

Review on Advanced Plastic Waste Recycling Technologies

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Abstract — The rapid growth in plastic production and consumption has resulted in a substantial increase in plastic waste, creating serious environmental and resource-management concerns. Conventional mechanical recycling is an important method for recovering plastic materials; however, its effectiveness is limited when dealing with contaminated, mixed, multilayer, and repeatedly processed plastics. In response to these limitations, advanced recycling technologies are being developed to improve material recovery and enable the conversion of difficult plastic waste into useful resources. This review examines emerging plastic waste recycling techniques, including pyrolysis, gasification, chemical depolymerization, and solvent-based recycling. These processes can transform waste plastics into valuable products such as fuels, chemical feed stocks, monomers, and reusable polymer materials. In addition, developments in automated sorting, artificial intelligence, robotics, and advanced separation systems are improving the identification and processing of different plastic types. The review also considers the environmental and industrial significance of these technologies in supporting resource conservation and circular-economy practices. However, the large-scale application of advanced recycling remains associated with challenges such as high capital requirements, energy consumption, process complexity, variations in waste composition, and insufficient collection and recycling infrastructure. Effective implementation therefore requires improvements in technology, waste segregation, process efficiency, economic feasibility, and regulatory support. Overall, advanced plastic recycling technologies provide promising pathways for managing complex plastic waste and recovering valuable resources. Their integration with efficient waste-management systems and circular-economy strategies can contribute to reducing plastic pollution and promoting more sustainable utilization of plastic resources.

Keywords: Plastic Waste, Mechanical Recycling, Chemical Recycling, Pyrolysis, Depolymerization, Gasification, Biological Recycling

I. INTRODUCTION

With Rise in the Demand of the plastic over last 60 years in the different applications due to inexpensive, lightweight and durable and can readily be moulded into a variety of product [1]. This plastics are nothing but by product of world oil and gas production, which are the hydrogen based monomers that can be converted into polymers by polymerisation process to tackle ongoing packaging day to day used products medical and many more fields which is a derivative of a non-renewable resource [1]. From 1950-2015 Global production of plastic is 8300 million metric tonnes which bio accumulate across all levels including human bodies affecting total earth biodiversity at critical level [2]. Nowadays, global economy is playing around plastic production and damage by it to ecosystem [3] and human health. Only 9% of plastic is

recycled [2], and other is landfilled, send to marine environment and incineration but still it is merely impossible to recycle plastic waste even though OECD policy scenario towards 2060[3]. Most of the plastic used in day to day life is categories under different types such as polypropylene(PP), Low Density Polyethylene(LDPE), High Density Polyethylene(HDPE) etc, depending upon the use and application[4]

A. Plastic generation

1) Global Plastic Waste

- The world produces over 400 million tonnes of plastic each year.
- Around 350–360 million tonnes become plastic waste annually.
- Only about 9% of plastic waste is recycled globally.
- Approximately 19% is incinerated, around 50% goes to sanitary landfills, and the remainder is dumped, openly burned, or leaks into the environment.
- An estimated 11 million tonnes of plastic enter oceans each year, harming marine life and ecosystems.
- Single-use plastics account for a significant share of plastic pollution.[5]

2) Plastic Waste in India

- India generates approximately 10–12 million tonnes of plastic waste annually (recent estimates vary by source and year).
- Plastic waste generation is increasing due to urbanization, population growth, and higher consumption.
- Packaging is the largest contributor to plastic waste.
- Many cities face challenges in collecting and processing plastic waste effectively.[5]

3) Waste Management Techniques:

Plastic recycling falls into four categories:

Primary, Secondary, Tertiary, And Quaternary - Each Has Its Own Processes and goals:

