such materials as supercapacitor electrodes.

Williams et al. [111] reported on the thermo-electrochemical conversion of plastic wastes involving the integration of thermal and electrochemical upcycling techniques. Accordingly, the thermo-electrochemical conversion of PE and salty brown seaweed at 500–600 °C produced high-purity (85%) hydrogen. Carbon materials sourced from seaweed and plastics were respectively converted to carbonate ions (using Li_2CO_3/K_2CO_3/LiOH electrolyte) and carbon nanotubes via electrosplitting.

3.2 Techniques for lignocellulosic biomass upcycling

Lignocellulosic biomass comprises the waste or byproducts generated during agricultural activities, broadly categorized into two main groups: direct residues of planting processes (such as stalks, seeds, stems, and wood chips) and residues from agricultural industries (including molasses, bagasse, husks, peels, cakes, etc.) [112]. These biomass sources offer potential for upcycling into various value-added products, including carbonaceous feedstocks, biofuels, biopolymers, and bio-extracts. The subsequent subsections will delve into different techniques for achieving this transformation.

3.2.1 Lignocellulosic biomass upcycling into carbonaceous products

Agricultural biomasses are highly regarded as valuable renewable feedstocks owing to their enriched carbon content, typically obtained via thermal decomposition in the absence of oxygen [113]. Consequently, various techniques involving varying temperature conditions have been employed to thermally decompose plant biomasses into carbon chars. Notably, the variation in operation temperature and other thermal decomposition conditions yields value-added products of different elemental compositions. The different thermochemical decomposition techniques are discussed further herein.

3.2.1.1 Pyrolysis

Pyrolysis is the process of thermally decomposing organic materials in the absence of oxygen, typically carried out at elevated temperatures (the specific temperature depends on the nature of the precursor feedstock). During pyrolysis, lignocellulosic biomasses undergo conversion into solid carbon, with minimal generation of liquid or gaseous byproducts. The resulting solid char product, rich in carbon, can undergo further processing to enhance its purity. Notably, this technique

involves two main stages. In the initial stage, the lignocellulosic biomass undergoes pretreatment. This involves washing the biomass with ultra-pure water at room temperature to remove any inherent impurities. Subsequently, it is dried at 80 °C until reaching a constant weight and then ground to achieve a uniform particle size [114,115]. Following pretreatment, the actual pyrolysis takes place. This step typically occurs gradually, with the biomass subjected to a specified heating rate in a tube furnace under an inert atmosphere of high-purity nitrogen for a specific duration.

Cruz et al. [115] conducted experiments involving the pyrolysis of coffee husks and corncobs. Grounded biomasses (particle size: 0.5 mm) were pyrolyzed in batches of 50 g each at 600 °C, with a heating rate of 10 °C·min^{-1} in a tubular furnace, while the nitrogen flux was controlled by a multi-gas controller to maintain a flow rate of 150 mL·min^{-1}. The duration of pyrolysis was 2 h, and the resulting carbonized materials were cooled to ambient temperature within the nitrogen atmosphere before storage for further use. Similarly, Wang et al. [114] conducted pyrolysis of bagasse. The heating rate was set at 5 °C·min^{-1}, and the biomass was subjected to 350 °C for 1 h under a nitrogen atmosphere. The pristine biochar obtained was further pyrolyzed at 950 °C for 3 h to achieve the desired product. Shan et al. [116] produced biochar from peanut shells. After three rounds of deionized water rinsing, the shells were oven-dried for a whole night at 80 °C before being broken up. Pyrolysis occurred in a tubular furnace under a flow of nitrogen, with the temperature ranging from 350 to 600 °C, at a heating rate of 10 °C·min^{-1}, for a carbonization time of 2 h. Zhou et al. [117] optimized biochar production from water hyacinth. Initially, the water hyacinth was cut into smaller segments (approximately 1–2 cm), washed, and dried at 70 °C until reaching a constant weight. After being dried, the material was put into a quartz boat that could withstand high temperatures and put into a tube furnace. Over the course of two hours, the temperature changed between 200 and 700 °C while maintaining a constant heating rate of 20 °C·min^{-1}.

3.2.1.2 Hydrothermal carbonization (HTC)

The HTC process entails the direct thermochemical conversion of moist lignocellulosic biomass into biochar, also referred to as hydrochar [118]. In HTC, biomass is submerged in water and subjected to temperatures ranging from 180 to 250 °C within an autoclave. This thermal treatment leads to a pressurized environment within the autoclave, maintaining the water in a subcritical state with a high proton concentration [119]. Biomass undergoes reactions such as hydrolysis, dehydration, decarbonylation, decarboxylation, polymerization and recondensation to produce hydrocarbon solid residues. Unlike pyrolysis, which requires an initial dewatering pre-treatment stage to reduce moisture content, HTC directly converts moist biomass into biochar, thus eliminating the need for drying and its associated costs [120]. Notably, the HTC process is highly influenced by a number of process variables, including temperature, residence time, heating rate, pH, and substrate concentration. These variations result in differences in the hydrochar yield and physiochemical characteristics. Pressure, however, has been observed to have a negligible effect on the process as long as it remains below the critical limit [119].

Kızılduman et al. [121] employed an HTC route to upcycle rice husk into biochar. In this method, pre-treated rice husk was dried at 105 °C for 48 h, and a portion of aqueous hydrochloric acid and distilled water were introduced to the autoclave system. The resulting samples were then thoroughly washed with distilled water using a vacuum motor, subsequently rinsed with ethyl alcohol, and finally dried at 80 °C for 6 h.

Sultana et al. [122] successfully generated biochar from food waste using a similar approach. In their method, a dry mass of food waste suspended in deionized water at a ratio of 1:10 was loaded into the autoclave reactor. Maximum temperature and pressure conditions throughout the HTC process are 220 °C and 650 ± 20 psi. The process liquid after HTC is separated from the solid char by a vacuum filtration system. The separated biochar needs to be dried in an oven at 105 °C and stored in centrifuge tubes for future utilization.

3.2.2 Lignocellulosic biomass upcycling into bioactive compounds and extracts

Throughout the agri-food chain, significant amounts of byproducts are produced, especially from harvesting through food processing processes. These leftover lignocellulosic biomasses are made up of lipids, proteins, and carbohydrates. These compounds have the ability to store bioactive materials, such as natural colors, which can be recovered and used as feedstock or additives [123]. To effectively recover these bioactive constituents and other intracellular compounds from lignocellulosic biomasses, it is imperative to mitigate mass transfer resistances by enhancing the contact/interaction between the solvent and the precursor materials [124]. Notably, extraction stands as a pivotal unit operation in extracting bioactive compounds from their native state within lignocellulosic sources [125]. Consequently, the various techniques for extracting bioactive components are further elaborated upon herein.

3.2.2.1 Solvent extraction

Solvent extraction is a technique employed to separate compounds based on their varying solubilities. Typically, this method involves contacting biomass, often compri-

sing small-sized particles, with a suitable solvent (known as an extractant) within a beaker or a soxhlet extractor. To optimize the extraction process, the system's temperature is often gently raised to a level that preserves the integrity of the bioactive compounds [126]. Following extraction, the resulting slurry undergoes cooling and vacuum filtration, while the clear extract is subjected to centrifugation, further precipitation, or separation through vacuum distillation.

In the study conducted by Kamal et al. [126], pectin was extracted from fresh guava (*Psidium guajava* L.) fruit residue. Mature and fresh guava fruits underwent cleaning, slicing, and juicing using a juice extractor. The resultant juice was filtered, leaving behind residue that was subsequently dried, ground into a powder, sieved, and stored for later use. Guava fruit pomace powder was then mixed with various extractants at different pH levels and subjected to extraction according to the experimental design. After extraction, the mixture was cooled and filtered, while the resulting clear extract underwent centrifugation. Ethanol was introduced to the precipitate, followed by refrigeration overnight. The obtained pectin underwent multiple ethanol washings to eliminate sugars, and the damp pectin was dried until reaching a constant mass at 50 °C.

3.2.2.2 Hybrid solvent extraction

The solvent extraction method is employed to separate compounds based on their solubility, typically utilizing organic solvents such as alcohol. However, despite its simplicity and effectiveness, this method is frequently characterized by time-consuming procedures, high solvent consumption, and insufficient reproducibility [127]. In response to these limitations, recent advancements have led to the development of innovative green extraction methods tailored for extracting bioactive components from lignocellulosic biomass. These progressive techniques will be elucidated in the following subsections.

(a) Ultrasound-assisted solvent extraction

Among emerging technologies, ultrasound-assisted extraction, which harnesses specific frequencies, amplitudes, and wavelengths of sound waves, stands out as one of the most extensively explored and effective methods for recovering natural pigments from byproducts [128]. Ultrasound is generated through ultrasonic transducers, which convert electrical energy into acoustic waves at the appropriate frequency and intensity [124].

