Science of the Total Environment 881 (2023) 163433

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Review

# A critical review and future perspective of plastic waste recycling

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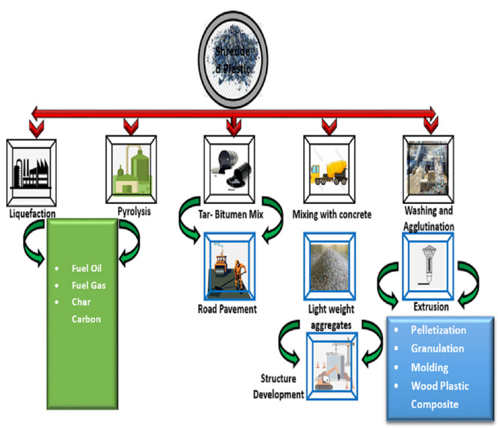
## HIGHLIGHTS

- Conventional and modern recycling of plastic waste is highlighted.
- Degradation process of plastic waste is discussed in detail.
- Technological applications of PW and fuel production are discussed.
- Economic and ecological aspects of PW are highlighted.
- Challenges and perspective of PW recycling are emphasized.

## GRAPHICAL ABSTRACT




## ARTICLE INFO

Editor: Huu Hao Ngo

*Keywords:*
Chemical recycling
Gasification
Mechanical recycling
Plastic degradation
Microorganism
Plastic waste (PW)
Pyrolysis

## ABSTRACT

Plastic waste is increasing rapidly due to urbanisation and globalization. In recent decades, plastic usage increased, and the upward trend is expected to continue. Only 9% of the 7 billion tonnes of plastic produced were recycled in India until 2022. India generates 1.5 million tonnes of plastic waste (PW) every year and ranks among top ten plastic producer countries. Large amount of waste plastics could harm environment and human health. The current manuscript provides a comprehensive approach for mechanical and chemical recycling methods. The technical facets of mechanical recycling relating to collection, sorting, grading, and general management to create plastic products with additional value have been elaborated in this study. Another sustainable methods aligned with the chemical recycling using pyrolysis, gasification, hydrocracking, IH2 (Integrated Hydropyrolysis 2), and KDV (Katalytische Drucklose Verolung) techniques have also been highlighted with the critical process parameters for the sustainable conversion of plastic waste to valuable products. The review also adheres to less carbon-intensive plastic degrading strategies that take a biomimetic approach using the microorganism based biodegradation. The informative aspects covering the limitations and effectiveness of all PW technologies and its applications towards plastic waste management (PWM) are also emphasized. The existing practices in PW policy guidelines along with its economic and ecological aspects have also been discussed.

*Abbreviations:* Atm, Atmospheric Pressure; $NH_3$, Ammonia; $CO_2$, Carbon-di-Oxide; CO, Carbon Monoxide; CFCs, Chlorofluorocarbon; GHGs, Green House Gases; $H_2S$, Hydrogen Sulphide; $H_2$, Hydrogen; HC, Hydrogen chloride; IH2, Integrated Hydropyrolysis 2; HDPE, High Density Polyethylene; IWM, International Waste Management; KDV, Katalytische Drucklose Verölung; LCA, Life Cycle Assessment; LDPE, Low Density Polyethylene; MT, Metric Tonne; MSW, Municipal Solid Waste; $CH_4$, Methane; $N_2$, Nitrogen; NOx, 'Nitrogen Oxides; $O_2$, Oxygen; PVC, PolyvinylChloride; PE, Polyethylene; PET, Polyethylene Terephthalate; PS, Polystyrene; PWM, Plastic Waste Management; PW, Plastic Waste; PMMA, Polymethyl Methacrylate; PP, Polypropylene; VOCs, Volatile Organic Compound; CRI, Criterion Catalyst Company.

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http://dx.doi.org/10.1016/j.scitotenv.2023.163433
Received 31 January 2023; Received in revised form 26 March 2023; Accepted 7 April 2023
Available online 13 April 2023

**Contents**



## 1. Introduction

Plastic waste (PW) created serious problems including clogging of drains, environmental damage and health problems to humans. Globally, 348 million tonnes of PW were generated in 2017 which will be quadrupled by 2050 (Purwendah and Periani, 2019; PlasticsEurope, 2018). Worldwide around 8 million metric tonnes of PW are reportedly poured into the ocean each year which is destroying aquatic wildlife and contaminating human supplies of food (Purwendah and Periani, 2019). Many nations produce huge quantity of PW pyramids that need to be properly disposed off with efficient waste management, and their rapid proliferations in the wastewater cause serious problems (Ghayebzadeh et al., 2020; PlasticsEurope, 2018). Plastic is a substance that is primarily made of a high-molecular weight and organic substrate that maintains solidity (PlasticsEurope, 2018). According to the studies, landfills now hold 79% of the world's 6300 million-tonnes of PW (Geyer et al., 2017). Only 2% of the plastic packaging material gathered over the past 40 years has been recycled (Kedzierski et al., 2020a, 2020b; MacArthur, 2017a; Awoyera & Adesina, 2020). Plastics accumulate and remain in the environment at a rate of approximately 25 million-tonnes per year as a result of their endurance (Geyer et al., 2017). This has led to building up of these materials in dumpsites, endangering health of people and animals as well as posing problems for the environment.

Scientific and effective techniques like pyrolysis can have an efficient way of plastic recycling towards the generation of fuel. The optimized physical and chemical processes are defending the merits of pyrolysis process (Sharuddin et al., 2016). There are multiple factors which affect the plastic recycling process; still recycling industries of PW face many technical challenges (MacArthur et al., 2016). Multi-layer plastic materials or additives like brominated flame retardants, phthalates, etc. create technical challenges in making plastic recycling process complex (Sakthipriya, 2021). Broadly, PW is managed with mechanical (sorting and reprocessing) and chemical (pyrolysis, gasification, hydrocracking, $IH_2$, and KDV method) processes. Chemical recycling technologies play a crucial role in the transition towards circular economy (Kaiser et al., 2017; Grause et al., 2011; Asgher et al., 2020a). In order to overcome these difficulties, finding an efficient and sustainable method of handling these waste products is essential. The handling of reclaimed plastics from municipal solid waste (MSW) is a very sensitive sector (Asgher et al., 2020b; Rai et al., 2022). In order to identify the most eco-friendly alternatives, MSW processes may be tackled using a life cycle assessment (LCA) method that makes it possible to identify the basic environmental effects connected to the alternatives (MacArthur, 2017b; Jeswani et al., 2021). International waste management (IWM) system follows the steps for waste management as waste production, trash movement, source screening and treatment, collection; waste transfer and transport, and disposal. This methodology should be followed by top PW producer countries. Assessing the influence of potential variability in solid waste functions, these functional categories are essential. Fig. 1 shows the percentage growth of top ten countries in the world (Debrah et al., 2022). The recycling system had several drawbacks due to the expensive labour, which further caused water pollution and reduced the operation's reliability. Therefore, as a consequence of these shortcomings, research efforts have shifted towards different forms of energy recovery (Kedzierski et al., 2020a, 2020b). Thus, the transformation of PW to energy arose via extensive and diligent technology (Grause et al., 2011; Material Economics, 2018). Modern technologies (pyrolysis, gasification, hydrocracking, KDV) have significantly utilised plastic goods that are converted into fuel and are currently used to make bricks, tar, and concrete in order to lower PW.

