



A REVIEW ON CONVERSION OF MICROPLASTICS INTO VALUE-ADDED PRODUCTS: CHALLENGES AND PERSPECTIVES

(Ulasan Tentang Penukaran Mikroplastik Kepada Produk Nilai Tambah: Cabaran dan Perspektif)

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Abstract

Microplastics have emerged as a pressing environmental concern, exerting profound impacts on ecosystems, water bodies, terrestrial landscapes, and human food sources. In light of the global plastic waste crisis, innovative strategies are being explored to manage and recycle plastic waste, with an emphasis on microplastics. Research endeavours aimed at transforming waste microplastics into valuable resources align seamlessly with circular economy principles. Microplastics can be collected using surface water sampling, air sampling, sediment sampling, soil sampling, shoreline sampling, as well as wastewater and effluent sampling. Microplastics can be chemically and physically characterised for composition selection and then converted using biological, chemical, and mechanical approaches. Biological conversion involves microbial activity and enzyme utilisation, chemical conversion involves chemically breaking down polymers into smaller molecules that can be used as feedstock for valuable materials, while mechanical conversion applies physical force to reduce polymer size. Both conventional and biodegradable plastics can undergo biological, chemical, and mechanical recycling to an extent to maintain their value and prevent the waste of non-renewable resources. However, there are challenges to overcome in the conversion of microplastics, including cost-effectiveness, scalability, environmental friendliness, and regulatory considerations. Appropriate macroplastic management and life cycle assessment analyses are still crucial for transitioning to a sustainable and circular economy.

Keywords: microplastics, conversion techniques, value-added products

Abstrak

Mikroplastik telah muncul sebagai kebimbangan alam sekitar yang mendesak, memberikan impak yang mendalam terhadap ekosistem, badan air, landskap terestrial, dan sumber makanan manusia. Dalam konteks krisis sisa plastik global, strategi inovatif sedang dikaji untuk mengurus dan mengitar semula sisa plastik, dengan penekanan pada mikroplastik. Usaha penyelidikan yang bertujuan untuk mengubah mikroplastik sisa menjadi sumber daya bernilai selari dengan prinsip ekonomi bulat. Mikroplastik boleh dikumpulkan melalui pengambilan sampel air permukaan, pengambilan sampel udara, pengambilan sampel sedimen, pengambilan sampel tanah, pengambilan sampel garis pantai, serta pengambilan sampel air sisa dan air buangan. Mikroplastik

boleh dicirikan secara kimia dan fizikal untuk pemilihan komposisi, dan kemudian diubah menggunakan pendekatan biologi, kimia, dan mekanikal. Penukaran biologi melibatkan aktiviti mikrob dan penggunaan enzim, penukaran kimia melibatkan pemecahan kimia polimer menjadi molekul yang lebih kecil yang boleh digunakan sebagai bahan mentah untuk bahan bernilai, manakala penukaran mekanikal menggunakan daya fizikal untuk mengurangkan saiz polimer. Plastik konvensional dan plastik terbiodegradasi boleh mengalami kitar semula biologi, kimia, dan mekanikal untuk mengekalkan nilai mereka dan mengelakkan pembaziran sumber tidak boleh diperbaharui. Walau bagaimanapun, terdapat cabaran yang perlu diatasi dalam penukaran mikroplastik, termasuk kos-efektif, skalabiliti, kemesraan alam sekitar, dan pertimbangan peraturan. Pengurusan makroplastik yang sesuai dan analisis penilaian kitar hidup masih penting untuk bergerak ke arah ekonomi lestari dan bulat.

Kata kunci: mikroplastik, teknik penukaran, produk bernilai tambah

Introduction

Microplastics have ubiquitously permeated the ecosystems of the planet, penetrating the atmosphere, water bodies, terrestrial regions, and even human food sources, signifying a critical predicament of global contamination [1-4]. Microplastics, small plastic particles less than 5 millimetres in size, are at the forefront of significant environmental concerns and thus have been intensively studied to understand their abundance, distribution, and sources [5-7]. The various sources of microplastics include fragmentation of larger plastic items, personal care products, textiles, industrial processes, and plastic resins used in manufacturing [8, 9]. In addition, the potential impacts of microplastics on aquatic organisms include feeding, growth, reproduction, as well as bioaccumulation of environmental pollutants from microplastic-pollutant complexes due to the vector ability of microplastics [10-13].

The persistence of microplastics in the environment and their potential to cause adverse ecological and health effects have escalated the search for sustainable solutions to address their accumulation. Research into the waste utilization of microplastics for value-added products is a new cutting-edge field being presently considered and expected to further intensify, staying abreast with the presence of multiple driving forces from international, national, environmental, economic, and social aspects [14]. The global plastic waste crisis has reached an annual microplastic waste generation of 3 million tonnes [15], leading to increased international and national interests, such as UNEP, in finding innovative ways to manage and recycle plastic waste, including microplastics [16]. Resource scarcity and the circular economy are also at the leading edge of the environmental drives propelling research in utilising waste plastics [17]. While the extraction of virgin materials and fossil fuels for manufacturing is

resource-intensive and can contribute to environmental degradation, research into converting waste microplastics into value-added products can help to reduce resource consumption and thus align with the principles of the circular economy [18]. From an economic viewpoint, industrial opportunities arise from transforming microplastics into valuable materials, generating revenue from value-added products, reducing costs associated with waste disposal, and developing new markets for recycled materials [19, 20]. Consumer and industry demand for environmentally friendly and sustainable products is growing due to the plastic-free movement and public awareness of plastic pollution and environmental issues [21]. Additionally, the conversion of microplastics can occur through biological, chemical, and mechanical conversion techniques but research is lacking compared to macroplastics and conventional plastics [22].