The primary advantages of this technology include reduced extraction and processing times, lower energy requirements, decreased carbon dioxide emissions, reduced solvent volumes, and enhanced extraction yields [129]. The process of ultrasound-assisted solvent extraction generally entails dissolving powdered biomass in a chosen solvent at an appropriate pH. The solution is then transferred to an ultrasound extractor set to specified operating conditions. The extraction proceeds for a predetermined duration to allow for the propagation of ultrasound waves. As these waves traverse the fluid, the liquid vaporizes due to alternating compression and rarefaction, creating gas bubbles [130]. These bubbles explode when they hit a critical point, releasing a large quantity of energy and raising the surrounding pressure and temperature. Acoustic cavitation is a process that causes physical shearing effects [124].

Given that bioactive pigments in plants are contained within organelles inside cells, the rupture of these organelles and cell walls during ultrasound-assisted extraction facilitates greater pigment release. Following ultrasound extraction, the mixture is cooled to room temperature and then centrifuged. The resulting pure extract is further processed based on its intended use. According to Nabi et al. [125], an ultrasound probe system is preferred over an ultrasound bath for extraction due to its ability to deliver more intense ultrasound energy through a smaller surface area. Probes typically operate at 20 kHz and are connected to a transducer, enabling direct delivery of ultrasound waves to the extraction media with minimal energy loss.

(b) Microwave-assisted solvent extraction

This method employs a procedure akin to the ultrasound-assisted extraction technique, yet its extraction mechanism relies on the direct impact of microwave radiation on material molecules. Here, microwaves are utilized to disrupt plant cells, facilitating the absorption of bioactive compounds by the extraction solvents [131]. The bioactive molecules are efficiently released as a result of increased pressure on the cell tissue, leading to the breakdown of cellular matrices and enhanced porosity, thereby facilitating mass transfer from within the cell to the external environment [132]. Ionic conduction and dipole rotation are the two methods that concurrently convert electromagnetic energy into thermal energy.

Ridlo et al. [133] demonstrated microwave extraction of bioactive compounds from karamunting fruit using 400 W of power and a specific extraction duration. The resulting extract exhibited a vibrant yellow color and subsequently evaporated using a rotary vacuum evaporator at 55 °C for 5 min. The filtrate was then separated from the solid residues via centrifugation at 5000 $r \cdot min^{-1}$ for 10 min at 25 °C. Ethanol was selected as the extraction solvent due to its non-carcinogenic nature and its high capacity for absorbing bioactive compounds.

(c) Enzymatic-assisted solvent extraction

Enzyme-assisted extraction involves treating samples with enzyme(s) before solvent extraction [134]. This pre-extraction enzymatic hydrolysis enhances the extraction efficiency of bioactive components [135]. Enzyme-assisted solvent extraction follows a procedure similar to ultrasound-assisted extraction and microwave-assisted extraction, but it incorporates the use of hydrolytic

enzymes to disrupt cell walls, primarily composed of complex polymers like lignin, hemicellulose, cellulose, and pectin.

3.2.2.3 Supercritical fluid extraction (SFE)

SFE offers an environmentally friendly alternative to organic solvent extraction [136]. These fluids possess low viscosity and high diffusion constants, which enhance the extraction efficiency of bioactive components [137]. In this technique, mass transfer occurs more rapidly compared to traditional organic solvents, resulting in shorter extraction times. Water, carbon dioxide, benzene, toluene, ethane, and ethanol are among the numerous chemicals suitable for use as supercritical solvents. However, carbon dioxide stands out as the most commonly utilized supercritical fluid due to its affordability, non-toxic nature, chemical inertness, and ability to dissolve a wide range of organic molecules when heated to 31.1 °C and compressed to 7.4 MPa [137]. Furthermore, the application of a compressible gas demands an adjustment in the solvation power of the solvent through manipulation of its density. Also, by reducing the pressure of the CO_2 gas to atmospheric levels, a solvent-free collection of extracted analytes can be achieved at the outlet of the extraction cell [138].

The SFE process involves grinding the biomass into uniform particle sizes and drying it to a constant dry weight. Subsequently, the ground sample is placed in the extraction vessel, ensuring proper fluid flow. The reaction temperature and pressure are set above the solvent's critical point (typically 31–100 °C, 72–500 bar). The supercritical fluid is then introduced into the extraction vessel to dissolve the target compounds, maintaining the reaction conditions throughout the extraction duration. Upon reaching equilibrium, the supercritical fluid is directed to a collection vessel as it is depressurized, causing the bioactive compounds to precipitate.

3.2.2.4 Hydrothermal liquefaction (HTL)

The thermochemical process known as HTL, which operates in a water-based environment at high pressure and temperature, is used to transform biomass into biocrude [139]. Although the experimental methodology for HTL bears similarities to that of HTC, the key distinction lies in temperature parameters. Whereas HTC typically operates within the temperature range of 180–250 °C, HTL employs notably higher temperatures, typically ranging from 250 to 375 °C, along with pressures spanning between 10 and 22 MPa [118]. At the conditions mentioned above, the biomasses are chemically transformed into a complex mixture of organic compounds (biocrude), with renewable energy potentials [140]. Subsequently, this biocrude can be subject to further refinement and upgrading processes to yield fuels meeting transportation fuel standards, such as diesel, gasoline, or jet fuel [141]. HTL's utilization of subcritical water as a reaction medium circumvents the necessity for energy-intensive drying procedures, enhancing its efficiency and sustainability [119].

3.2.3 Lignocellulosic biomass upcycling into biopolymers

The ubiquitous use of plastic in industrial products, toy packaging, fluid containers, shopping bags, trash bags, and the wrapping and packaging of building materials has made plastic products an integral part of contemporary life [142]. However, the non-biodegradable nature of plastics has raised significant environmental concerns due to their extensive disposal. Achieving environmental sustainability has emerged as a pressing challenge amid the exponential growth of urbanization, population, and living standards. The excessive reliance on synthetic/petroleum-based plastics has intensified these concerns, prompting the search for renewable materials to develop biodegradable alternatives [143].

In recent years, biodegradable plastics have emerged as a promising and sustainable substitute for conventional plastics. A growing number of biopolymers are being used to produce bioplastics, including those produced from agro-based sources including starch, cellulose and pectin, as well as proteins like zein, gluten. Because of the complex intra- and inter-molecular interactions and cross-links between polymeric components that these natural polymers display, a semisolid three-dimensional polymeric network that can hold solvents is formed [142]. Various techniques for obtaining these biopolymers are discussed further in this paper.

3.2.3.1 Hydrolysis

Based on the findings of various studies, hydrolysis reactions emerge as a prevalent technique for biopolymer synthesis from lignocellulosic biomasses. Typically, this process entails the breakdown of powdered biomass in a solution of a hydrolyzing agent, followed by bleaching treatment and, ultimately, the regeneration of a solubilized biopolymer in a nonsolvent. The literature demonstrates the successful utilization of different reagents, including alkaline solutions [144,145], alcohol [146], and acid [147] as hydrolyzing agents.

Hoque and Janaswamy [144] extracted lignocellulosic fibers from banana peel via alkali and bleaching treatments, followed by solubilization in a 68% $ZnCl_2$ solution and crosslinked using various concentrations of Ca^{2+} ions to produce the desired biopolymer films. Ahmed and Janaswamy [147] also synthesized biodegradable film from avocado peel powder. The process involved washing the avocado peels in warm water, followed by oven-drying at 50 °C for 24 h. The dried peels were then crushed to uniform fine particle size, and

the avocado peel powder subsequently underwent acid hydrolysis at a 1:12 ratio (powder: acid) and was further treated overnight with a mixture of acetic acid and hydrogen peroxide at 95 °C to remove lignin. To create a white fibrous extract, the delignified pulp was next impregnated for three hours in a 90% sodium hydroxide solution. This extract was neutralized by repeatedly washing it with distilled water, and it was then let to dry overnight at 50 °C. The dried extract was crushed and then regenerated in an ethanol solution.

3.2.3.2 Fermentation

Lignocellulose serves as a plentiful biomass of sugars for bacterial fermentation. Traditionally, a sequence of ambient alkaline pretreatment, enzymatic hydrolysis, and bacterial fermentation has proven effective in yielding desired biopolymers [148]. The alkaline pretreatment typically involves the use of a dilute alkaline solution at ambient conditions. This procedure entails mixing powdered lignocellulose biomass samples with the dilute alkaline solution, followed by mechanical stirring at ambient temperature for various pretreatment durations [149]. The pretreated material is next separated using vacuum filtration and cleaned with distilled water until its pH is balanced. The final products are then kept in storage at 4 °C until they are needed for fermentation and enzymatic hydrolysis. Enzymatic hydrolysis experiments are conducted in a rotary shaker at 50 °C and 250 $r \cdot min^{-1}$ in a phosphate buffer [148]. Finally, fermentation is achieved by employing an appropriate microbial strain [150].