Different microbial activities were also employed for the effective reduction of PW (ORA, 2015, Connor, 2014; Rahimi and García, 2017). PW recycling got momentum during the last few decades (De Weerdt et al., 2020). It was found that pyrolysis is a popular technique which is largely used because of lowering harmful emissions and lower carbon footprint of plastic goods (Shome, 2020). Recycling properties of different plastic

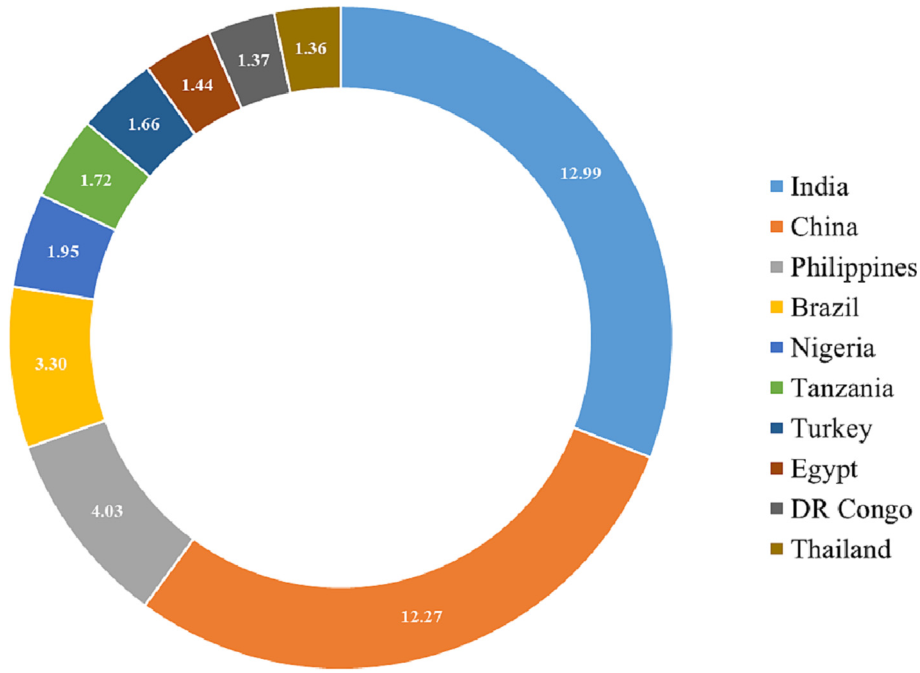


**Fig. 1.** Percentage (%) share of top plastic producer countries.

depends on its specific properties. Thermosetting plastics make up 78 % weight of the total amount while polyolefins like PP, PE, PVC, and PS make up the majority of thermoplastics, which are readily recyclable (Meier et al., 2013).This review will provide a better view on limitations and effectiveness of all conventional and recently used PW technologies and its applications towards plastic waste management (PWM). All the degradation technologies of PW are discussed in detail. Economic and ecological aspects of PW are also discussed to understand the effect of PW on economy. Regulatory guidelines and challenges are also described to understand the complexity of plastics in the recent world.

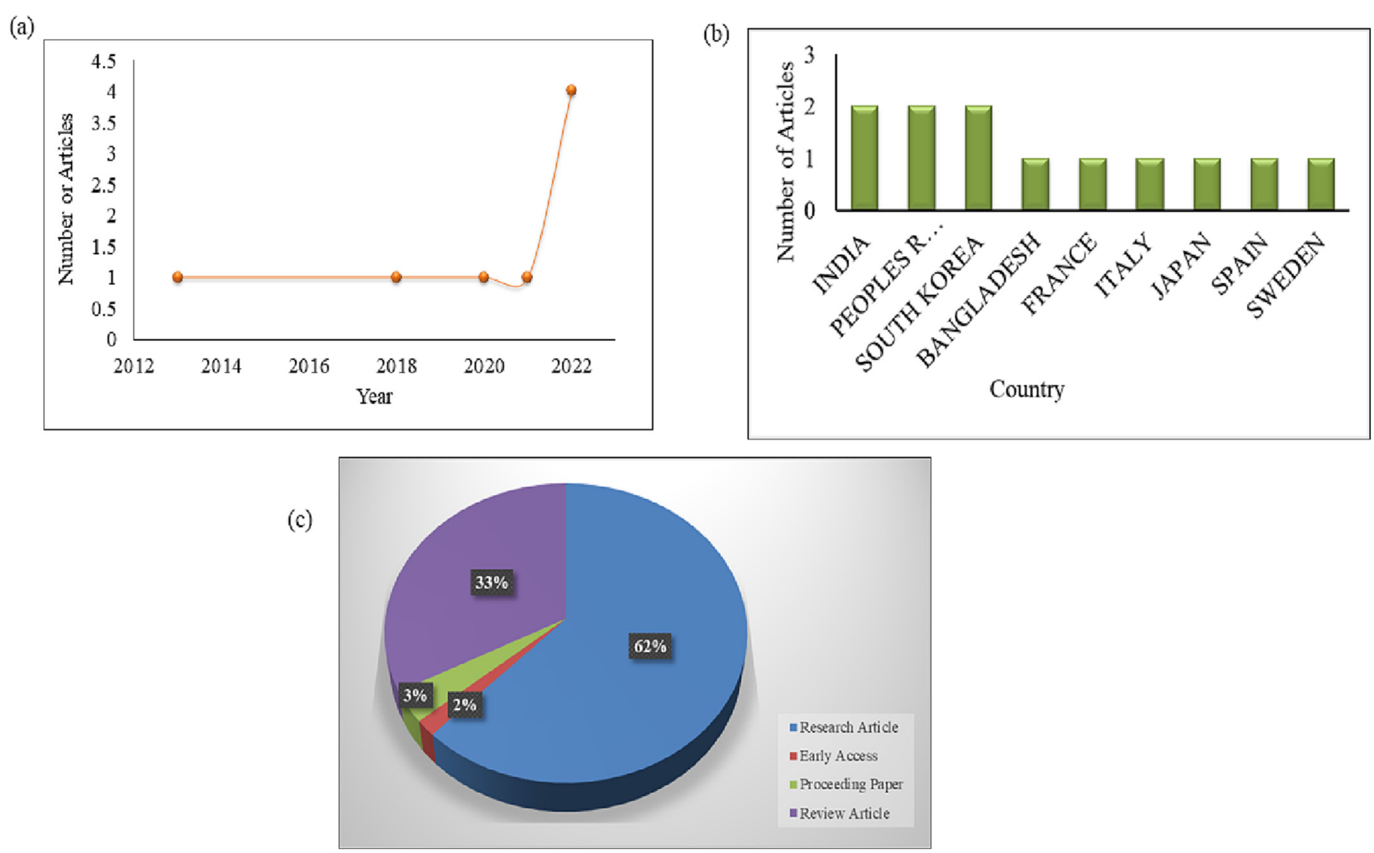


**Fig. 2.** Bibliometric study showing (a) Number of articles published during the period of 2013 to 2022; (b) Number of articles published by different countries; (c) Percentage of different types of publication in this study area.

## 2. Bibliometric study

To understand the research trends in the present topic, a bibliometric study, based on the data obtained from Web of Science, was carried out. A total of 8 publications were obtained with the keywords, "plastic waste, management, conventional technology, and advanced technology". The results obtained were analysed and shown in Fig. 2 **(a).** From the data, it was found that there was a sudden increase in the rate of publication of articles in this study area in the year 2022 as shown in Fig. 2(a). Moreover, Fig. 2 **(b)** showed that India, Peoples Republic of China, and South Korea are publishing their work more as compared to other countries like Bangladesh, France, Italy, etc. The bibliometric study also analysed the percentage of different types of articles published viz. 62% research articles, 33% review articles, 3% proceeding papers, and 2% early access as referred in Fig. 2(c). Therefore, in the present era, owing to the importance of PWM to save the environment and human health, there is a dire need to study about the different technologies (conventional and the advanced) to meet the concept of circular economy.

## 3. Conventional technology for plastic waste management

As a result of industrialization and societal increase, PW is created and released at a significant pace. Fig. 3 shows life cycle and recycling process of plastic waste. PW is creating a serious issue for the environment after reaching to the last recipient (Rahimi and García, 2017; Scott et al., 1990). The natural events of living things as well as human-made operations produce large amounts of both biodegradable and non-degradable waste (Meier et al., 2013; Lim and San, 2022). The safe incineration methodologies and environmental safety guidelines could be placed into practices that have been issued by the Government, municipalities, social communities, and local officials to direct the populace how to manage PW after its use (Vermeulen et al., 2011). Among different PWM techniques, recycling, incineration, biological treatment, and dumpsites are fewer and older techniques to handle the PW (Yadav et al., 2020; Benson et al., 2021). The goal of these techniques are used for disposal of PW and maintain the environment but these techniques have certain pros and cons which are described in this review.

Recycling practise (Fig. 3) involves waste items gathering and turning them into useful goods. Due to carbon-based composition and use of additional polymers, plastics are non-biodegradable. It includes bottles and other items that may be melted down and used to make furniture. Six procedures are used to complete this process i.e., gathering plastic wastes, classifying or categorising plastics, rinsing to eliminate pollutants, cutting and reshaping, detecting and segregating, and compounding (Thiounn and Smith, 2020). Recycling is eminently used to reduce $CO_2$ from the atmosphere which is produced by incineration of plastic (Garforth et al., 2004). Table 1 presents calorific value and generation of greenhouse gas (GHG) emission from different PW. This is the advantage of recycling and protecting human life. Recycling uses less energy, lessens pollutants across the ecosystem, and promotes the preservation of the environment and conserves landfill space (David and Joel, 2018). This process emits harmful gases like GHG, sulphur and Carbon, which contributes towards acid rain and global warming (Szostak et al., 2020; Bhaskar et al., 2003).