Therefore, in the pressing quest to address global plastic pollution, the efficacy of converting conventional microplastics into value-added products presents a pivotal state-of-the-art juncture in sustainable resource management and environmental mitigation. This article reviews the collection, physical and chemical characterisation, biological, chemical, and mechanical conversion methods, potential value-added product applications, and environmental considerations associated with conventional microplastics.

Collection and characterisation of conventional microplastics

Supply chain management is essential for successful waste material manufacturing by coordinating the flow of materials from waste collection to final product manufacturing [23]. In other words, microplastic collection methods are vital for adequate material

supply in manufacturing and vary depending on the environment where microplastics are collected. In microplastic research, microplastics are commonly collected using manta trawl, grab sampling, and bulk water filtration targeting marine and freshwater [24, 25]. In general, major collection methods include surface water sampling, air sampling, sediment sampling, soil sampling, beach and shoreline sampling, wastewater and effluent sampling, and biota sampling (Table 1) [26-29]. Surface water sampling involves collecting water samples from rivers, lakes, and oceans, and filtering them to separate microplastics [27, 29]. Sediment sampling isolates microplastics

from water bodies, while air sampling collects airborne particles [26, 30]. Biota sampling for microplastics has been used to examine organisms like fish and shellfish to determine ingestion occurrence or their ingestion rates on microplastics [29, 31]. Soil sampling extracts microplastics from sources like plastic mulch in agriculture or atmospheric deposition [28], while wastewater and effluent sampling at wastewater treatment plants provides insights into microplastic presence and fate in waste streams [32]. Additionally, beach and shoreline samplings involve manually picking up debris or using specialised devices to collect microplastics [33].

Table 1. The method types, advantages, and limitations of common collection approaches for microplastics

Methods	Advantages	Limitations	References
Surface water sampling	- Provides information on plastic distribution. - Comparatively simple and widely used.	- Restricted to surface-bound microplastics. - May underestimate the subsurface microplastic amount.	[24] [25] [29]
Air sampling	- Helps assess the microplastic amount in the atmosphere. - Non-invasive and can cover large areas.	- Difficult to distinguish microplastics from other particles. - Limited information on microplastic sources.	[26]
Sediment sampling	- Gives information on the accumulated history of plastic. - Allows study of buried microplastics.	- Time- and effort-consuming. - Sediment and benthos disturbance during sampling.	[30]
Soil sampling	- Gives information on plastic contamination of terrestrial ecosystems. - Can evaluate the uptake potential of plants.	- Microplastics might be mixed with natural particles. - Separating microplastics from organic matter is challenging. - Limited standardized protocols.	[28]
Beach and shoreline sampling	- Direct observation of shoreline plastic pollution. - Aids in understanding the ocean-to-land plastic transfer.	- Only a small portion of all marine microplastics are captured. - Limited to accessible shorelines. Microplastics may not be as noticeable if macroplastics are present.	[33]
Wastewater and effluent sampling	- Perspectives on plastic input from different sources. - Allows targeting of pollution sources.	- Variation in microplastic loads and types in different effluents. - Small particle detection in complicated matrices is difficult. - Limited data on microplastic fate after release.	[32]
Biota sampling	- Identifies potential harm that microplastics could cause to ecosystems. - Links plastic pollution to higher trophic levels.	- Invasive on living organisms. - Requires specialized techniques for extraction and analysis. - Limited species-specific data. Distinguishing environmental particles from ingested microplastics is challenging.	[31] [29]

Among the microplastic collection methods listed, air sampling and surface water sampling can be considered

relatively clean and hygienic with less time and effort consumption, since air and water samplings mainly

involve collecting particles that are airborne, in marine, or freshwater environments, reducing the risk of direct contact with potentially contaminated materials. However, the process faces numerous challenges, such as microplastics from wastewater and effluent for conversion into food packaging or clinical applications may require additional treatment for consumer safety, the polymers making up microplastics contain chemical additives such as plasticizers, flame retardants, and antimicrobial agents. These additives need to be discarded prior to the conversion process. The wide range and intricate nature of microplastics in terms of their types, shapes, sizes, colours, compositions, and additives pose challenges in their separation, classification, and characterization. In real environment, the low quality and purity of microplastic

waste, potentially harboring contaminants like organic matter, metals, pathogens, and other pollutants, pose risks to the functionality and safety of the resultant products. Biota sampling involves not only contact with biological samples that may have been infected but also the dissection of living organisms [34, 35]. On the other hand, sediment sampling, soil sampling, beach and shoreline sampling, may have varying levels of cleanliness, hygienic conditions, and time and effort consumption (e.g., separation of sediment and microplastics) depending on the specific circumstances and precautions taken during the sampling process. Sample processing includes collection, transportation, storage, filtration, separation, and extraction techniques (Figure 1).