4 Applications of upcycled plastics and biomass

4.1 Construction and building materials

Several studies have successfully transformed upcycled plastic and biomass materials into construction and building materials. Saeli et al. [151], for instance, utilized used coffee grounds to develop eco-friendly architectural energy-saving products using green geopolymeric materials. This aligns with the goals outlined in the European Green Deal, which aims to achieve zero-energy buildings. Virtual energy modeling was employed to investigate the performance of building models under different climatic conditions and evaluate the potential real-world effectiveness of the proposed product in enhancing management and efficiency, following the guidelines outlined in the EU 2018/844 Directive concerning structural energy performance. The key outcome of this research indicates that the newly developed material serves as an ideal alternative to conventional construction materials. It offers significant cost savings in manufacturing, up to 37% for a 17.5% spent coffee grounds content, and an energy enhancement of approximately 19% per annum. Consequently, this translates to further savings in annual building management costs.

Erdogmus et al. [152] conducted pioneering research on utilizing expanded PS (EPS) and waste recycled rubber tire powder (WRTP) in bricks made of sintered clay, aiming to promote environmentally friendly and sustainable construction practices. The study focused on exploring the unique mechanical, physical, and microscopic characteristics of clay brick samples manufactured with EPS and WRTP. To achieve their objective, the researchers produced bricks made of sintered clay by substituting clay with varying proportions of EPS (0.5%–2% of the clay's weight) and WRTP (5%–15% of the clay's weight) during the sintering process at 1000 °C. The results revealed that increasing quantities of EPS and WRTP resulted in improved thermal performance and decreased weight of the bricks. Brick samples with 0.5% EPS combined with 5% WRTP satisfied the minimum compressive strength requirements, whereas samples with 0.5% EPS alone fulfilled weathering resistance norms.

A newly published article by Liu et al. [153], studied the eco-friendly repurposing of artificial lightweight cold-bonded aggregates (ALCBAs) created from biochar and concrete slurry waste (CSW) into porous carbon materials for carbon dioxide capture. In this study, the carbon sequestration of CSW-ALCBAs changes was assessed with time using a novel testing apparatus. The relationship between the carbon absorption capacity of CSW-ALCBAs and their physical and mechanical characteristics was thoroughly examined, along with an exploration of the processes of hydration and carbon sequestration. The sustainability of CSW-ALCBAs was thoroughly assessed by taking into account ecological indicators and production expenses. It was found that CSW-ALCBAs exhibited significant potential for carbon sequestration, with the highest carbon absorption recorded at 18.2 wt % with 15% biochar dosage and the lowest at 16.2 wt % with 5% biochar doping. Additionally, carbon absorption increased proportionally with higher biochar dosage. Moreover, under standard and sealed curing conditions, compressive strength reached its peak at 5% biochar dosage, registering approximately 2.76 MPa, before declining notably with increasing biochar dosage. At 15% biochar dosage, compressive strength decreased to 1.86 MPa.

Yoon and Lee [154] introduced a groundbreaking concept known as waste upcycling-powered zero-energy building (W-ZEB), with the primary objective of meeting carbon neutrality, as illustrated in Fig. 5. Using cutting-edge functional materials from waste-repurposing technologies and producing additional energy through waste-to-energy processes, this novel idea seeks to improve the energy efficiency of structures. It entails

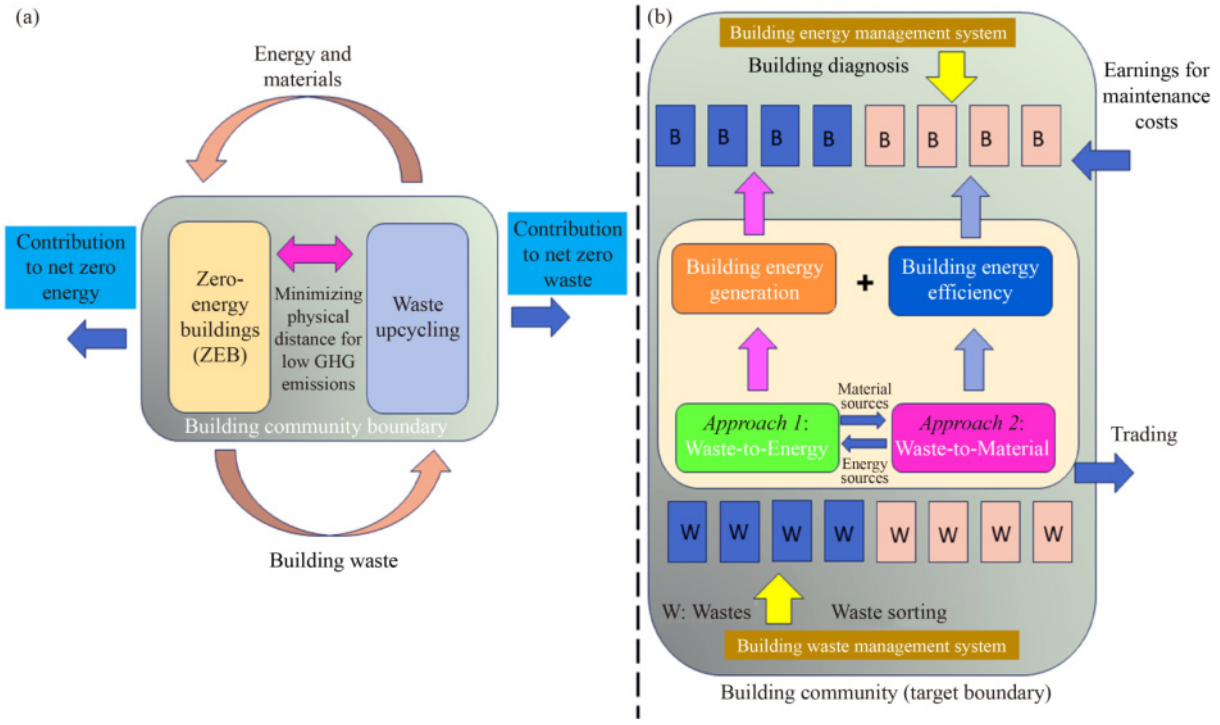

Fig. 5 (a) Proposed concept of W-ZEB, and (b) illustration depicting the concept, methods, and tactics of W-ZEB within the building community. Reprinted with permission from Ref. [154], copyright 2024, Elsevier.

integrating waste management techniques with net-zero methods in a cohesive and synergistic way. By combining these typically separate features, the concept seeks to enforce synergistic effects and expedite the realization of zero-energy structures that efficiently address MSW within the context of net-zero energy and waste management in the construction sector. This helps overcome the existing limitations of individual approaches such as waste-to-energy and waste upcycling.

Additionally, the proposed W-ZEB concept integrates grid-interactive building initiatives at the community level to enhance implementation viability and address current constraints within individual buildings. This strategy aims to reduce the geographical separation among waste generation, gathering, sorting, transportation, treatment, and utilization processes within the building community, resulting in a decrease in CO_2 emissions compared to traditional waste management techniques. Furthermore, profits from the sale of waste-upcycled materials support the W-ZEB concept's financial sustainability throughout the course of a building's lifetime. In the end, W-ZEB seeks to build interactive and cooperative ways to achieve carbon neutrality through the integration of waste upcycling and net-zero energy technologies, therefore making major strides toward environmental conservation and sustainable development goals.

4.2 Packaging and consumer goods

The combination of recycled plastic and biomass offers up a world of possibilities for packaging and consumer products manufacturing. These materials may be used to make a variety of items. In this regard, Tripathi et al. [155] explored converting the discarded jute biomass into advanced biocarbon materials via a valorization process. This study shows that the created environmentally-friendly biocarbon can undergo additional upcycling. Biocarbon subjected to high temperatures (~1000 °C) during pyrolysis could potentially serve as biographite, replacing fossil fuel-derived materials in specific semi-conductive applications. The findings from the examines confirmed the improvement in electrical conductivity. Therefore, adjusting the properties of burlap biocarbon is expected to result in significant enhancements in electrical conductivity, potentially substituting finite graphite, which requires increased electrical conductivity tailored for specific applications. The electrical conductivity of burlap biocarbon increased by 250% when pyrolyzed at a temperature of 1000 °C compared to commercial graphite. The biocarbon yield ranged from 71% to 22% when carbonized between 325 and 1000 °C. Under a temperature of 600 °C, the change in yield was minimal (within ± 1%). The yield remained constant at 22% at higher temperatures ranging from 800 to 1000 °C.

In George et al. [156] study, the efficacy of utilizing biocarbon sourced from coconut shells to enhance the electrical and mechanical characteristics of polymer composites, particularly polylactic acid/polybutylene adipate-co-terephthalate, for applications requiring antistatic attributes was demonstrated. Experimental findings

revealed that the loading of 10 wt % of biocarbon effectively imparted antistatic characteristics to the composite materials. This improvement was attributed to the high carbon content, characterized by sp^2 hybridized graphitic carbon, which enhanced conductivity. Moreover, the biocarbon served as a nucleating agent, encouraging polylactic acid crystallization and subsequently increasing the composite's tensile strength through strong interactions with the polymer matrix. With a surface resistivity of roughly 1011 $\Omega \cdot sq^{-1}$, the resultant composite—which contained 10 wt % biocarbon—is appropriate for use in protective gear and antistatic packaging.