### 3.1. Incineration

Incineration is the high-temperature (260 °C – 470 °C) burning of PW (Vollmer et al., 2020).Incineration is used at large scale, a little quantity of HCl, ash, and other VOCs make the waste created during incineration. Energy, commonly referred as fuel, is produced by the burning of organic molecules (Shen and Worrell, 2014; Netzer et al., 2021). Instead of producing energy, it makes a significant contribution to reducing garbage and generating power from waste (Miandad et al., 2016; Shome, 2020). In comparison to other MSW technologies, incineration process has some major drawbacks, such as costly set-up, generates harmful ash and gases ($CO_2$ and water vapour) that might be harmful to both individuals. The benefits of PW incineration are confined to lowering waste volume; nevertheless, the release of harmful gases into the atmosphere during this process has an adverse effect on the environment (Westerhout et al., 1998). Integration of the pyrolysis plant with an existing chemical complex (naphtha cracker) should be preferred in order to lessen the drawbacks of the incineration process (Shome, 2020; Westerhout et al., 1998). Only in cases when a separate product separation section is necessary due to non-technical, non-economic, or non-geographical factors, this should be taken into consideration (Shome, 2020; Westerhout et al., 1998).

### 3.2. Dumpsites

A site used to dispose off solid wastes without environmental controls are called dumpsites. It requires a lot of labour and land part of the

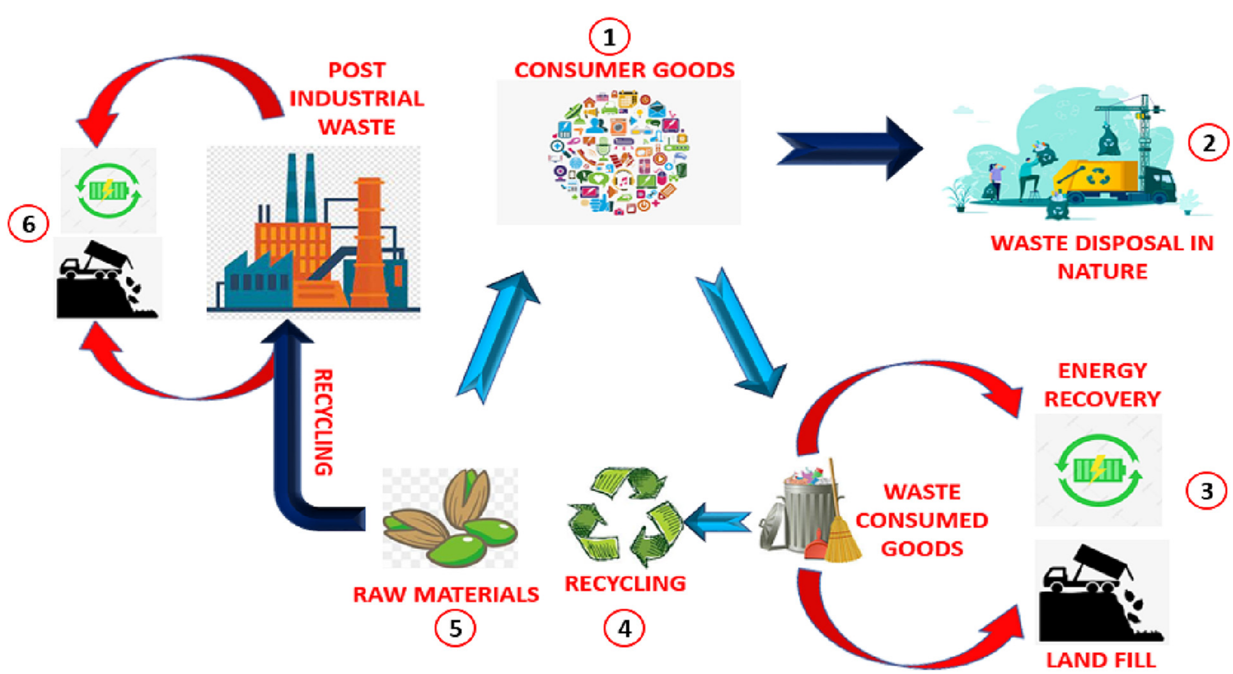


**Fig. 3.** Life cycle and recycling process parameter of plastic waste.

**Table 1**
Types of plastic, calorific value, $CO_2$ and toxic gaseous emission.

| Types of plastic | Calorific value (MJ/kg) | Carbon emission (kg $CO_2$/tonne) | Dioxide of toxic emissions | References |
|---|---|---|---|---|
| LDPE | 40–44 | 3060 | $C_4H_4O_2$ | (Taghavi et al., 2021) |
| HDPE | 37–40 | 3072 | | (Taghavi et al., 2021) |
| PP | 41–44 | 3349 | Furans | Wasielewski and Siudyga, 2013 |
| PS | 38–40 | 4757 | | Wasielewski and Siudyga, 2013 |
| PET | 21–23 | 4137 | $CO_2$ | Zheng and Suh, 2019 |
| Mixed plastic | 35–40 | 3673 | | Zheng and Suh, 2019 |
| | | | $C_6H_6$ | |
| | | | $CH_2O$ | |
| | | | PAHs | |

community, covering an area with garbage, and allowing it to decay is easy but dangerous practice (Sharuddin et al., 2016; Mondal et al., 2023). Biodegradation process takes place at dumpsites which generates methane ($CH_4$) gas and this makes dumpsites a great energy source (Zheng et al., 2005). This process has many disadvantages, such as $CO_2$ and $CH_4$ generated continuously which could be very harmful to the society and living creature sand contaminates the land and water (Miandad et al., 2016). Dumpsites arrangements are designed to offer a safer region for the disposal of PW besides protecting marine life and airspace (Liang et al., 2021; Thiounn and Smith, 2020). Landfill sites are upgraded and the scientific version of dumpsite involves bio-mining and generation of energy source. Many safety precautions are taken throughout this manual disposal procedure to prevent adverse effect. The dumping of PW in landfills has a huge polluting potential due to the presence of toxic chemicals like hydrocarbons, dioxins, furans and traces of Al, C, Si, O, N, Cl. These impurities are technically difficult to remove by mere sorting, scrapping. Hence, incineration and treating the PW as refuse derived fuels (RDFs) for recovering the metals could be a mitigative option to treat PW (Zhou et al., 2014; Okuwaki, 2004).

### 3.3. Bioremediation

The term "bioremediation" refers to a sub-field of biotechnology that uses microorganisms to decompose PW via the microbial activities (Williamson et al., 2016). It has been found that some beetles families, such as Dermestidae, Anobiidae, and Tenebrionidae, had a fascinating ability to ingest plastic materials. It requires a variety of culture medium parameters (pressure, temperature and microorganism), nutrients end enzymes which must be adjusted at an ideal level for microorganism's growth (Hopewell et al., 2009). The bioremediation process won't work effectively if any of the previously listed elements are missing or if growth inhibitors are present (PlasticsEurope, 2018; Haider et al., 2019). Plastic may be split and biodegrade when it exposed to heteroatomic molecules like $N_2$ and $O_2$ in the existence of C=C double bond. Dioxins, Chlorofluorocarbons (CFCs), polyvinyl chloride (PVC) and vinyl monomers are produced during the natural breakdown of plastics. The drawback of this process is that enzymes for the breakdown of synthetic substances are expensive and only technically sound person can handle this process which could be a herculean task at a large level (Coszach et al., 2013; Ragaert et al., 2017). The process of bioremediation might have some process hindrances as the factors like time for incubation, process of degradation have not been optimized.