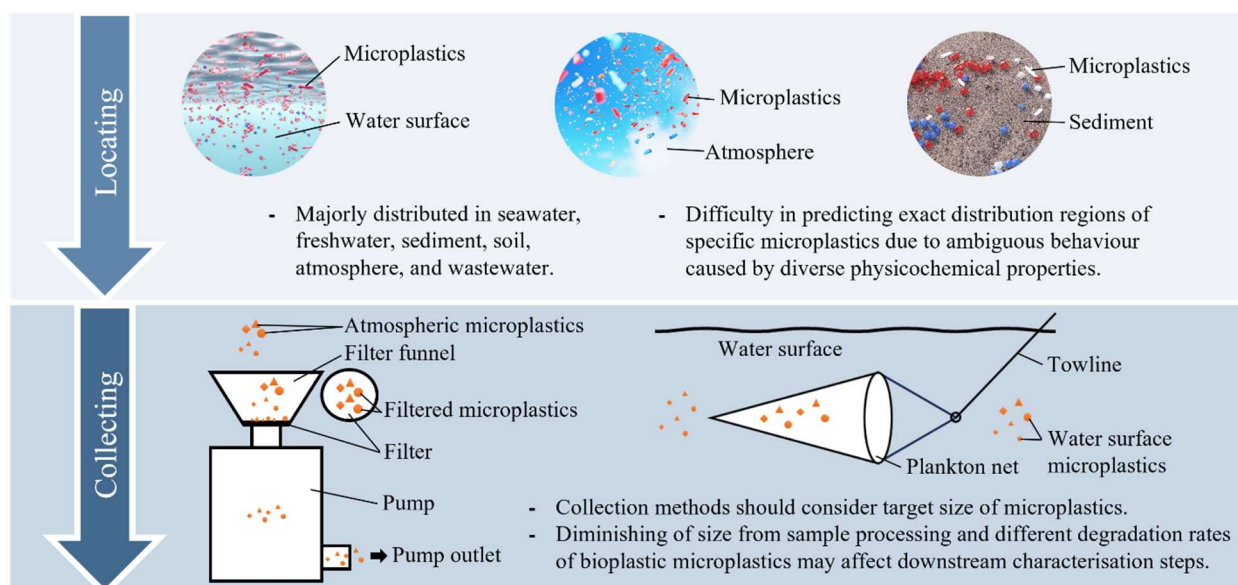


Figure 1. General conceptual illustration of collecting microplastics [26-29, 36-40]

In microplastic conversion to value-added products, additional microplastic characterisation steps are required to categorise or selectively collect microplastics according to their composition, using fluorescent spectroscopy, Fourier-transform infrared spectroscopy (FTIR), micro-Raman spectroscopy, mass spectrometry, chromatography, pressurized fluid extraction (PFE), density separation, and fluorescence microscopy via hydrophobic fluorochrome dye staining (e.g., Nile red staining) to verify the composition or properties of the collected microplastics. Presently, a blend of physical methods such as microscopy and chemical methods like spectroscopy is extensively

employed for microplastic examination. This strategy reduces the occurrence of inaccurate positive and negative results. [41-44]. In plastics manufacturing, identical resin compositions are crucial for homogenous products as variations in these compositions can lead to defects, inconsistencies, or undesirable characteristics, affecting the appearance and performance of the final product [45, 46]. For industrial conversion of microplastics to value-added products, rapid collection and characterisation methods of high capacity are required to channel the microplastics to the appropriate manufacturing techniques and product types.

Physical characterisation

Physical characterization of plastic plays a significant role in determining and better understanding the properties of a plastic polymer including to determine the optimum surrounding condition to catalyse high-efficiency biodegradation of the plastic polymer and to ensure a higher quality and reliability of the plastic product that can adapt to a variety of applications. Due to the complicated nature and properties of the polymer, specific tests are required for each unique characteristic of each polymer and among the physical properties that are commonly tested and measured are comprising of mechanical properties such as flexural rigidity, tensile strength, hardness and wear and tear resistance [47]. Tensile strength of a plastic polymer is described and tested through the application of the maximum tensile stress before the polymer is fractured into fragments which are commonly utilized in load-bearing applications. According to Sola et al. [48], the tensile test is one of the commonly used mechanical tests in the industrial sector due to multiple factors such as relatively short, simple procedures and lack of in-depth requirements of research and development allowing industrial players to test for tensile strength without spending an extra cost for external services.

As the world has reached a point of a global boiling era as mentioned by the UN secretary general, studying the effect of heating of plastic to the polymer and its degradation properties have never been more relevant as the temperature of the global surface increasing at an alarming rate since the past decade [49] (Niranjan, 2023). Thermal-based analysis of polymers comprises a few analyses that are thermogravimetric analysis (TGA), differential thermal analysis (DTA), differential scanning calorimetry (DSC) and evolved

gas analysis (EGA). As summarized by Ng et al. [50], TGA functions to analyse mainly the thermal stability, properties of composites and oxidative stabilities of polymer samples. The above-mentioned thermal analysis: DMA are reported to study the viscoelastic properties of polymeric samples that would further complement the TGA analysis. Another similar analysis that applies the thermal-based analysis is Melt Flow Index Measurement (MFI), which studies the process of thermoplastic polymers by measuring of flow of molten plastic [51]. This process is crucial for the application of moulding injection as well as extrusion processes.

Chemical characterisation

Polymers regardless of size have their respective monomers, linkages, reactive chains, or end-groups that determine their characteristics that could enable the creation of polymer networks reliably and repeatedly with desired features. Through chemical characterization, researchers can unveil surface functionalities, including oxidation, hydrophobicity, and adsorbed substances. Moreover, they can understand changes in polymer structure resulting from UV exposure, mechanical forces, and microbial activity. [52, 53]. There are many methods for identifying objects and determining their chemical composition as shown in Figure 2 [54]. SEM-EDS aids in quick differentiation between non-plastic and plastic pellets and can find microscopic particles that are missed by optical inspection. EDS was used to determine the qualitative elemental composition of the microplastic surface. In addition, tool plays a critical role in the identification of pollutants linked to microplastics, such as toxic metals. [55, 56].