In another relevant study, Umerah et al. [157] investigated biodegradable polymers made of polylactic acid and potato starch (BIOPLAS GF 106/02), which are mixed in a 75:25 ratio known as BPB (BIOPLAST GF 106/02/PLA 75/25 blend). Biocarbon from leftover coconut shells was also added to the mixture. The waste coconut shells biocarbon underwent synthesis under elevated temperature and pressure, followed by the production of composite filaments using solvent-based blending and extrusion techniques. The outcomes of their research showcased notable improvements in mechanical strength, including a noteworthy 50% rise in tensile strength when compared to the unprocessed BPB material. Thermal gravimetric analysis revealed enhanced decomposition characteristics and reduced weight loss, while the electrical conductivity exhibited an increment with greater filler content. These findings highlight the possibility of incorporating biocarbon derived from waste coconut shells as a viable strategy for enhancing the performance of biodegradable polymer composites in various applications.

Mohammed et al. [158] showed a study focusing on the production of high-grade semi-crystalline biocarbon obtained from waste from starch-based packaging. In their work, they suggested employing sulfur hexafluoride (SF6) gas for low-temperature plasma treatments to change the exterior properties of biochar carbon made from sustainable starch-based packaging waste in an environmentally friendly way at high pressure and temperature levels. Its application in reinforcing polymer composites was investigated. Ultrasonication, a technique employing high-frequency acoustic waves, was employed to disintegrate particles. This process induced high-pressure zones upon the biocarbon particles, causing collisions and fragmentation, consequently diminishing their size. The key findings were that the tensile strength experienced a significant enhancement of 91% compared to pure polymers and 31% compared to biochar-reinforced polymers without treatment, with a loading of 0.75 wt %. Breakage elongation surged from 12.7 to 38.78, indicating a remarkable 216% rise attributed to the efficient reinforcement through plasma functionalization. Additionally, the initiation temperature of decomposition and the maximum rate of decomposition increased by 60 and 49 °C, respectively, in comparison to pure polymers.

Filament extrusion was used by Alhelal et al. [159] to create epoxy composites that were created by 3D printing and contained biocarbon that was obtained from used coffee grounds. Using a mechanical stirrer, they combined the biocarbon with epoxy glue and a hardener. The resulting mixture was then extruded using a customized extrusion equipment to create filament. The research findings suggested that at a reduced concentration of 1 wt %, the addition of biocarbon improved the mechanical characteristics. However, a significant decrease in mechanical properties was seen at an increasing concentration of 3 wt % due to the development of agglomerates and inadequate polymer chains cross-linked.

4.3 Energy generation and fuels

The utilization of recycled plastic and biomass for energy generation and fuel production holds substantial promise in transitioning to an energy system that is more sustainable and resilient. By harnessing the energy potential of waste materials and renewable resources, we can minimize environmental pollution, mitigate climate change impacts, and lay the groundwork for a more sustainable future.

A critical literature review on the various applications of durian biochar was carried out by Chua et al. [160]. These applications included briquettes, bio-sorbents for removing organic pollutants from wastewater, biocomposite materials, fertilizers, electrode material for supercapacitors, and catalysts. Tan et al. [161] investigated the durian rind pyrolysis with the utilization of silica-alumina catalysts in a tubular reactor to improve the bio-oil yield and composition. It was found that the bio-oil generated at elevated catalytic temperatures comprises numerous aromatic compounds, suggesting the enhanced efficacy of silica-alumina catalyst in promoting aromatization and selectivity shaping. Concerning the investigation into catalyst loading during rapid catalytic pyrolysis of durian rind, a higher quantity of catalyst does not contribute positively to the facilitation of deoxygenation; rather, it leads to excessive cracking into gases. In another relevant study, Tan et al. [162] investigated the deoxygenation process of pyrolysis vapors derived from durian shells in the presence of industrial wastes serving as catalysts for bio-oil production. The primary objective of this research was to assess catalysts derived from industrial waste rich in iron, calcium, silicon, and aluminum to enhance the catalytic conversion of pyrolysis vapors obtained from durian shells. The study evaluated their impact on both product yield and characteristics through comparison. The findings revealed that electric arc furnace slag promoted the generation of liquid products while reducing the production of gaseous byproducts at higher catalytic temperatures. As the catalytic temperature rose, the bio-

oil's esters content rose as well. However, because there were more active sites available for cracking processes when the ratio of electric arc furnace slag to durian shell was low, the liquid yield dropped and the gas yield rose. Bio-oil produced at ratios of 1:30 and 3:30 of electric arc furnace slag to durian shell contained more nitrogen-containing compounds, indicating the suboptimal denitrogenation efficiency of the catalyst derived from electric arc furnace slag. Furthermore, the bio-oil's oxygen content dropped as the catalyst loading increased. Operational factors affected the electric arc furnace slag catalyst's product selectivity; the maximum hydrocarbon production was obtained at 500 °C with a catalyst-to-durian shell ratio of 2:30.

Yao et al. [163] explored the potential of microwave-assisted catalytic pyrolysis of PP waste for hydrogen production. The study aims to understand the mechanism behind microwave heating and its impact on the reaction process. Molecular dynamics (MD) simulations using the ReaxFF method were conducted to compare the bonded and non-bonded interactions under conventional and microwave heating conditions across various power levels. The results demonstrated that microwave heating enhances the adsorption capacity of Fe clusters, lowers the dissociation energy of C–H bonds, and enhances the cleavage of C–C bonds due to the presence of H radicals at lower temperatures. This leads to increased hydrogen generation, reduced reaction temperature requirements, and decreased formation of minor gaseous hydrocarbon molecules and tar. The findings support the use of ReaxFF MD as a reliable tool and provide a theoretical basis for utilizing microwave-assisted pyrolysis of waste plastics. The research emphasizes the significance of catalyst selection in microwave-assisted pyrolysis. It was shown that metallic Fe catalysts efficiently absorb microwave radiation and aid in the cracking of C–H complexes. The particle size and dispersion of Fe were identified as critical factors influencing wave absorption and catalytic performance. The study suggests that Fe-based catalysts with small grain size and high dispersion can achieve superior performance for microwave-assisted pyrolysis. This research contributes to the field of hydrogen production from plastic waste by demonstrating the benefits of microwave-assisted catalytic pyrolysis. The use of microwave heating not only enhances hydrogen generation but also allows for lower reaction temperatures, offering a cleaner and more energy-efficient technology for plastic waste valorization.

Wang et al. [164] discussed the application of a biochar catalyst derived from nanocellulose for the pyrolysis of waste plastics to produce hydrogen and liquid fuels. The study aimed to explore a simple and efficient method to transform waste plastics into valuable energy resources. The researchers conducted experiments using LDPE as a model plastic. They discovered that LDPE may completely degrade into liquid and gas at 500 °C with a biochar to LDPE ratio higher than three without producing wax. However, at 450 °C and a biochar to LDPE ratio of 4, a wax yield of 16% was observed, significantly lower than that with the absence of biochar condition (77% wax yield at 500 °C). With a yield of 36%, the gaseous product had up to 92% hydrogen. Higher ratios of biochar to LDPE and the application of biochar promoted the production of hydrogen at the expense of light gas, especially methane. The biochar catalyst derived from nanocellulose also proved effective in converting real waste plastics, into valuable liquid and hydrogen-enriched gas. These results point to the possibility of employing biochar made from nanocellulose as a catalyst for the effective synthesis of hydrogen and liquid fuels from waste plastics. The results of this study demonstrate that the catalytic pyrolysis of waste plastics using nanocellulose-derived biochar catalyst can lead to significant hydrogen production. The use of biochar and optimized process conditions resulted in high hydrogen yields, with up to 92% of the gaseous product being hydrogen. This research offers a promising strategy for addressing the environmental issues associated with plastic waste while simultaneously producing valuable energy resources.

In Arregi et al. [165] research, pine wood waste and HDPE mixes were subjected to continuous pyrolysis and in-line catalytic reforming to produce hydrogen-rich gas. The purpose of the study was to evaluate the impact of co-feeding HDPE on catalyst deactivation, conversion efficiency, and hydrogen generation. The investigations employed a two-stage reaction system consisting of a conical spouted bed reactor and a fluidized bed reactor. The outcomes demonstrated that co-feeding pine sawdust and HDPE greatly enhanced the generation of hydrogen. Hydrogen yield increased from 10.9% when using only pine sawdust to 37.3% when using only HDPE. Moreover, the presence of HDPE reduced catalyst deactivation caused by coke formation because of the reduced presence of oxygenated compounds in the reaction environment. The study demonstrated the potential of the two-step pyrolysis-reforming strategy for hydrogen production from renewable raw materials and waste. In comparison to gasification, the method has benefits, including reduced operating temperatures, effective biomass and plastic mixture valorization, and increased hydrogen yields. These findings aid in the creation of sustainable hydrogen generation pathways.