## 4. Gaps in existing chemical and mechanical techniques

Reusing something and putting it to use once again is recycling. Many new methods (pyrolysis, hydrogen based technologies, and gasification) have been adopted for PW recycling while many old methods (incineration, dumpsites and bioremediation) have been abandoned because these methods were not cost-effective and cannot be employed at large-scale (Anjum et al., 2016). Reusing things help to save time, cost, power, and commodities by taking value-added products and swapping them without further processing (Miandad et al., 2016). Recycling is a technique that transforms PW into new goods to stop the loss and plastic garbage. Recycling is beneficial for the society but this technique generates moderate emissions (Miandad et al., 2016). Table 2 presents management strategies and societal impact of PW. A country like India's recycling industry is split between the legitimate and unofficial sectors (Zohoori & Ghani et al., 2017). Among all the PWM techniques as per Table 2, landfill disposal of PW seems to be high energy intensive whereas the mechanical and chemical recycling for the processing of PW could cause comparative low emissions as compared to landfill practices. The advantage of the complete use of PW as a filler/constituent material could be the best option as of now since the complete consumption of plastic for tar production and concrete mix designs does not cause any process emissions (Miandad et al., 2016).

Formal sectors are registered with the Government and follow the rules and tax payers but informal sectors are illegally involved which create serious negative environmental impacts (Singh and Sharma, 2016). An informal sector does not treat the PW in a scientific way and does not keep the proper data of waste. Incinerating waste is harmful for the society as this process emits harmful GHGs (Miskolczi and Nagy, 2012; Qureshi et al., 2020). During the incineration step of this process, waste is converted to ash, flue gas, and heat. Incineration is commonly used by underdeveloped countries. The oldest method of waste treatment is the burying of waste products at dumping site. Dumping sites are old and popular method to dispose off organised trash which is still in practice in many parts of the globe today (Singh and Sharma, 2016). It has major drawbacks, such as contributing to the emission of $CH_4$ and contaminates the ground water. Bioremediation emits GHGs and toxic pollutants into the atmosphere and this technique is also not useful at large-scale (Miskolczi and Nagy, 2012). Now, world uses new techniques, such as mechanical and chemical these days to reduce the quantity of PW. These techniques are far better than conventional techniques and generating energy from PW. Still more work is required to improve these techniques as these are very costly and more complex. Chemical recycling has significant impact on the environment specially with reference to the emission of GHG.

## 5. Recent technologies for PW management

Many approaches were suggested for recycling of discarded plastics including different new techniques like mechanical (sorting and reprocessing) and chemical (Fig. 4). Mechanical recycling entails isolating plastics from the impurities that are present and then processing them further using techniques like melting or shredding. Different plastic resins are separated according to their chemical orientation during the mechanical recycling of plastics. A batch of plastic resins may change completely whereas another batch may show partial variation because different melting points occur at certain temperatures. Temperature and catalyst play useful role in recycling of PW. Different plastics melt at different temperature while catalyst plays an important role to precede the specific reaction. A specific feedstock (plastic) decomposes at specific temperature and

**Table 2**
Performance indicators of various PWM techniques.

| Management strategy | Carbon emissions | Energy requirement | Cost | Impact on society | Sustainability of product | Localization | References |
|---|---|---|---|---|---|---|---|
| Landfills | High carbon emissions | Low energy requirement | Cost-effective | Pollutes the land and water | Difficult to keep landfills ecologically pleasant | Easily constructed and adopted anywhere | (Iwanczuk et al., 2015) |
| Recycling | Moderate emissions | Moderate energy required | Expensive | Prevents hazardous plastic waste | Favourable impact, plastics are continuously transformed into other products | Easily adopted anywhere | (Su et al., 2015) |
| Pyrolysis | Low levels of carbon | High energy required | Highly expensive | Produces liquid and gaseous fuels | Significant impact | Not feasible due to cost and complexity | (Wong et al., 2017) |
| Liquefaction | Low carbon emission. | Thermal degradation required high energy | Highly expensive | Produces liquid fuels and charcoal | Significant impact | Not feasible due to cost and complexity | Chen et al., 2019 |
| Use of plastic waste as a tar | Low levels of carbon emissions | Low energy required | Cost effective for mixing with tar | Increases the availability of tar | Favourable effect because roads made with plastic waste | Feasible for small scale | (Arena et al., 2009) |
| Concrete application | Negligible carbon emissions | low energy required | Low cost required | Constituent material for construction (building) | Favourable impact | Feasible for small scale | Siddique et al., 2008a, b |

converts into other product with the help of catalyst. Chemical recycling eventually leads to full or partial depolymerisation of polymers and is another significant method for recycling of plastic. The process emissions caused due to chemical reactions could be a challenging burden to make the techniques more environmentally sound. However, there is a huge scope for the chemical processing of the PW since the product and by-product of this process is useful tar and fuel/oil with comparatively good calorific value.

### 5.1. Pyrolysis

Pyrolysis (Fig. 5) is used for depolymerisation of plastic. At high temperatures (500 °C, 1–2 atm), oxygen is not present throughout the pyrolysis. In pyrolysis process, normal radical chain mechanism consists of the three steps i.e., initiation, H-abstraction, radical recombination, and b-scission. By allowing the macrostructure of the polymer to disintegrate at high temperatures, smaller molecules are produced (Angyal et al., 2007). This