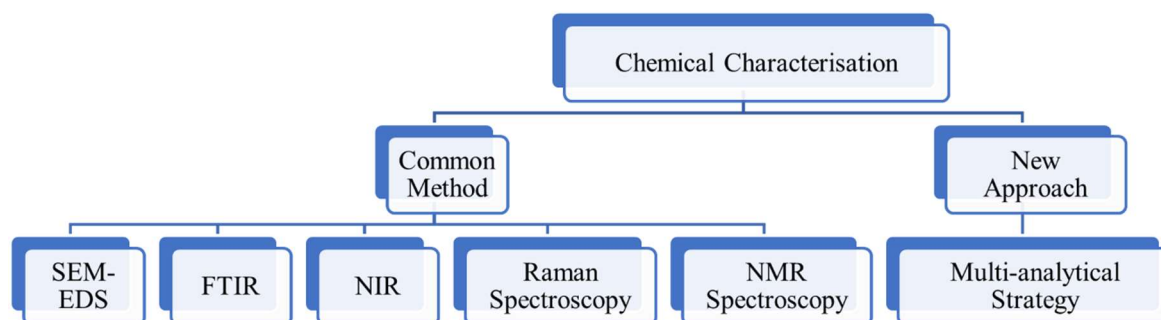


Figure 2. Methods in chemical characterisation

The most popular method for locating microplastics is Fourier-transform infrared (FTIR) which is typically used to determine the polymeric composition of the microparticles, while Raman spectroscopy since it is straightforward, reliable, and non-destructive [52, 57-59]. However, the detection of domain differences within a sub-micrometre region with traditional Raman or FTIR spectroscopy offers average chemical information at a bulk area with very limited spatial resolution, which may restrict the analysis of nanoplastics that are smaller than the spatial resolution [60, 61]. The use of hybrid approaches, namely atomic force microscopy-Raman (AFM-Raman) and AFM-IR techniques, have been considered to map and identify composites at the nanoscale on sample surfaces. AFM has the ability to function in various modes, such as contact mode, tapping mode, or phase mode, which are determined by the force feedback type and the probe's oscillation frequency. [62, 63]. Apart from that, NIR spectroscopy also can be used to characterize and differentiate microplastics and is capable of seeing deeper into the plastic compared to other spectroscopy methods [54, 64]. Quantitative ^1H NMR spectroscopy gives a way to identify microplastics both qualitatively and quantitatively which is also a cost-efficient, quick, and easy technology that provides a significant advantage over other detection techniques. In fact, this technique is non-destructive and non-invasive, eliminating the need for sample preparation or solvents. [65-67]. Thermal degradation of MPs has been discovered to be advantageous since it can simultaneously identify the type of polymer and detect chemical components, additives, and gases in the intricate formulation [68]. Thermal degradation includes pyrolysis as well as GC-MS where the product of pyrolysis (heating and melting of the microplastics) will undergo GC-MS for separation and detection of compounds present. This method has the capability to address certain drawbacks of spectroscopy approaches, including low detection limits, matrix interferences, and sample heterogeneity. [69, 70].

Analysis of MPs in environmental samples is hampered by microplastic contamination from the sampling and laboratory environments, which can affect both qualitative and quantitative determination that includes the most popular methods [71]. A series of newly created analytical protocols for the precise and selective detection of the polymers, along with

specialized methods that include extraction of polymer using different solvents, hydrolytic depolymerization, purification, and quantification procedures that are tailored for condensation polymers, pyrolysis-gas chromatography-mass spectrometry (Py-GC/MS), and followed by physical characterization process [72]. ^1H NMR spectroscopy and the thermal desorption gas chromatography-mass spectrometry (TD-GC-MS) technology were used in a multi-analytical strategy to characterize the microplastics in different degradation times. Utilizing multiple strategies can surpass the limitations of each individual method, offering a more thorough and dependable insight into the characteristics of microplastics, including particle number, size, shape, mass, composition, and additives. [73, 74].

Conversion of conventional microplastics

As the development and applications of plastic have revolutionized the modern-day world, the constant increase in the usage of plastic in daily life has raised environmental concerns as plastic waste persists in the environment longer than intended. The valorisation of plastic waste, conventional plastic, shows a prospect in supporting the circular economy model [75]. Conversion of conventional microplastic to added value products takes the recycling principle to another level which is not just the recycling of the product itself but down to the monomer recycling of the said products through depolymerization of microplastic. Depolymerization of the polymer allows the monomeric products to be recycled to produce different yet environmentally friendly and economically valuable products closing the loop of recycling [76].

Research regarding the conversion of waste products to added value has been done extensively in the past decade as the valorisation of waste offers a prospective solution supporting the circular economy [77]. The waste-to-energy conversion technology involves the utilization of waste products to produce a variety of fuels that can be further used to generate other products and maintain a sustainable energy supply (Figure 3) [4]. Among the pathways discovered to increase the conversion of waste products into added value are biological, chemical, and mechanical pathways. Biological conversion utilizes the natural ability of microorganisms to further recycle the end-of-use plastic to produce simpler compounds that can be

recovered [78]. In addition, pyrolysis has gained popularity recently as the chemical pathway of conversion of plastic waste toward the production of gasoline, diesel and oils via heating of waste materials in the absence of oxygen [79]. Mechanical conversion

of waste to value added products on the other hand, involves the change in the physical state of the waste products via the shredding and grinding process without altering the chemical or biological structure of the waste products [80].