According to Wei et al. [166], converting plastic waste into valuable fuels and chemicals via chemical processes is vital for promoting sustainability, and catalysis is becoming increasingly instrumental in accomplishing this aim. The utilization of heterogeneous catalysts for transforming polyolefin plastic waste into fuels and beneficial chemicals represents a promising solution in catalytic transformations. Due to the strong C–C bonds within the polymer structure, it is essential to have a high-energy and high-temperature process [166]. Currently,

thermal or catalytic pyrolysis, cross-alkane metathesis, thermal pyrolysis with subsequent catalytic hydrotreatment, and direct hydroprocessing are methods for improving the chemical properties of polyolefins [167].

Liu and Duan [168] mentioned that methods such as photo-, electro-, and photoelectro- have demonstrated promise in repurposing plastic waste in environmentally conscious and energy-efficient ways. Nevertheless, these techniques are still emerging and commonly encounter challenges such as limited productivity, incomplete conversion of raw plastics, sensitivity to impurities, and the inability to simultaneously process various mixed plastics from real-world waste streams. The most recent research involving photocatalytic strategies is the conversion of PS into benzoyl products via the hydrogen atom transfer process. Zhang et al. [169] investigated the oxidation of alkyl aromatic compounds, which is targeted toward the oxidative breakdown of PS into aromatic acids. This process is catalyzed by cheap and abundant available $FeCl_3$ along with 2,2,2-trichloroethanol (CCl_3CH_2OH) under blue light irradiation at room temperature and atmospheric pressure of oxygen (1.103×10^5 Pa). This system could potentially streamline the targeted breakdown of PS into benzoic acid, offering a significant and pragmatic means to produce valuable chemicals from PS waste. In another study conducted by Wang et al. [170], the irradiation of $FeCl_3$ with blue LEDs, along with tetrabutylammonium chloride and CCl_3CH_2OH, was investigated. This process induced the formation of chlorine or alkoxy radicals. These radicals subsequently activated benzylic C–H bonds within PS, leading to its degradation into benzoic acid with a yield of 67%.

Meanwhile, Meng et al. [171] used uranyl-photocatalysis in a synergistic way at room temperature and pressure to accomplish the depolymerization of nine distinct kinds of plastics using a mild and flexible photodegradation technique. A process for turning five types of mixed plastics into a high-value product is included in this protocol. Nickel-phosphorus nanospheres, or nanoNi-P, were created electrochemically by Lin et al. [172], and their versatility in catalyzing hydrogen generation, water oxidation, and PET reforming was shown. This research sets the groundwork for the creation of an artificial leaf capable of both environmental remediation and the synthesis of renewable fuels and valuable chemicals through photosynthesis. The key finding from this work is that effective and precise production of hydrogen and formate from photoelectrochemical (PEC) PET reforming was achieved using a nanoTiO_2|nanoNi-$P_{op(CV)}$ ($C = 0.02$ C·cm^{-2})//CNT-nanoNi-P_{op} PEC device employing Earth-abundant materials.

4.4 Chemicals, polymers, and bioproducts

Currently, bio-based plastics are attracting considerable attention as substitutes for traditional petrochemical-derived products to promote sustainable societal development goals [173]. In this scenario, a new polymer called PE furandicarboxylate (PEF), which is entirely bio-based, can be manufactured using monoethylene glycol (MEG) and 2,5-furandicarboxylic acid (2,5-FDCA). Both MEG and FDCA can be sourced from widely available biomass materials such as lignocellulosic and agricultural sources. PEF serves as an environmentally friendly substitute for PET and demonstrates significantly decreased oxygen and water permeability, rendering it suitable for applications in electronic devices. Therefore, the adoption of renewable and bio-based PEF holds significant importance in reducing reliance on fossil fuel resources [174−178]. Huang et al. [173] documented the development of a substrate composed entirely of bio-based PEF for use in flexible organic photovoltaics. Polylysine, a biomaterial derived from natural sources, is uncommonly encountered in the realm of photovoltaics. Research has shown that the magnitude of ΔWF (change of work function) is closely linked to the presence of ionic functionalities, leading to diverse dipole formations and orientations at the interfaces. Given its positive charge as an α-amino acid, polylysine exhibits promising potential as an excellent interfacial layer material capable of tuning work function [179−182].

Huang et al. [183] developed a supramolecular *in situ* assembly technique to combine a bio-based epoxidized soybean oil vitrimer with recovered glass fiber textile that was obtained from wasted wind turbine blades to create sustainable materials. By advancing toward energy systems with zero net emissions, this upcycling method, which blends plastic waste with biomass, not only opens up new avenues for the production of sustainable materials but also advances global sustainability goals. It is reported that the produced materials exhibit outstanding mechanical properties, with a tensile strength of 152.9 MPa and toughness of 33.9 MJ·m^{-3}, providing effective stress-energy dissipation at multiple levels during service. Because of the dynamic nature of the disulfide bonds in the soft matrix, they also have good recyclability, making them attractive options for commercial plastics. Additionally, their favorable dielectric modulation greatly improves their capacity to trap charges, making triboelectric energy harvesting—which produces an 11.6-times increase in surface potential—efficient and long-lasting. Furthermore, life-cycle assessment suggests that triboelectric nanogenerator devices based on sustainable materials represent a significant advancement in reducing environmental impacts.

Diao et al. [184] examined a mixed approach to upcycling PET into lycopene, a versatile platform chemical, involves employing alkaline hydrolysis of PET alongside the microbial host *Rhodococcus jostii* strain PET. Using systematic metabolic engineering, they successfully enhanced the lycopene production by over

500 times compared to the natural strain. Furthermore, they produced 1300 $\mu g \cdot L^{-1}$ lycopene from PET by combining this strain with PET alkaline hydrolysis.

Zhang et al. [185] transformed discarded PET into a valuable and efficient material using an eco-friendly and energy-efficient technique, presenting a feasible approach for plastic waste recycling. Bis(2-hydroxyethyl) terephthalamide (BHETA) was derived from waste PET through aminolysis under gentle conditions following pre-swelling with acetic acid, featuring multiple polar groups and cross-linking with diphenylmethane diisocyanate to create a BHETA-centered adhesive. It is found that the BHETA-based adhesive possesses notable urethane linkages, endowing it with commendable water resistance and adhesive strength (0.6 MPa), maintaining stable adhesion in water, organic solvents, and diverse climatic circumstances. Additionally, through the refinement of the curing procedure, the adhesive's bonding strength can be elevated to 1.34 MPa.

Another way to solve the recycling of plastic food packaging is the introduction of self-cleaning plastic films. Wong et al. [186] noted that Aizenberg's group had developed a promising method, namely the slippery liquid-infused porous surface (SLIPS) technique, for self-cleaning plastics production. This method inhibits the adherence of liquids to a surface by employing a porous coating saturated with a hydrophobic liquid, like oil. The oil infused within the porous coating remains trapped and effectively deflects contaminants away from the surface. Wong et al. [186] initially investigated the use of an inorganic porous coating combined with perfluorinated oil, which led to numerous similar studies exploring the application of the SLIPS technique in packaging materials to achieve self-cleaning capabilities.

Recently, various strategies for upcycling PET have emerged, aiming to generate products of increased value. Particularly noteworthy is the conversion of PET-derived hydrolysates into high-value chemicals. Specifically, the depolymerized PET monomers (terephthalic acid and ethylene glycol) can undergo conversion into various chemicals [91,187,188].

Wang et al. [189] utilized the harmful algal blooms as a carbon source to fabricate electrocatalysts for nitrate reduction reactions (NO_3RR) aimed at efficient ammonia production across varying nitrate concentrations. To address the challenges of low current density and sluggish kinetics in NO_3RR, a tactic involving augmenting catalytic site density was implemented. Utilizing nitrogen inherent in algal biomass facilitated the achievement of iron single-atom confinement. In this research, a carbon-based catalyst containing dispersed iron, derived from biomass sourced from harmful algal blooms, is introduced. It exhibits a peak rate of ammonia production of 16449 $\mu g \cdot h^{-1} \cdot cm^{-2}$ (equivalent to 1.2 $mmol \cdot h^{-1} \cdot mg_{cat}^{-1}$) and an ammonia Faradaic efficiency of 87.3%. Furthermore, this catalyst demonstrates satisfactory stability, maintaining consistent performance throughout continuous operation for 50 h.