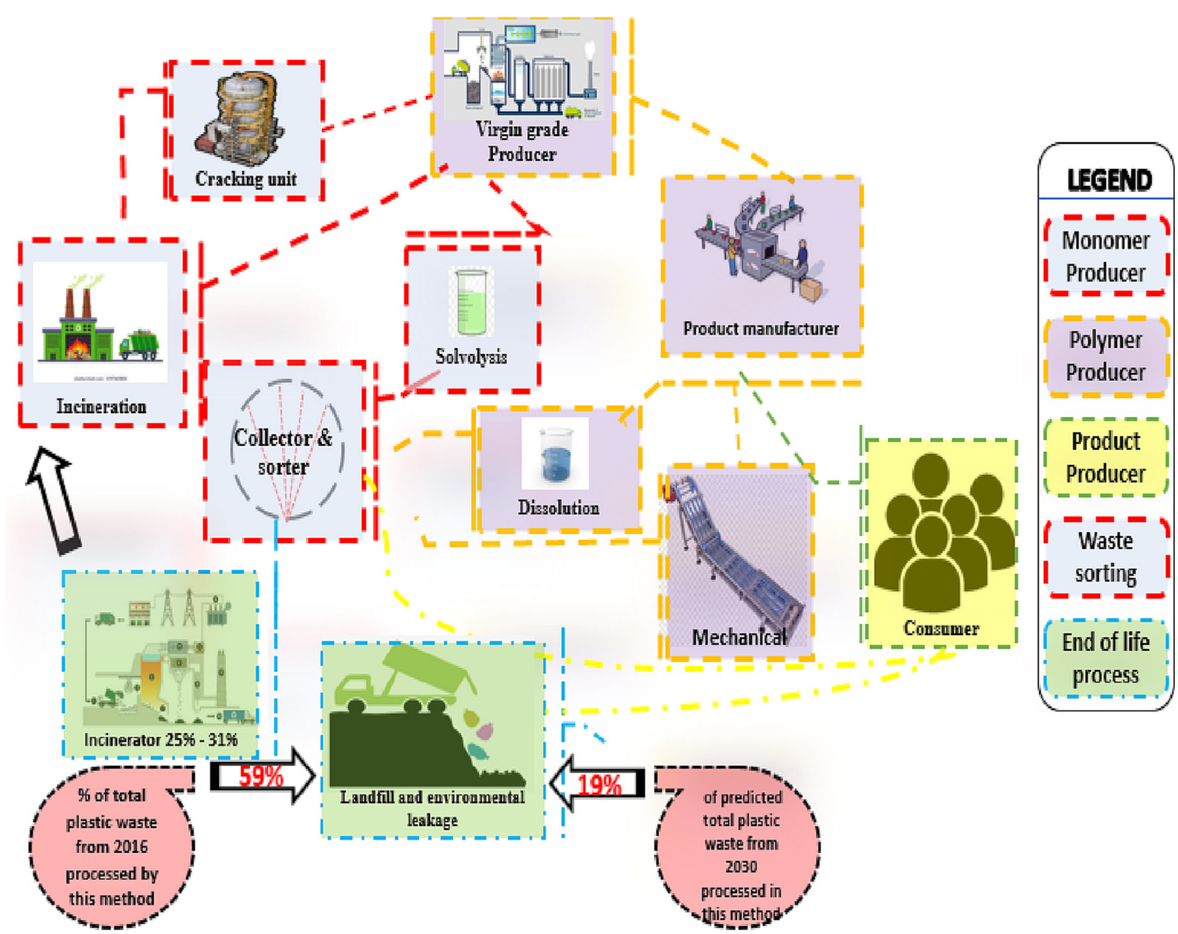


**Fig. 4.** Illustration of an envisioned plastics value-chain, transition to circularity.

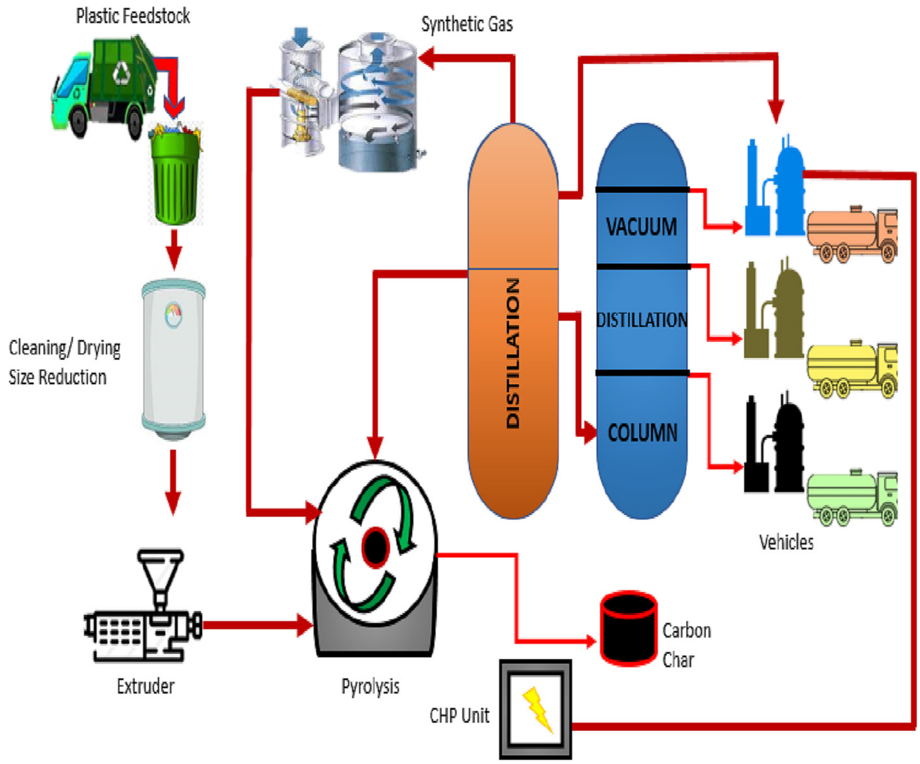


**Fig. 5.** Pyrolysis process of plastic waste.

process can handle highly polluted materials like car shredder leftovers and extremely heterogeneous combinations of plastics (Vermeulen et al., 2011). Three fractions may be created from the pyrolysis by products of P i.e.,: solid residue, gas and liquid(Al-Salem et al., 2009a, 2009b). PS, PA, PE, PP, PTFE and polymethyl methacrylate can be pyrolyzed into products that primarily contain their respective monomers. For instance, yield of PMMA pyrolysis is close to 98 % (Garforth et al., 2004). Petrochemical feeds, such as naphtha in the distillation process, are produced via pyrolysis. Despite being a straightforward process, pyrolysis is currently commercially feasible when done in huge quantities. The pyrolysis of PVC creates significant problems (Bhaskar et al., 2003; Okuwaki, 2004; Rijpkema, 1999; Sadat-Shojai and Bakhshandeh, 2011). There are many design types for the main pyrolysis reactor as given in Table 3 which provides detailed information on the types of reactor which plays an important role. If halogens are present in PW, then it could not be used as petrochemical and chlorine should not be more than 10 ppm (Bhaskar et al., 2003). Many researchers found that fluidized based bed reactors show the best choice for plastic recycling through pyrolysis because of many benefits, including identical end-product and better translation rates (Westerhout et al., 1998). Majorly pyrolysis process is influenced by temperature, structure of PW, presence of impurities and additives in the PW. The main challenges in enhancing the easiness of pyrolysis are the absence of compact and comprehensive dynamic prototypes that have been confirmed with reliable empirical data, composition and quality of PW.

### 5.2. Gasification

One of the most well-known technologies for converting a PW to fuel is gasification. The most widely used and recognised technology is the Texaco gasification method. The initial pilot-scale tests of 10 tonnes/day were conducted in the United States. Syngas is primary end product of the gasification step. In addition to $H_2$ and CO, syngas also contains trace amounts of $CH_4$, $CO_2$, and HC. Most plastic feeds are converted using this approach (Puig-Arnavat et al., 2010). It is made of organic components that underwent partial oxidation to produce a vaporous mixture that contained CO, $CO_2$, $CH_4$, $H_2$, and other light (Heidenreich and Foscolo, 2015; Kumar et al., 2009; Ruiz et al., 2013; Trippe et al., 2011). Using air has drawbacks, including greater gas flow rates and lower throughputs, which have an impact on overall costs (Wilhelm et al., 2001). Additionally, from a pollution perspective, gasification produces more NOx which needs to be closely controlled because it could be harmful to the environment. The feed passes through a number of reactions during the gasification process, some of which can be exothermic or endothermic in nature. The complete reaction is endothermic (Munasinghe and Khanal, 2010). Utilizing gasifiers improves thermal efficiency while reducing the atmospheric discharge of dangerous gases. In gasification, contaminants, such as $H_2S$, $NH_3$, alkali metals, NOx, and tars are present in the syngas that is produced ((Ruiz et al., 2013); Dudyński et al., 2015; (Spath and Dayton, 2003)). Particular focus would be placed on pollutants that are poisonous to processes (Spath and Dayton, 2003). The major cost of producing syngas is incurred during the purification phase (Haro et al., 2013; Munasinghe and Khanal, 2010; Spath and Dayton, 2003; Wilhelm et al., 2001). The molar ratio of $H_2$ to CO in syngas, which is measured for biomass, ranges from 1.5 to 1.8. Oxygen and steam are employed to gasify the substance between 1200 and 1500°C. A clean and dry synthesis gas is created after several cleaning procedures (including, among others, the removal of HF and HCl) and contains mostly $H_2$ and CO, with minor amounts of $CO_2$, $CH_4$, $H_2O$, and inert air (Brems et al., 2013).

### 5.3. Hydrocracking

The presence of hydrogen makes the catalytic breaking of PW the most notable difference (Ding et al., 1997). The reaction occurs at high temperatures (375–400°C) and elevated hydrogen pressures (about 70 atm) (Ding et al., 1997). This process involves catalyst support, and the catalyst that is frequently employed in this procedure is either Ni/S or NiMo/S. Due to the presence of inorganic components, plastics are first liquefied and filtered to eliminate non-distillable material (Ding et al., 1997). After the liquid is sent over the catalyst bed, this occurs through low temperature pyrolysis. The product quality is considerably enhanced by hydrogen. According to the experiments using various catalyst types, there is a high yield of paraffin produced, heteroatoms are handled flawlessly, and no