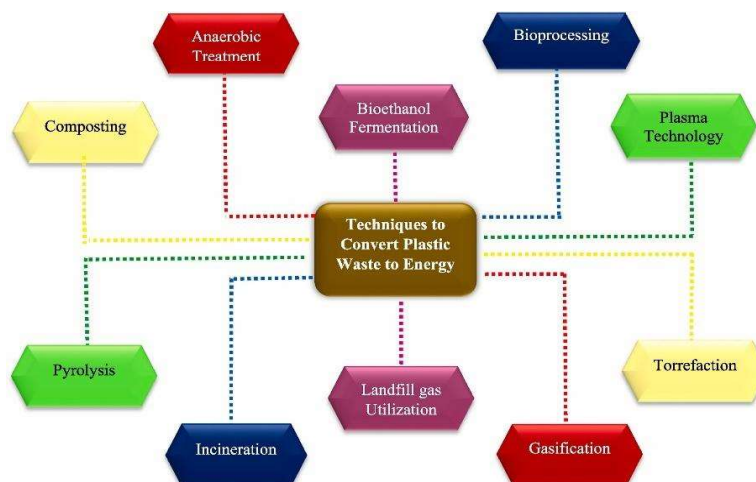


Figure 3. Techniques to convert plastic or microplastics waste to energy

Biological conversion

In general, the bioconversion of traditional biowaste such as agricultural, domestic, and industrial waste to value-added products comprises four primary conversion pathways, microbial, enzymatic, fermentation, and composting conversion pathways [81]. In this review, the valorisation of plastic waste through bioconversion pathways will be further explored. Biological conversion of plastic waste refers to the recent advances of innovative strategies for adding value to end-of-life plastic-based products by exploiting the fundamental abilities of the microbial factory [82]. Conventional petrol-based polymers are categorized into two groups depending on their chemical structure. The two categories of petrol-polymer are polymers that possess hydrolysable ester bonds and functional groups of esters and amides (PET and PUR) that have higher biodegradability compared to non-hydrolysable (PE, PS, PP, and PVC) which possess a stable carbon chain backbone [23, 78]. Recent advances in biological plastic conversion comprise two main elements: plastic-degrading microorganisms and enhancing enzymes for degradation. Both elements play a crucial part in the process of bioconversion of plastic to obtain the desired end-products. The efficiency and productivity of biological conversion of plastic waste into substrate

depends on multiple factors such as the type of plastic-degrading microorganism used, depolymerization through enzymatic reactions and end-product value [23, 83].

Plastic-degrading microorganisms

Studies on the utilization of microorganisms in the degradation of plastic waste have been extensively done in the pursuit of a sustainable approach to plastic waste solutions. In a study conducted by Yoshida et al. [84], reported that *Ideonella sakaiensis* 201-F6 can produce enzymes with the ability to degrade PET into terephthalic acid (TPA) and ethylene glycol (EG) which can be assimilated for metabolic activity. It has been found that *I. sakaiensis* is capable of surviving on PET alone as a carbon source whilst utilizing two main enzymes that are PETase and MHETase [85, 86].

The genus *Pseudomonas* sp. is also among the most researched bacteria due to its versatility in degrading a wide range of polymers. A study conducted by Lee et al. [87] showed that *Pseudomonas aeruginosa* isolated from the guts of superworms exhibit biodegradability properties towards four synthetic plastics, PE, PS, PPS and PP with the fastest degradation on the PE type plastic. The terrestrial bacterium *Bacillus subtilis* possesses synthetic degrading abilities and has been

reported to efficiently degrade conventional plastic type PET with the rate of 9.26% in 30 days which supports biodegradation of conventional plastic through microbial factory [88]. To date, there are currently 949 microorganisms associated with plastic according to the plastic microbial biodegradation database (PMBD) [89].

Enzymatic depolymerization

Degradation of synthetic oligomers and polymers by enzymatic activity commonly involves two categories of enzymes that are hydrolases (e.g., esterases, lipases, cutinases, proteases) and oxidases (e.g., dehydrogenases, laccases) [90]. Depolymerization functions to chemically breakdown polymers from macromolecules to lower compounds of oligomers and monomers through the process of enzymatic activities such as hydrolysis, oxidation, or hydroxylation that will allow the reuse of these monomers through repolymerization process [78, 91]. For example, conventional plastic such as PP, PE, and PVC poses similar structure of C-C as the main chain that can be further turned into various type of fatty acids through the act of enzyme activity [75, 92, 93]. In a different study by Zhang et al. [94], conventional plastic PS can be converted into aromatic monomers, which leads to the oxidation of styrene epoxide catalyzed by the enzyme styrene monooxygenase (SMO) or styrene dioxygenase (SDO).

The biodegradation of PET employs a two-enzyme system which utilizes the PETase to hydrolyze PET into TPA, EG and MHET and MHETase enzyme to further hydrolyze MHET into TPA and EG [84, 86, 95]. To date, most PET-degrading enzymes have been found in two main genera of bacteria, *Pseudomonas sp.* and *Bacillus sp.* While other bacterial strains produce PET degrading enzymes such as *Brevibacillus parabrevis*, *Staphylococcus aureus*, *Streptococcus pyogenes* and *Clostridium thermocellum*, research studies have shown that the usage of microbial consortia comprising *Pseudomonas sp.* and *Bacillus sp.* have proven to have increased degradation efficiency of PET polymer [96, 97].

Chemical conversion

Chemical conversion or chemical upcycling approaches for converting conventional microplastics into value-added goods are gaining popularity as a

potential solution to the world's plastic pollution problem. It involves a process that breaks down the polymers into smaller molecules which could then be used as a feedstock for a variety of valuable chemicals and materials. Microplastics are microscopic plastic particles, frequently less than five millimetres in size, found in a variety of environmental compartments such as oceans, rivers, and soil. Converting these microplastics into valuable materials has the potential to minimize their environmental impact while also providing economic rewards. This section briefly discusses the two techniques of chemical upcycling widely studied over the years.