5 Environmental and economic benefits of upcycling

5.1 Reduction of plastic pollution and landfill waste

The escalating concern regarding plastic pollution and landfill waste has prompted a surge in research efforts from 2018 to 2023, as evidenced by data from Scopus, as shown in Fig. 6. Waste plastic is recognized as one of the major contributors to plastic pollution primarily due to its extensive global production, estimated at 380 million tonnes, constituting approximately 7% of fossil fuel consumption owing to its widespread use in everyday products [190]. According to Seah et al. [191], around 55% of global waste plastic, roughly 255 million tonnes per year, is either landfilled or discarded in the natural environment, with 8 million tonnes ending up in the ocean annually, of which Asian countries contributed approximately 60%. Characteristics such as lightweight, cost-effectiveness, processability, and high-performance nature have driven their extensive utilization, particularly in packaging [192]. However, despite attempts to manage waste plastic through policies and practices, only a mere 9% is currently recycled, leading to the majority ending up in landfills, being incinerated or improperly disposed of [193]. The challenges in recycling waste plastic are multifaceted, including issues with mixed compositions and contaminants in post-consumer waste, slow decomposition, high recycling expenses, as well as the production of lower-quality products after the recycling process [194,195].

Moreover, Hassan et al. [26] highlighted the agricultural sector and MSW as significant contributors to yearly biomass waste, accounting for approximately 140 billion metric tonnes and 2.01 billion tonnes, respectively. Despite the vast availability of biomass

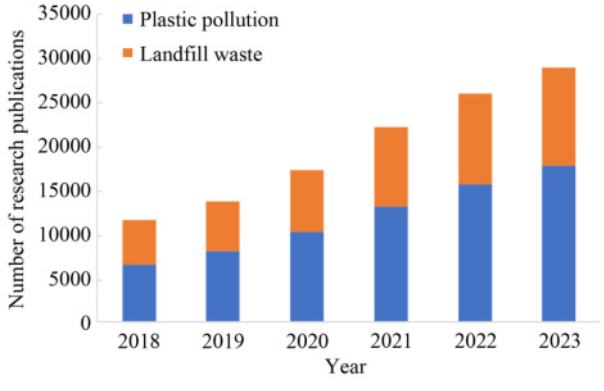

Fig. 6 Number of research publications on plastic pollution and landfill waste from 2018 to 2023 as retrieved from the Scopus database.

waste, concerns regarding its proper management persist. Studies by Seah et al. [191] indicated that a mere 19% of collected MSW is recycled, with only 11% for energy recovery, while a staggering 70% is directed to landfills, contributing to the escalating landfill waste issue.

Therefore, the concept of upcycling has emerged as a crucial strategy for addressing these environmental concerns. Upcycling, distinguished from conventional recycling by its emphasis on creatively reusing, repairing, and enhancing materials at the end of their life cycle or destined for disposal, has attracted considerable attention among researchers [194]. Notably, upcycling offers a more promising solution compared to conventional recycling, with its potential to either reduce solid waste generation or delay waste accumulation in landfills, thereby conserving valuable landfill space [196]. Landfilling, being unsightly, has detrimental effects on ecosystems, aquatic life, and public health due to the generation of waste that easily infiltrates agricultural land and the food chain [26,197]. The disposal of biomass and waste plastic often leads to substantial organic waste in landfills, causing groundwater pollution as well as pathogen spread [198,199]. Upcycling plays a crucial role in preventing the materials from becoming waste initially by transforming them into usable and valuable resources, reducing landfill waste volume, easing the burden on these facilities, and mitigating environment impacts.

Moreover, Balu et al. [200] underscored upcycling as a technically sound method for efficient waste management, transforming waste into entirely new items of increased value or functionality compared to their original form. Innovative chemical upcycling methods, such as catalytic processes and depolymerization, efficiently convert waste plastic into valuable liquid products and monomers for creating new polymers, highlighting upcycling as an effective waste management approach [190,192]. Adelodun et al. [198] highlighted waste plastic and biomass upcycling through pyrolysis as a sustainable alternative to incineration and landfilling, significantly reducing environmental pollution. Apart from that, upcycling aids in eliminating the concept of waste from the environment and reducing toxic waste leakage [196]. Through the upcycling of waste plastic instead of disposal, the release of harmful chemicals such as phthalates and bisphenol A from waste plastic can be prevented, preserving soil quality and mitigating potential long-term adverse health effects on organisms [200]. Although some of the waste material is recyclable, the potential for their disposal in landfills, especially if they are non-biodegradable, underscores the importance of upcycling.

5.2 Conservation of natural resources and energy savings

Plastics, renowned for their diverse applications across consumer and industrial domains, entail significant fossil fuel consumption, with global production exceeding a staggering 390 million tonnes in 2022, predominantly derived from fossil fuels [201]. This substantial output raises alarming concerns about resource depletion, especially considering the imminent depletion of fossil fuel sources like gas, diesel, and petrol [202]. Conventional incineration is widely utilized in developing countries for energy recovery from waste plastic and biomass but presents significant drawbacks, such as increased toxic pollutant emissions, greenhouse gas emissions, and higher energy consumption [192,203].

Amidst these challenges, upcycling emerges as a crucial solution for conserving natural resources and achieving energy savings. The accelerated rate of plastic production far outpaces recycling efforts, resulting in a substantial release of waste plastic into the environment [202]. Research studies highlight the efficacy of upcycling in reducing the need for raw materials, thereby decreasing the demand for virgin materials and conserving natural resources on this earth. Recent advancements, particularly in pyrolysis and gasification technologies, showcase the potential to convert waste plastic into high-value products such as syngas, bio-oil, and biochar [204]. Notably, pyrolysis operates at lower temperatures (450–700 °C) and in the absence of oxygen, offering a more environmentally friendly alternative to incineration methods that utilize excess oxygen at higher temperatures (> 1000 °C) [205]. Moreover, research has extended into the advancement of pyrolysis technology to produce clean hydrogen gas and carbon nanomaterials [192]. The resulting pyrolysis oil serves as a substitute for virgin oil in various applications, contributing to the further conservation of natural resources [202]. Moreover, studies from Yang et al. [206] demonstrate the efficiency of pyrolysis in generating fuel from waste plastic, leading to increased brake thermal efficiency by 4.7% and decreased fuel consumption by 7.8% compared to diesel.

Furthermore, Hassan et al. [26] conducted a life cycle assessment for 3D printing with recycled plastics, revealing a significant reduction with an 80% decrease in energy consumption, greenhouse gas emissions, and water usage and a 90% reduction in waste compared to using virgin plastics. These findings demonstrated that the upcycling approach via 3D printing offers environmental sustainability toward conserving resources and waste reduction, aligning with the principles of a circular economy. Also, research by Oladapo et al. [207] highlighted that employing recycled plastic as feedstock holds the potential to achieve net-zero emission and contributes to climate change mitigation while simultaneously reducing material waste and enabling decentralized production.

5.3 Carbon footprint reduction and climate change mitigation

Upcycling plays a key role in reducing carbon footprint

and mitigating climate change. The carbon footprint concept includes the total greenhouse gas emissions from various direct and indirect activities, measured in carbon dioxide equivalent (CO_2e) [208]. Climate change has emerged as a pressing global threat, attributed to the rising concentration of atmosphere carbon dioxide, evidenced by its pervasive influence across all regions, with increasing ocean temperatures, rising sea levels, acidification of oceans, and a surge in extreme weather events [209−212].

The inadequate recycling of plastic and biomass results in their large accumulation in landfills or incinerators, significantly impacting the environment. Recent research has identified MSW incineration as a major contributor to greenhouse gas emissions, contributing to global warming and climate change [213]. Biomass, the second contributor to greenhouse gas emissions after the energy sector, primarily from agricultural waste, accounts for 19.9% of emissions and only 40% of which is repurposed for fuel, feed, or power generation, with the remaining often incinerated, posing severe environmental threats and contributing substantially to climate change [191,214]. Waste plastic, estimated at 0.86 gigatonnes of CO_2e ($GtCO_2e$) in 2019, is projected to surge to 2.80 $GtCO_2e$ by 2050, adding further strain to the environment, especially with approximately 140 million tonnes of CO_2e released annually from incinerating non-recycled waste plastic [193,215]. A comprehensive estimation of greenhouse gas emissions throughout the plastic lifecycle is depicted in Fig. 7, utilizing data derived from [193].

Therefore, upcycling has emerged as a crucial strategy to address these environmental challenges. Mechanical upcycling of post-industrial waste demonstrates the promising potential to reduce the product's carbon footprint by 29.3% [216]. However, it is essential to acknowledge that while mechanical upcycling reduces carbon footprint, achieving a fully sustainable loop proves challenging due to limitations in re-use, as highlighted in recent studies [217]. In contrast, chemical upcycling, encompassing technologies such as pyrolysis and gasification, offers a more sustainable path toward fostering a circular economy. These technologies efficiently convert waste into fuel, providing solutions to incineration and landfilling, potentially reducing carbon dioxide and greenhouse gas emissions [217]. Moreover, recent research explores upcycling waste plastic into advanced material aimed at capturing carbon. Waste plastic materials such as PET bottles and disposable surgical masks are transformed into activated carbon for carbon capture, showing promise in mitigating climate change [209,218]. Most importantly, these approaches hold substantial potential in aligning with multiple United Nations Sustainable Development Goals (SDGs), particularly with SDG 13 (climate change), SDG 14 (life below water), and SDG 15 (life on land). Also, analyses revealing the viability of upcycling waste plastic into carbon black and pyrolysis gas, demonstrate its immense potential, exhibiting a negative 449 kg CO_2e per tonne waste plastic, thereby reducing the carbon footprint significantly [103].