**Table 3**
Reactors and process parameters for conversion of PW to fuel.

| Type of plastics | Reactor | Process parameters | | | | Yield | | | References |
|---|---|---|---|---|---|---|---|---|---|
| | | Pressure | Heating rate (°C/min) | Temperature (°C) | Duration (min) | Oil (wt%) | Gas (wt%) | Solid (wt%) | |
| HDPE | Fluidized bed | – | – | 500 | 60 | 85 | 10 | 5 | (Luo et al., 2000) |
| PVC | Fixed bed | – | 10 | 500 | – | 12.3 | 87.7 | 0 | Çepelioğullar and Putun, 2013 |
| LDPE | Pressurized batch | 0.8–4.3 MPa | 10 | 425 | 60 | 89.5 | 10 | 0.5 | (Onwudili et al., 2009) |
| HDPE | Semi-batch | 1 atm | 25 | 450 | – | 91.2 | 4.1 | 4.7 | Abbas-Abadi et al., 2014 |
| HDPE | Batch | – | – | 450 | 60 | 74.5 | 5.8 | 19.7 | Miskolczi and Nagy, 2012 |
| HDPE | Semi-batch | 1 atm | 7 | 400 | – | 82 | 16 | 2 | Lee et al., 2003 |
| LDPE | Batch | – | 3 | 430 | – | 75.6 | 8.2 | 7.5 | Uddin et al., 1997 |
| HDPE | Horizontal steel | – | 20 | 350 | 30 | 80.88 | 17.24 | 1.88 | (Ahmad et al., 2015) |
| PP | Batch | 1 atm | 3 | 380 | – | 80.1 | 6.6 | 13.3 | (Sakata et al., 1999) |
| PP | Horizontal steel | – | 20 | 300 | 30 | 69.82 | 28.84 | 1.34 | Abbas-Abadi et al., 2014 |
| HDPE | Batch | – | 5 | 550 | – | 84.7 | 16.3 | 0 | Marcilla et al., 2004 |
| PET | – | 1 atm | 6 | 500 | – | 38.89 | 52.13 | 8.98 | Fakhr Hoseini and Dastanian, 2013 |
| HDPE | Fluidized bed | – | – | 650 | 20–25 | 68.5 | 31.5 | 0 | Mastral et al., 2003 |
| LDPE | Fixed bed | – | 10 | 500 | 20 | 95 | 5 | 0 | Bagri and Williams, 2002 |
| PVC | Vacuum batch | 2 kPa | 10 | 520 | – | 12.79 | 0.34 | 28.13 | Miranda et al., 1999 |
| PET | Fixed bed | – | 10 | 500 | – | 23.1 | 76.9 | 0 | Çepelioğullar and Putun, 2013 |

harmful by-products like dioxins are created during this process (Ding et al., 1997). The ability to create high-quality naphtha feed and use of PW mixes are two benefits of hydrocracking.

### *5.4. Integrated hydro pyrolysis and hydro conversion (IH2)*

IH2, sometimes referred to as integrated hydro conversion and hydro pyrolysis, is a catalytic thermo-chemical conversion method that may turn organic fractions into a variety of hydrocarbon fuels. Gas Technology Institute of Des Plaines is the organisation created this technology (Ragaert et al., 2017). Three reactors make up this process i.e., a fluidized bed reactor for hydro pyrolysis, a hydro conversion reactor, and a reactor for reforming (Marker et al., 2013; Marker et al., 2012). At temperatures between 400 and 500 °C and pressures between 15 and 35 atm, this approach is effective. Consequently, in a manner comparable to rapid pyrolysis, the hydro pyrolysis reactor releases VOCs, and in the gas phase, molecules interact with the catalyst and hydrogen. As a result of deoxygenation, oxygen atoms are converted to $CO_2$ and water. These exothermic events balance out pyrolysis's endothermic nature (Marker et al., 2013; Marker et al., 2012). In the second reactor, a fixed bed reactor, a CRI-exclusive catalyst is utilised more. This stage sees a further decrease in the number of hetero-atoms, with the oxygen concentration falling from about 2.7 wt% to under 1 wt% (Marker et al., 2013). Gas and liquid streams are separated, and the product stream is condensed. The liquid is composed of two phases i.e., an aqueous phase and an organic phase with extremely little oxygen. Small molecules like $CH_4$, ethane, propane, CO, and $CO_2$ are present in the gas stream (Puig-Arnavatet al., 2010). The produced water and the gas are both fed to a steam reformer. Hydrogen can be produced in sufficient quantities by the steam reformer for hydro pyrolysis and hydro conversion. To do this, a suitable hydro pyrolysis catalyst must be used, and the hydro pyrolysis reactor's operating parameters must be chosen in a way that balances the hydrogen-free decarboxylation reactions with the hydrogen-consuming dehydration events (Puig-Arnavatet al., 2010). The IH2 technique allows for the direct synthesis of liquid hydrocarbons from PW, much like pyrolysis followed by hydrotreatment (Puig-Arnavatet al., 2010).

### *5.5. KDV (Katalytische Drucklose Verölung) method*

The German company Alphakat GmbH invented KDV (Ragaert et al., 2017). It promotes the almost atmospheric pressure catalytic conversion of biomass and PW into liquid fuels. Since oxygen atoms are almost entirely removed during this procedure, the resultant liquid fuel can be used right away in typical internal combustion engines (Ragaert et al., 2017). With the use of this technology, petroleum, diesel, and kerosene can be produced from any kind of substrate that contains hydrocarbons, both organic and mineral-derived. PET and PP are used in the KDV process as a feedstock (Fakhrai and Saadatfar, 2015). For this procedure, a pre-treatment was necessary to get the water content down to about 5 % weight percent and the particle diameter down to less than 3 mm. After that, carrier oil is heated to 180 °C and combined with the shredded PW, lime and catalyst (Broach et al., 2012). The catalyst in this process is sodium mineralized doped zeolite of type Y with faujasite structure, which is a 100 % crystalline alkali-doped aluminium silicate. The creators assert that using this naturally occurring catalyst will hasten the imitation of the natural process of oil generation (Koch, 2011). To maintain the pH at a level of about 9, which is the ideal setting for the catalytic process, $Ca(OH)_2$ lime is added. The oil mixture is then sent to the turbine reactor, which is then heated to a temperature of 250°C. KDV diesel's high sulphur concentration causes problems (Koch, 2011). The sulphur concentration is routinely found to be high while being highly reliant on the nature of feed material. Another problem is the cetane number, which is typically a little lower than what the European Standards. Higher HC, NOx, and CO emissions compared to conventional diesel were observed. Despite the fact that these emissions would not exceed the allowable emission limits (Labeckas and Slavinskas, 2013). It is shown that the KDV technique can turn Solid Recovery Fuel (SRF) into synthetic fuel (Gonzalez-Quiroga et al., 2016). The studies on KDV reactor's reactions are not thoroughly researched.

## 6. Different degradation technologies of PW

### *6.1. Degradation with invertebrates*

Researchers discovered that some beetles and their larvae, particularly those belonging to the *Dermestidae, Anobiidae* and *Tenebrionidae* families, have intriguing capacity to consume plastic Gerhardt and Lindgren, 1954). (Yang et al., 2014) identified the microbial species that can dissolve PE films in the intestines of wax worms. Additionally, it is discovered that *Kosakonia* sp. and *Citrobacter* sp. are both associated with the degradation of PE and PS (Brandon et al., 2018). YP1 and Enterobacter YT1 are the predominate bacteria in the stomach that break down PE. *Kosakonia* sp. and *Citrobacter* sp. are the microorganisms that break down both PE and PS. Mealworms were also utilised by Brandon et al. (Brandon et al., 2018) to break down both PE and PS, and they discovered that PE degrades at a rate like that of PS. Only few researchers described that mealworms consume plastic, but still no attempts have been made to understand the mechanism (Brandon et al., 2018). Recently, it has been discovered that about half of the polystyrene consumed by super worms which is transformed to $CO_2$ by mealworm gut bacteria. Only PS and PE have been explored because this technology is still relatively new, but it should be further investigated whether some particular species of microbes in particular invertebrates can break down the majority of PW. To increase the technology in industrial application, further study on it should examine more types of plastics employed to more invertebrate species.

### 6.2. Degradation with microorganism

Microorganism used for PW degradation, decomposable materials are needed which gets mineralized throughout the biodegradation process into water and biomass (CEN/TR 15351, 2006). Fig. 6 shows the degradation process of PW with microorganism. Generally, there are four phases in the biodegradation of polymers (Lim and San, 2022): (1) Bio-deterioration, where organisms conceal extracellular enzymes that catalyse and degrade the polymer surfaces in smaller particles; (2) Biofilms can depolymerize microorganisms in polymer chains by converting them to oligomers, dimers, or monomers; and (3) Bio-assimilation, in which microbial cells absorb the small molecules created during the disaggregation process to create new molecules. Under aerobic settings, microbes typically mineralize organic molecules into $H_2O$ and $CO_2$, but in anaerobic conditions, $H_2O$, $CH_4$ and $CO_2$ are created (Shah et al., 2008). Numerous factors, including the biochemical composition, additives of the plastic, thickness and molecular weight might affect how quickly microorganisms degrade plastics. Plastics typically require a lot of time to degrade microbiologically. Only few researches have examined the final mineralization of plastic following microbial breakdown. In order to boost industrial viability, research should concentrate on breeding microorganisms that can quickly destroy plastics.