Depolymerization

Depolymerization is a process where long polymer chains are broken down into small monomer units allowing new products to be synthesised using these monomers. Research was done to investigate the techniques of depolymerization such as using transition metals [98], enzymes [99], catalysts [100], electrocatalysis [101] and more. In 2012, a team of researchers used a PNP-Ru pincer complex (Ru-1, 0.1 mol %) as a catalyst to perform the first hydrogenative depolymerization of waste poly(propylene carbonate) (PPC) which yielded 1,2-propylenediol and methanol [102]. Besides, Mao et al. [101] reported the utilization of electrocatalytic upcycling of PET microplastics to formate, terephthalic acid and potassium sulphate using a novel catalyst Mn_{0.1}Ni_{0.9}Co₂O₄- δ rod-shaped fibre (RSFs) catalyst. Recently, enzymes are being used to facilitate the hydrolysis of amides, esters, or urethane bonds within microplastics, such as polyamides, polyesters, or polyurethanes, for the generation of monomers or oligomers, which can subsequently undergo analysis using techniques includes chromatography or spectroscopy. In addition, fungi are introduced to secrete various digestive enzymes and proteins that attach to the polymer surface, penetrate it, and degrade macromolecules into small organic compounds, such as carbon dioxide, water and methane [103, 104].

Pyrolysis

Pyrolysis is a thermochemical technique that decomposes waste materials into energy products such as liquid oil and gases in hypoxic conditions and at high operating temperatures ranging from 400 to 800°C [105, 106]. A myriad of studies has been

conducted on the conversion of microplastics to value-added products via the pyrolysis technique. Nabgan and coworkers [107] investigated the potential of utilizing microplastic wastes to produce value-added products using the pyrolysis-catalytic steam reforming technique. They synthesized the nano-catalyst, Ni-Pt/Ti-Al, and loaded it into the pyrolysis reactor before introducing the phenol-dissolved microplastics into the fixed-bed continuous flow quartz reactor at 500 – 700°C at standard atmospheric pressure. Several liquid oils were generated such as 1,2-bis(trimethylsilyl)benzene, bis(2-ethylhexyl) phthalate, cyclohexane-1,3-dione, 2-allylaminomethylene-5,5-dimethyl- and more. Agriculture is one of the largest plastic waste producers. The generated waste plastic mulching films are normally disposed of conventionally (incineration and landfilling) which introduces greenhouse gases and microplastics in the ecosystem [108]. Because of this Jung and coworkers [108] investigated the disposal of the mulching films through a CO₂-assisted catalytic pyrolysis. It was reported that hydrogen gas, short-chained and long-chained hydrocarbons were formed through thermal degradation of the mulching films. When a Ni/SiO₂ catalyst was used the hydrogen gas production skyrocketed to 100 times more. Furthermore, when CO₂ was introduced as a flow gas CO production was observed.

Gasification

Gasification is a technological process that converts any carbonaceous (carbon-based) raw material into synthesis gas (syngas). Gasification takes place in a gasifier, which is typically a high temperature/pressure vessel in which oxygen (or air) and steam come into direct contact with the coal or other feed material, resulting in a sequence of chemical processes that convert the feed to syngas and ash/slag (mineral wastes) [109]. The gasification of polypropylene was studied by Wang et al. [110]. They compared the effects of the presence of a catalyst with none. Expectedly, the catalyst (Ni/Al₂O₃) set-up has vastly improved the yield of H₂, CO, hydrocarbons and total syngas by 137%, 38.2%, 98.2%, and 44.1%, respectively. Not only that, Moghadam et al. [111] conducted a study on syngas production from palm kernel shells and polyethylene wastes via the gasification process. The paper reported that a co-gasification process under optimized conditions was

able to yield 422.4 g/kg feedstock and 135.27 g/kg feedstock of syngas and H₂, respectively.

Mechanical conversion

Mechanical conversion is the mechanical force applied as a catalyst to reduce the molecular weight of the polymer [112]. Properties of plastics can be classified in terms of weight, hardness, tensile strength, thermal properties, electrical properties, and chemical properties [113] (Alauddin et al., 1995). Thus, breaking the plastic with external mechanical force could break and change those properties to some level. A study highlighted that mechanical conversion affects the structure of the polymer and reduces the quality of the product in terms of mechanical properties regardless of the type of the polymer [114]. Yet, mechanical recycling is a practical method for maintaining plastic's inherent worth, preventing the waste of non-renewable resources [115].

Grinding and milling techniques

Milling in general is a technique or process of cutting or grinding material using a rotary cutter and incorporates the conversion of mechanical energy into thermal energy and was the first technique to produce microplastic particles [116, 117]. The milling and grinding process is a crucial step before thermal conduction [118]. Meanwhile, a study by Eitzen et al [116] shows that longer cryogenic milling and pre-cooling duration could produce small particles of polystyrene (PS).

Cryogenic grinding with a wet-sieving technique could enable maximum yield of the polyvinyl chloride (PVC) and smaller microparticles could be obtained if the microparticles undergo 2 cycles of the grinding process [119]. There is also a new grinding technique that has been revealed which is the melt grinding technique that has the advantage of not having drying steps in the usual grinding technique where the time consumption was high [120]. Cryogenic milling and grinding are the processes that incorporate low temperatures to overcome the issue mentioned before such as heating despite milling or grinding conventional microplastic as each type of microplastic has respective characteristics that differ by physical and chemical properties. In conclusion, the grinding and milling technique is the early stage before the plastics are further proceeded for extrusion and injection moulding

as smaller plastics can be melted in large quantities in a shorter time compared to large plastics.

Extrusion and injection moulding

Injection moulding is a technique where injecting material into a mould with high temperature and pressure in a closed system [121], meanwhile, extrusion is a technique of pushing out a material through an opening with the help of an extruder [122]. The extrusion and injection moulding of conventional plastic can cause issues such as degradation of their features and usability arise when a combination of heat and mechanical shear affects the recycling of both post-industry and post-consumer plastics [123]. Changes in chain length and mechanical characteristics are a constant problem, even though the methods of

degradation vary among polymers, especially upon thermal conduction [124]. For instance, the thermomechanical process results in a drastic reduction in poly (ethylene terephthalate) (PET) characteristics [125]. Also, polyolefins that include HDPE, LDPE, and PP shows varied mechanism; HDPE and LDPE have a high probability in chain branching, but PP has a high probability in chain scission upon extrusion [124, 126]. Extrusion is best for long, uniform products and is cost-effective for mass production. Injection moulding suits complex, irregular items with precision for custom orders. Unlike extrusion, it handles both thermoplastics and thermosets [127]. Figure 4 shows a combination of mechanical and chemical technique to convert plastic waste into value added products such as fuels.