Anaerobic digestion stands out as a significant advancement in biomass upcycling, praised for its low-carbon attributes and seamless integration with waste management and renewable energy practices [219]. This versatile technique yields two key byproducts, biogas and biofertilizer, significantly contributing to the reduction of carbon emissions when compared to landfilling and incineration [219]. Recent investigations underscore the effectiveness of anaerobic digestion not only as a waste treatment solution but also as a means to diminish waste volume, minimize odors, and establish diverse revenue streams [220].

5.4 Economic opportunities and circular economy advancement

The practice of upcycling, which involves the transformation of discarded materials into higher-value products, serves as a critical driver not only in addressing environmental challenges but also in offering substantial economic opportunities and the advancement of the circular economy. The adoption of a circular economy model at the corporate, regional, and national levels is on the rise, underscoring the potential of waste plastic as a valuable resource that can be reintegrated into new

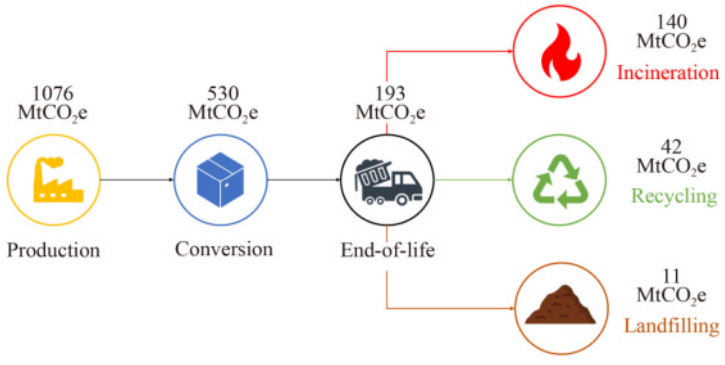

Fig. 7 Estimation of greenhouse gas emissions across the plastic lifecycle.

material cycles [221]. Beyond its environmental advantages, upcycling introduces novel economic prospects by redefining waste as a valuable resource. Companies embracing upcycling strategies position themselves to create new revenue streams through the innovative transformation of discarded materials into high-value products. This approach not only diversifies their products but also allows access to niche markets, expanding consumer bases and reinforcing brand loyalty. For instance, noteworthy collaborations, such as the partnership between Adidas and Parley, underscore the success and market potential of upcycled goods. Their collaboration resulted in the creation of sought-after running shoes crafted from recycled ocean plastic, captivating consumers keen on sustainable products [222]. This signifies an increasing demand for eco-conscious goods and exemplifies the potential of upcycling strategies to drive economic prosperity while addressing environmental concerns. Similarly, initiatives like the Coca-Cola Company, producing sample plastic bottles utilizing recycled ocean plastic collected from the beaches and the Mediterranean Sea, mark significant strides toward a circular economy, reducing reliance on new materials and embracing recycled resources [223].

The economic advantages of upcycling extend far beyond cost-saving measures. Embracing a circular economy through upcycling introduces a shift from a traditional linear 'take-make-dispose' model to a circular model that fosters resource optimization [26], as shown in Fig. 8. By creatively repurposing waste materials into higher-value products, companies reduce their reliance on virgin resources, resulting in a substantial cost reduction associated with raw material procurement.

Furthermore, a recent research article has explored the potential of 3D printing by recycling various plastics to promote a circular economy [224], as depicted in Fig. 9. The 3D printing industry is projected to grow with a market size of 40.8 billion USD by 2024 [207]. As 3D printing technology advances, the escalating volume of waste plastic from 3D printing filaments poses significant environmental challenges; however, upcycling offers a holistic approach by promoting the reuse and recycling of this plastic throughout its entire lifecycle, thereby creating a closed-loop system. This technology not only reduces the need for virgin materials but also optimizes design and production processes while promoting local and decentralized production methods [26].

6 Challenges and future perspectives

Despite the significant progress achieved in plastics and biomass upcycling, the future development of this technology will continue to present both challenges and promises. This section delineates four challenges and four prospects for this technology, as depicted in Fig. 10.

6.1 Technical limitations and scalability

The primary reason for technical limitations lies in the inadequacy of collection, sorting infrastructure, and

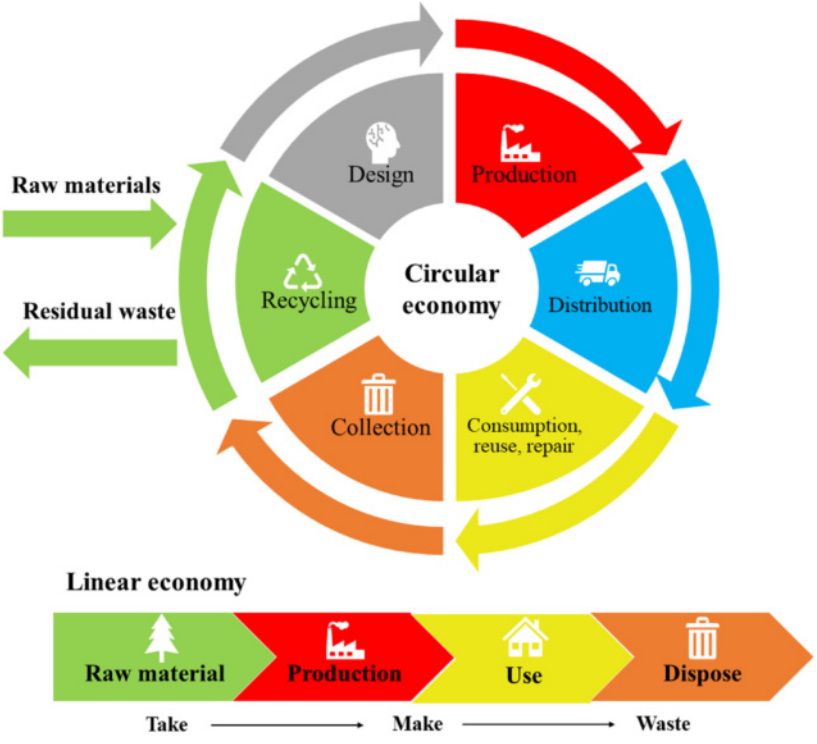

Fig. 8 Transformation of linear into circular economy.

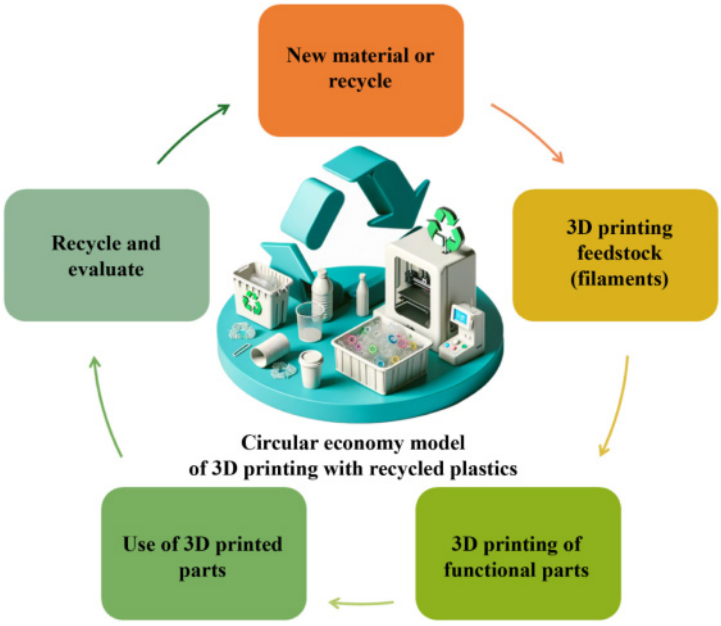

Fig. 9 Implementation of circular economy in 3D printing with recycled plastics.