### 6.3. Treatment with composting

Composting is used to treat the plastic, which can stop plastic from degrading and turns it into something that resembles composting fungus (Shah et al., 2008). A specific weight of no-moisture plastic is added to a predetermined volume of degraded compost, and the combination is heated to a high or intermediate temperature to treat it with the microorganisms which is already present over 50 °C (Semitela et al., 2019). The mesophilic and thermophilic microorganisms including microorganism, actinomycetes and fungusare are included in PW composting (Sharma et al., 2014). When plastic is composted, the water content is preserved (~60–80 %), and after a predetermined amount of time, it transforms into biomass, $CO_2$, minerals, $H_2O$and $CH_4$ (Shah et al., 2008). Due to the limited availability of land resources, PW composting offers many possibilities for the management of plastics in the upcoming events.

### 6.4. Oxo-biodegradation of plastic

PW can be broken down via bacteria. Some studies have been done on oxo-biodegradation, which breaks down plastic in two stages i.e., abiotic and biotic degradation (Ammala et al., 2011). This process takes place in two stages. At the initial stage, the PWs are biodegraded and then further microorganisms are used. According to the studies, the effectiveness of the abiotic degradation stage has an impact on the overall effectiveness of oxo-biodegradation (Wiles and Scott, 2006). The oxo-biodegradation has a special quality that can not only significantly shorten the time needed for plastic microbiological deterioration but also makes it easier to turn plastics into safe products. This process could be best for PW treatment.

## 7. Technological options and applications

PW is used in different applications which could be utilised as bitumen road, concrete and fuel production.

### 7.1. Polymer blended bitumen road

PW is co-processed with other substances which are chemically active, trace metals and large amount of tar is formed (Arena et al., 2009; Mastellone and Arena, 2008). Tar is used extensively and contributes in different industries, despite having a negative impact on gas producing plants. Tar has numerous uses, such as coatings industry, to treat human and plant ailments and it is also used for road construction (Kurt and Isik, 2012; Limantara et al., 2019; Siham et al., 2008). The potential expenses of PW segregation are also reduced by adopting a mixed plastic feed tar. One kilometre of paved road requires almost one tonne of PW (Manju et al., 2017). The use of PW during the construction of roads was found to save roughly US $40,000 every kilometre of road (Bondre et al., 2015). Roads made of plastic survive longer and are more resistant to ultraviolet light (Jafar, 2016; Behl et al., 2014). Some countries like India, Netherlands, and United Kingdom have adopted PW in road construction (Hongthong et al., 2020).

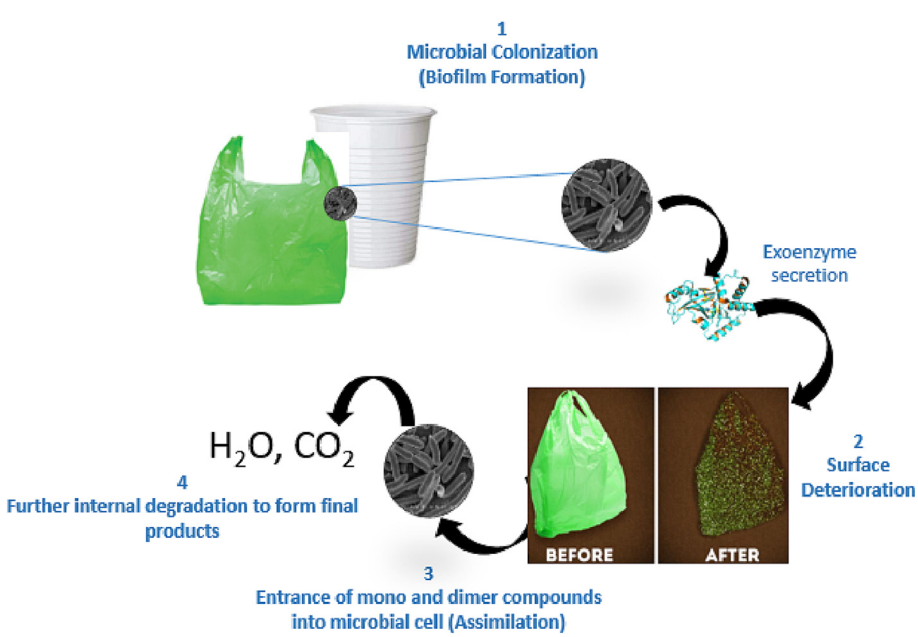


**Fig. 6.** Microbial degradation of PW into the environment.

### 7.2. PW as a concrete production

PW is used as an alternative for the production of concrete (Mohammed et al., 2019; Manjunath, 2016; Basha et al., 2020). It has a negative impact on the strength of concrete (Liguori et al., 2014). PW may be utilised in concrete applications when lower pressures are applied and stability is not as important (Gu and Ozbakkaloglu, 2016). Concrete made with PW is an appropriate for thermal and insulating purposes (Rahman et al., 2012; Rahmani et al., 2013; Yesilata et al., 2009). Utilizing PW in concrete will be helpful for reducing the price of production and natural resources. However, because of the significant reduction in strength, it is not used in large amount in concrete. Typically, a material with appropriate mechanical characteristics can be produced with a replacing ratio of 10.0–15.0 % of PW (Kaur and Pavia, 2020; Ferreira et al., 2012; Yang et al., 2015). Researchers have developed new uses for PW in construction, including the use of plastic materials in concrete blocks and bricks and plastic wires in concrete (Safinia and Alkalbani, 2016; Sharma and Bansal, 2016; Babafemi et al., 2018; Mokhtar et al., 2016).

### 7.3. Conversion of PW into fuel

Conversion of PW polymers into liquid fuel is liquefaction which could be used for various activities. Different approaches are used for liquefaction process. The common technologies for liquefaction of biomass are indirect liquefaction (Fischer-Tropsch) and direct liquefaction (hydrolysis fermentation and thermodynamic) (Tiwari et al., 2023). Thermodynamic liquefactions are divided into pyrolysis and hydrothermal liquefaction techniques, which have been modified to consume PW, and are especially exciting because it makes liquid fuel (Prawisudha et al., 2012). The components are distributed more evenly across the products as a result of biomass liquefaction than they are competing waste-to-value methods (Yang et al., 2016). Every liquefaction technique requires a precursor/catalyst, which is essential and significantly affects the effectiveness of the procedure. Mixed catalysts are typically employed in the liquefaction method to minimise corrosion risk and enhance reaction interactions (Xu et al., 2018). The three processes that make up a hydrothermal system are depolymerization, disassociation, and recombination. The production of coke tends to be decreased when polymers are used in the liquefaction process. As a result, there are two advantages to employing plastics in liquefaction i.e., PW recycling and development of current liquefaction yields (Hongthong et al., 2020; Zhang et al., 2016; Manju et al., 2017; Vasudevan et al., 2012).

## 8. Economic and ecological aspects

The economy is currently based on a linear paradigm that extracts natural resources, converts, consumes, and then discards it **(**Fig. 7**)**. Material recovery is one of the key pillars of the circular economy (Steyn et al., 2021). Usage of recycled PW can help to safeguard the natural resources. PW has no value at all or very little, therefore using it in the production of other products reduces the need for raw resources and lowers the cost (Al-Maaded et al., 2012; Awoyera and Adesina, 2020a, 2020b). PW management is categorised into major categories like recycling, dumping, fuel production, tar and road manufacturing and concrete production. Table 4 provides mechanical and chemical processes, advantages and challenges of PW conversion. By using recycled PW, sustainable items may be produced at a lower cost. On the other hand, recycling PW for a variety of uses might solve the problems with landfill disposal. PW and fly ash is used to produce concrete and fuel these days (Chen, 2018). Circular economy aids in the protection of finite fresh material supplies. Such a strategy supports the preservation of useful materials in opposition to the culture of