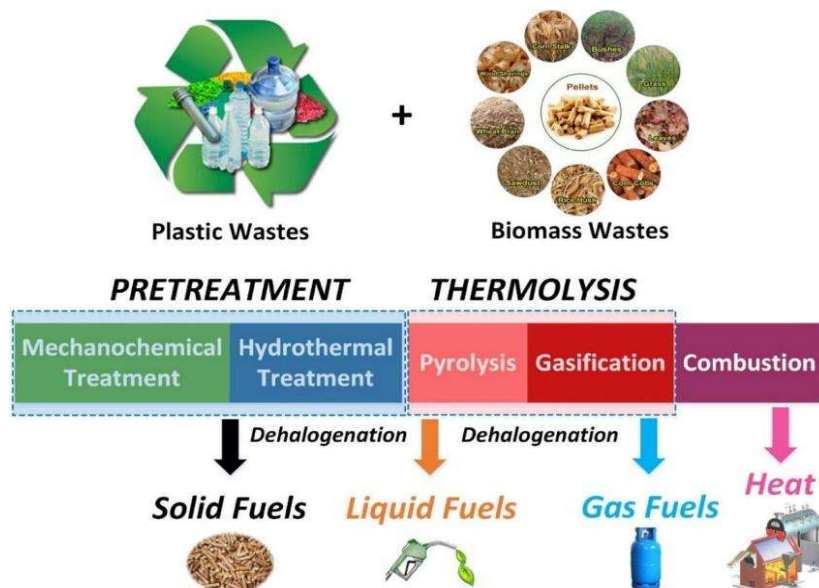


Figure 4. Mechanical and chemical treatment of valorisation of plastic waste

Potential applications of value-added products

The transformation of microplastics into value-added products requires consideration of material properties, process selection, waste utilisation, and environmental concerns. Material properties, such as composition, size, and shape, play a significant role in determining the suitability of waste materials for specific manufacturing processes [128], as well as the compatibility between waste materials and other components or additives for proper integration and performance since the properties of manufactured products should meet the required standards and specifications for their intended applications [129]. The

selection of conversion and manufacturing processes is dependent on available resources and technologies, where process optimization and innovation are required to improve efficiency and sustainability. In microplastic research, the state-of-the-art focus has presently pivoted towards the waste utilisation, material properties, conversion process selection, and environmental implications of all types of microplastics [20, 106, 129]. These leading-edge endeavours underscore the imminent potential to transform microplastics into a range of valuable products, emphasizing the timeliness and urgency of such innovative pursuits.

Utilizing nature's process of breaking down complex compounds into simpler compounds mechanism in the innovative approach of recycling plastic waste has opened a new door towards plastic waste management. The biological approach to converting plastic waste through the coupled act of plastic-degrading bacteria and enzymatic degradation has shown promising results. For example, the intermediate produced from enzymatic reactions of PETase and MHETase can be used for further metabolic reactions, in PHA polymer production through microbial fermentation [78, 97, 130]. Enzymatic hydrolysis of plastic waste, including impurities from PLA-PET, is being researched as an eco-friendly method of bio-recycling plastic trash. Recent studies suggest an innovative hybrid approach merging thermal and electrochemical techniques to convert both plastic waste and biomass into exceptionally pure hydrogen and carbon nanotubes. Moreover, the method introduces a carbon capturing process using a molten salt, which can subsequently be transformed into valuable carbon nanotubes through electrochemical means powered by renewable energy sources. [131, 132].

Challenges associated with the conversion of microplastics to value-added products

Regulatory and policy considerations

Plastic is the main material used for packaging and textiles in various sectors. Excessive plastic usage has led to tremendous plastic waste generation. According to Tiwari et al. [133], the top three countries that produce the most plastic are in Asia within the Indo-Pacific region, namely India, China and the Philippines. Many countries have established regulations, action plans and policies to regulate and control plastic waste generation (Table 2) Despite many regulations that have been enforced, the accumulation of plastic usage at the rate of 25 million tonnes per year continues due to their persistence in the environment [134]. In addition, in certain countries, the mitigation plans and regulations are mostly focusing on plastics but not microplastics. Today's microplastic is a global issue since it can be found everywhere. Vectors for drugs in medical sectors and microbeads in beauty care products are known as primary microplastics,

while secondary microplastics are tiny plastics deteriorated from primary microplastics [135, 136].

As a result of growing concern towards these tiny plastic particles, few countries have imposed national legislation to combat microplastic specifically (Table 3). All these plastic grains eventually end up in the ocean, posing major threats to the ecosystem, where they have been reported to be found in all levels of aquatic environments [137, 138]. Microplastics that are consumed by fish will eventually contaminate the human body through seafood consumption [139]. Consequently, this sparks a growing number of research and publications on the effects of microplastic towards fish and human beings. Kutralam-Muniasamy et al. [140] indicated that the actual consequences of microplastics are merely understood scientifically. In a recent study, Carrington [141] reported that microplastic has been detected in human blood for the first time. Although the impacts of microplastic in the human body are still being explored, a solution to substitute conventional plastic with an eco-friendlier alternative is urgently needed.