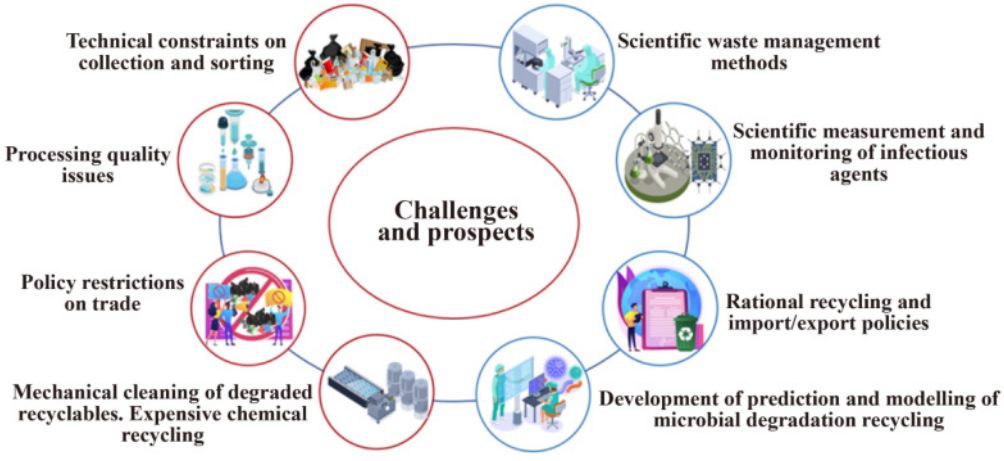

Fig. 10 Challenges and prospects for upcycling waste plastics and biomass.

scientific waste management methods [225]. Only 14% of plastic packaging is recycled, and only 2% of plastic completes the closed-loop collection-reprocessing process [226]. The waste separation process needs to be improved; recycling of waste plastics is still not widely implemented, plastic wastes are mixed and discarded in landfills, and separating a single substance for recycling is already a difficult challenge [227]. McKinsey & Company estimates that achieving 50% plastic recycling by 2030 will require an annual investment of 15 billion to 20 billion USD, a huge gap between what is needed and what is currently being invested [228]. The secondary reason is that the existing waste plastic upgrade technology is still insufficient.

Microbial-based plastic waste upcycling technologies are actively researched, but the range of plastics limits their applicability that they can effectively process. Common PVC materials, in particular, have not been extensively studied in terms of bioupcycling [229]. The non-biodegradable characteristics of PVC materials, the characteristics of low thermal stability, and the composition of high chlorine content have seriously hindered the biological upgrading and utilization of PVC [104]. Similarly, the process of chemical upcycling is difficult in industry. Factories need to accurately classify plastic waste according to material in advance, remove various impurities, and achieve efficient purification to avoid negative impact on reaction characteristics. Contamination of food, additives, colors, and other substances can complicate sorting, purification, and make the upcycling life cycle prohibitively expensive [230].

6.2 Quality control and standardization

Attention must be given to the processing steps involved

in upcycling, the materials used in the process, testing procedures for quality assurance, as well as addressing any quality issues that may arise and implementing solutions to mitigate them [231]. The recycling of plastic waste typically entails three stages: plastic waste collection, classification into pre-concentrates of specific materials, and subsequent processing of these pre-concentrates in processing plants. The quality of the specific material concentrates significantly impacts the overall efficiency of upgrading waste plastic recycling [232]. The quality of pre-concentration is determined by its purity, which refers to the proportion of the target material's mass in the pre-concentration. Low-quality pre-concentration inputs can result in material loss in processing plants and lead to poor quality of recycled materials, thereby hindering the upgrading and recycling of plastics and limiting environmental benefits [233]. Currently, the quality control method based on sensor pixel and particle level (SBQC) can automatically and in real-time measure the quality (purity) of the pre-concentrate, significantly improving the efficiency of waste plastic recycling and upgrading [234]. However, the composition of waste plastic pre-concentrate is defined by the mass (purity) composition of the input material flow, which aggregates thousands of particles based on their mass (purity) using sensor data. There is still limited research in this area, and further investigation is needed to develop suitable data aggregation methods and different counting bases [235]. Reducing the cost of sensors used in SBQC is a viable solution. Proper waste plastic disposal through the SBQC method requires monitoring support from a significant number of sensors. However, many existing sensor technologies are expensive, necessitating the industry to seek lower-cost alternatives for measuring the volume flow of material.

At the same time, exploring the latest object detection algorithms [236], developing more suitable data sets [237], developing sensor combinations for multiple sorting tasks within a single system, and developing more advanced sensors [238] are all directions for future research and development efforts [239].

6.3 Policy and regulatory considerations

The government needs to guide the upgrading and improvement of recycling technologies through policies. Existing policy commitments are insufficient to address the spread of plastic waste in the environment [240]. The government should offer consumers more convenient and efficient recycling options. For instance, in Shanghai, China, communities have implemented door-to-door garbage collection services, resulting in a 12.5% increase in the local residents' recycling rate and enhancing the efficiency of plastic waste recycling and degradation [241]. However, in many countries such as Cambodia, Algeria, and Morocco, over 95% of garbage is disposed of without further treatment, leading to extremely low recycling rates. The implementation of garbage classification incurs significant additional costs [242]. Therefore, adopting a reasonable and appropriate recycling policy is essential to facilitate smoother waste upgrading and recycling processes.

Governments worldwide should enhance regulatory efforts for the upgrading and recycling of waste plastics. Plastic waste is unevenly traded and recycled globally, with varying perceptions of its value across different social and technological contexts [243]. Before implementing policies banning the import of low-quality waste plastics, China imported a significant quantity of plastic, yet the recycling rate was only 25% [244]. Consequently, China disposed of the majority of plastic waste into the environment, leading to severe environmental issues [245].

Following China's cessation of low-quality waste plastic imports, Vietnam and Malaysia experienced a surge in waste plastic imports by more than 100%, prompting them to reestablish legal and policy frameworks related to waste plastic imports [246]. When most vulnerable countries prohibit low-quality waste plastics from entering their territories for landfill treatment, the circular economy becomes more equitable [247]. Unsustainable waste management practices involving the export of plastic waste will no longer be tolerated, thereby incentivizing developed countries to invest in iterative upgrades to recycling technologies.

6.4 Innovative research and development needs

Traditional recycling methods struggle to keep pace with the increasing quantity and variety of plastic waste. Mechanical recycling, a traditional method, requires classification and cleaning processes before recycling, often resulting in degraded materials. Moreover, the degradation properties of plastic materials limit the number of recycling cycles, a challenge that chemical recycling has begun to address [248]. However, chemical recycling methods tend to be expensive and involve the extensive use of chemicals, leading to the emission of harmful gases and the generation of toxic residues, which may not be the ideal treatment method [249]. Therefore, there is growing anticipation for biological upgrading and reconstruction technology to play a more intelligent, innovative, and sustainable role in the plastic industry [250]. To develop microbial cells capable of degrading and adding value to various types of plastic waste, it is essential to create predictive and simulation tools based on computational biology. These tools would enable the prediction of microbial metabolism and the construction of new plastic degradation pathways [251]. Consequently, continuous efforts are needed to identify new strains exhibiting high performance in degrading plastics in landfills or marine environments, thereby enhancing the

diversity of microbial metabolism pathway data and improving the accuracy of simulation tools in the future.

Indeed, the complexity and diversity of plastic waste pose significant challenges. The success of future upgrade and recycling strategies will hinge on the integration of various technologies and processes [252]. Interdisciplinary integration and the development of innovative upgrading and recycling methods will be essential avenues for exploration. By combining expertise from multiple fields and leveraging diverse approaches, we can enhance our ability to effectively manage and recycle plastic waste sustainably.

7 Conclusions

In conclusion, this comprehensive review has shed light on the synergistic technologies for a circular economy, specifically focusing on the upcycling of waste plastics and biomass. The review began by highlighting the types, sources, composition, and properties of waste plastics and biomass, emphasizing their environmental impact. It discussed the alarming rates of plastic waste generation, improper disposal practices, and the detrimental effects on ecosystems and natural resources. Similarly, the untapped potential of biomass as a renewable energy and chemical source was underscored, emphasizing the need for its efficient utilization. Various upcycling methods were explored, including mechanical, chemical, biological, and thermal approaches for both waste plastics and biomass. Each method offered unique advantages and challenges, showcasing the diverse possibilities for transforming these materials into value-added products. The applications of upcycled plastics and biomass were examined across sectors such as construction, packaging, energy generation, and chemicals, highlighting their versatility and potential for widespread implementation.

Furthermore, the review emphasized the environmental and economic benefits of upcycling. It outlined the reduction of plastic pollution, preservation of natural resources, carbon footprint reduction, and the advancement of circular economy principles as key advantages. The potential for economic opportunities and the promotion of sustainable practices through a circular economy framework were also highlighted. The review also addressed the challenges and future perspectives in the field, including technical limitations, quality control, policy considerations, and the importance of innovative research and development. These factors play crucial roles in achieving scalability, standardization, and regulatory frameworks that support the widespread adoption of upcycling technologies. Overall, this comprehensive analysis underscores the significance of upcycling in achieving a sustainable future. By transforming waste plastics and biomass into valuable resources, we can reduce environmental pollution, conserve natural resources, mitigate climate change, and foster economic growth. The recommendations provided in this review serve as a foundation for further advancements in technology and policy frameworks, facilitating the transition toward a circular economy and a more sustainable world.

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