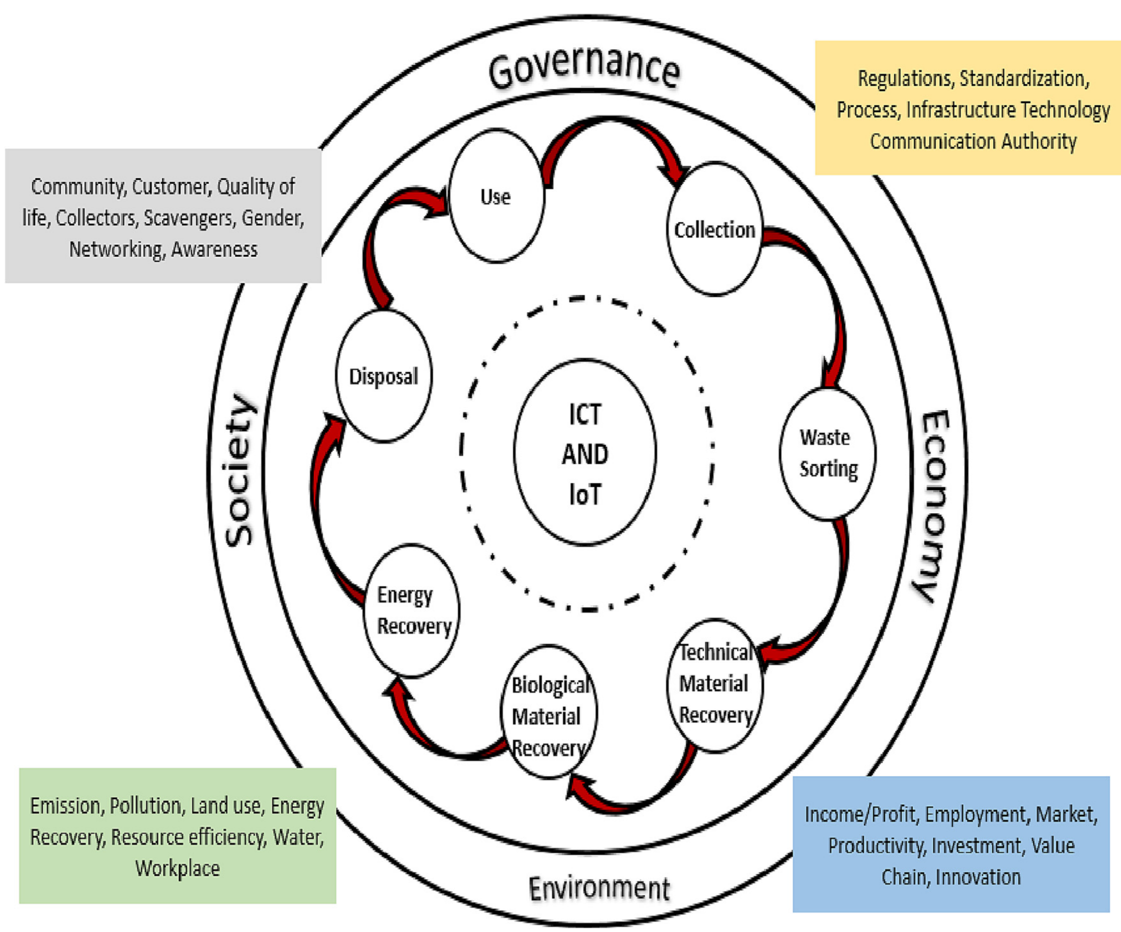


**Fig. 7.** Structure of a smart, sustainable waste management system.

**Table 4**
Mechanical and chemical processes, advantages and challenges of PW conversion.

| Processes | Types | Techniques | Advantages | Challenges | References |
|---|---|---|---|---|---|
| Machine-driven recycling | Sorting | Flotation | Profitable | Limited to dual mixtures | (Letcher, 2020) |
| | | Dissolve filtration | To remove non-melting components | Extruded flexibility is difficult | (Das et al., 2021) |
| | | FT-NIR | Processed drying of product not required | Only Dry Untraceable Plastic is preferred | (Alassali et al., 2018) |
| | | Tribo-electric | All sized plastics are allowed | Pre-treatment and precursor steps are required. | (Li et al., 2015) |
| | | Magnetic density separation | All sized plastics are allowed | Continued density overlaps happens | (Bakker et al., 2009) |
| | | X-ray detection | Accuracy for PVC | Affordable | (Turku et al., 2017) |
| | Reprocessing | | High end recycling is possible | Thermo-mechanical is challenging for heterogeneous mixer of plastic | (Ragaert et al., 2017) |
| Chemical recycling | Chemolysis | | High-end value added products could be produced | Only adequate for condensation of polymers | (Huang et al., 2022) |
| | Pyrolysis | | All sized plastics are allowed | Reaction inadequacy and costly technique | (Rajmohan et al., 2019) |
| | Fluid Catalytic cracking | | Unfeasible for better product recovery | Catalyst deactivation happens and no suitable reactor expertise could be attained | (Papari et al., 2021) |
| | Hydrogen based technologies | Hydrocracking | Inappropriate quality of naphta Suitable for mixtures of plastics | High cost of hydrogen. Cost ineffective | (Kartik et al., 2022) |
| | KDV method | $IH_2$ process | Efficient technique for development of fuel | Technological deficiencies | (Gaur et al., 2020) |
| | Gasification | | Syngas is a well-known technology | Large amount of NOx | (Zhu et al., 2015) |

constant consumption. Contrary to the linear economy, one of the fundamental sustainability principles is to treat natural assets as a valued series of resources and to develop with minimal damage (Howard, 2002). The intricacy of developing these systems, requiring innovation research as well as the work of economists and environmentalists, must also be highlighted (Darko et al., 2019). Maintaining a clean consumable flow will increase the effectiveness of PW recycling. To prevent resource stagnation, it is also necessary to reduce the stock in use so that the cost of secondary materials, which are recycled, is kept lower (Ahmad et al., 2021). The impact of variables including the need for land, energy needs, carbon emissions, the demand for skilled labour, costs, localization, the sustainability of the products, and repercussions on society can be demonstrated using comparative models (Enkvist & Klevnäs, 2018). Utilizing plastic-to-fuel techniques can greatly reduce the need for fossil fuels as an energy source. Pyrolysis and liquefaction are advantageous and efficient technologies because they can potentially recover energy and produce significant second products (fuel and char) (Enkvist & Klevnäs, 2018).

## 9. Challenges and perspectives

Numerous PW management strategies, recycling techniques and its application were discussed in this review. From the review, it was found that PW recycling technologies harm environment in terms of air, water and land pollution. From the literature, it was observed that incineration and dumping yards are not environment friendly. The conventional recycling of PW emits large amount of GHGs which harm the society. PW sorting is crucial in mechanical and chemical process to maximise the cost and rate of plastic garbage. Pyrolysis and liquefaction techniques are best in comparison to other techniques, but these are costly and the presence of contaminants in the PW affect the catalytic pyrolysis mechanism. Consequently, its operating procedure is completive which disperse the growth of products. Oxo-biodegradation of plastic is the best way for PW decomposition. Additionally, at the laboratory scale, it seems easy to get a satisfactory product development and composition, but industrial producers will have trouble achieving the appropriate outcome. To ensure the process viability, it is necessary to understand and regulate the effects of each of these variables (Temperature, catalyst, reactor, LCA of plastic). In order to develop solutions that can maintain the value of PW through repeated uses and reprocessing, it is better to understand the life cycle of PW. This consistency will lead to higher recycling proportions, more reused material in finished goods, and decrease the cost of plastic that is exported, disposed off in landfills, and burned. If these challenges are surmounted, it will be feasible to reduce imports of crude oil, reduce PW, the main cause of environmental pollution, and achieve a cost-effective, fractional replacement of decreasing fossil fuels. In order to decrease the quantity of PW, there is clear industry intent to switch to a circular economic model.

## 10. Conclusion

Mechanical or chemical methods may be used to facilitate the circular flow of recycled plastic throughout the industrial process chain. But it appears that inefficient recycling procedures are being made possible by managing the plastic garbage. Sorting and segregating PWs are crucial processes that could speed up the recycling process. Plastic's end of life could also be taken into account while using it to create high-value goods like fuel, concrete, and road tar fillers provided that there is a call for policy on source based waste segregation by implementing practices at the source point and capacity building among the plastic users. It is inferred that mechanical and chemical recycling have their own importance based on type, source, feasibility and requirement of the future demand.

## CRediT authorship contribution statement

**Rahul Tiwari**: Conceptualization, Writing–original draft, Methodology. **NumanuddinAzad**: Methodology, Writing–review & editing. **Deblina Dutta**:Writing–review & editing. **Bholu Ram Yadav**: Investigation, Supervision. **Sunil Kumar**: Supervision and editing.

## Data availability

All the data are provided.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

The authors would like to convey their special appreciation to Waste Reprocessing Division of CSIR-NEERI, Nagpur, India for providing the infrastructural facilities. The authors are also thankful to UNEP Geneva for funding the project entitled "Developing an Innovative Method for Improved Plastic Waste Management in India" through CSIR-NEERI's project number GAP-2707.

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