Fundamentally, reducing macroplastic usage through prohibition and restriction use of plastics will reduce the presence of microplastic in the ecosystem. However, Mitrano et al. [142] stated that it is unclear whether technical bans can help in the reduction of microplastic. They opined that proper macroplastic management is the ideal way to reduce microplastic as a transition towards a circular economy. An amendment to the government framework is suggested to focus on waste utilisation by repurposing and converting the waste into other products. Although many regulations were in place, microplastic pollution is hard to solve, so the focus should be concentrated on the utilisation of microplastic into value-added products, to address the circular economy concept and to comply with the Sustainable Development Goals 6, 7, 12, 13, 14, 15. We need specific guidelines, regulations and policies to regulate and control microplastic pollution, by regulating microplastic production, supporting microplastic conversion into value-added products, and encouraging a circular economy that reduces the usage of raw resources.

Table 2. Policies and regulations on plastic waste established by countries

Year	Country	Regulations
2016	India	Plastic Waste Management Rules (2016)
2008	China	China State Council had issued a Notice restricting the Production and Sale of Plastic Shopping Bags
2020	China	National Development and Reform Commission (NDRC) and the Ministry of Ecology and Environment (MEE) released an “Opinions on Further Strengthening the Control of Plastic Pollution
2022	Philippines	Extended Producer Responsibility Act (EPRA) 2022
2022	Philippines	Department of Environment and Natural Resources (2020) has banned the usage of unnecessary single-use plastics in offices under the National Solid Waste Management Commission.
2011	Italy	Banned traditional plastic bags and substituted them with biodegradable bags
2012	Sweden	Started to focus on the replacement of fossil-based raw materials with bio-based raw materials in their research and development needs
2013	Canada	Banned the usage of traditional plastic bags in Toronto
2023	United Arab Emirates (UAE)	Banned shopping bags that are not oxo-photodegradable.
2021	Australia	Published the National Plastics Plan 2021 to address and reduce plastic waste generation
2019	Scotland	Banned plastic cotton buds in 2019 and 2021, a ban was imposed on single-use plastic items
2018	Malaysia	Malaysia’s Roadmap Towards Zero Single-use Plastics 2018-2030
2021	Malaysia	Ministry of Environment & Water (2021) published the Malaysia Plastic Sustainability Roadmap 2021-2030

References [143-150]

Table 3. Policies and regulations on microplastic established by countries

Year	Country	Regulations
2014	Netherlands	Ban the usage of microbeads in cosmetic products.
2015	United States (US)	Microbeads-Free Waters Act of 2015
2017	Canada	Microbeads in Toiletries Regulations 2017
2016	France	Law n° 2016-1087 for the recovery of biodiversity, nature and landscapes
2018	Italy	General Budget Law 2018 no. 205 of 27
2017	New Zealand	Waste Minimisation (Microbeads) Regulations 2017
1998	Sweden	Ordinance (1998: 944) on prohibitions, etc. in certain cases in connection with the handling, importation and export of chemical products
2017	England	Environmental Protection (Microbeads) Regulations 2017
2018	Scotland	Environmental Protection (Microbeads) Regulations 2018
2018	Wales	Environmental Protection (Microbeads) Regulations 2018
2018	Northern Ireland	Environmental Protection (Microbeads) Regulations 2018
2023	United States (US)	National Strategy to Prevent Plastic Pollution proposed by the United States Environmental Protection Agency

References [151-158]

Future directions and emerging trends

In the future, there is a need for standardised methodologies for microplastic analysis, quantification, and classification. The accurate characterisation of microplastics is crucial for appropriate categorisation and isolation of microplastics before downstream conversion processing, hence escalating future research

is expected on the development of advanced techniques that allow for rapid and precise analysis of microplastics. For example, method improvisations on mechanical recycling and biodegradation optimisation through specific designs of microbial consortia or enzymes could recover high-quality conventional microplastics and accelerate the breakdown process of

biodegradable microplastics. As innovative conversion technologies emerge, future microplastic research could include the development and integration of circular economy models into broader frameworks that incorporate microplastic recovery, conversion, and reuse, thus reducing the dependence on virgin plastics. While future research expansion is expected on the conversion of conventional microplastics to biofuels, the simultaneous production of biodegradable microplastics and biofuels from renewable resources might also be considered. In addition, future regulatory frameworks are also expected to encompass both conventional and biodegradable microplastics, ensuring that products claiming to be biodegradable undergo rigorous testing to validate their claims before “green” or eco-friendly labels are permitted. Policymakers must collaborate with researchers and industries to develop effective waste management strategies that prevent microplastics from entering the environment. By embracing a multidisciplinary and holistic approach, international and national collaboration among researchers, industries, policymakers, governments, and non-governmental organizations is paramount for driving meaningful progress in microplastic research via the exchange of knowledge, resources, and expertise.

Conclusion

This study explores the potential of converting conventional microplastics into value-added products by comprehensively exploring the collection, characterisation (i.e., physical and chemical), conversion (i.e., biological, chemical, and mechanical) methods, providing valuable insights into the potential of mitigating microplastic pollution while deriving value from these materials. The physical and chemical characterisation of microplastics highlights the distinctive attributes of conventional microplastics to tailor suitable conversion approaches based on the various compositions of microplastics. Biological conversion is a promising avenue, as it shows the ability of microorganisms to degrade both types of microplastics, suggesting the potential for bioremediation of microplastic pollution. Chemical and mechanical conversion pathways also offer routes to synthesize value-added products such as biofuels from microplastic materials.

Furthermore, the exploration of potential applications of value-added products derived from microplastics underlines their potential to contribute to the transition towards a more sustainable and circular economy. Regulatory and policy considerations are also crucial, as the conversion processes may be subject to varying regulations, requiring coordination and adaptive governance structures. Moreover, challenges in the conversion processes, such as technical constraints and economic feasibility, emphasise the need for continued research and development efforts. Collaboration between academia, industry, and policymakers is essential in mitigating plastic pollution and fostering circular economies.

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