- Primary recycling: Primary recycling is the process of recycling clean, uncontaminated, and single-type plastic waste (usually manufacturing scrap) into products with properties similar to the original materials
- Secondary recycling: Secondary recycling involves mechanically processing post-consumer plastic waste into new products without changing its chemical structure. The recycled plastic usually has lower quality than the original material.
- Tertiary recycling: Tertiary recycling breaks plastic polymers into monomers or other valuable chemicals using chemical or thermal processes. These products can be used to produce new plastics or fuels.
- Quaternary recycling: Quaternary recycling recovers energy from plastic waste by controlled combustion or other thermal processes when material recycling is not feasible

From 1950-2023 Whatever may be the plastic production sited above will be managed as per the follows-

Sr no	Waste Management	Percentage
1.	Incineration	10%
2.	Recycling	5%
3.	Landfilling	35%
4.	Mismanagement	25%

Table 1: Waste Management of Plastic Waste [4]

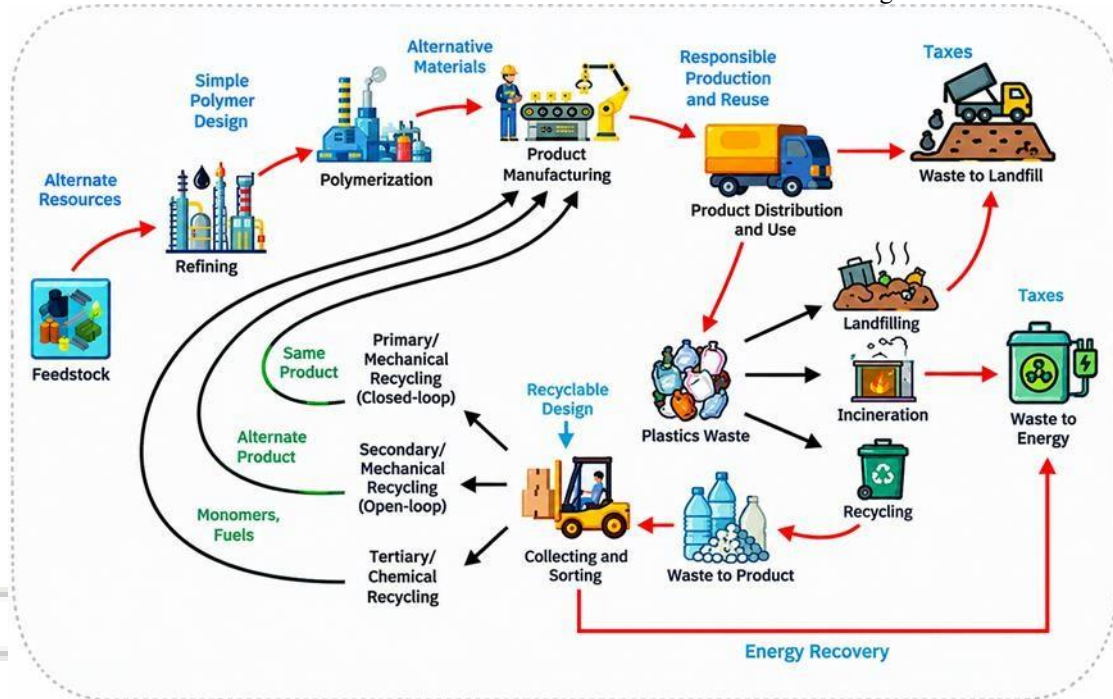


Fig. 1: Plastic Waste Management Techniques [4]

B. Incineration

During incineration, plastics cause permanent damage to the combustion heater in the flue systems and the resulting combustion products pose a serious threat to both humans and the environment. The burning of plastics is a complex chemical process. Depending on their structure, plastics can be micro-molecular or macro-molecular compounds. During plastic combustion, different phases take place, such as

warming, degradation, flashover, combustion – all which are present at the same time. Low-molecular compounds can be vaporized directly in the air, and depending on their variety, are able to form a combustible mixture, or oxidize in solid form. Macro-molecular plastics have to decompose into small molecule compounds to initiate the combustion process. Burning is accompanied by the formation of chark, coking extent depends on the conditions of combustion.

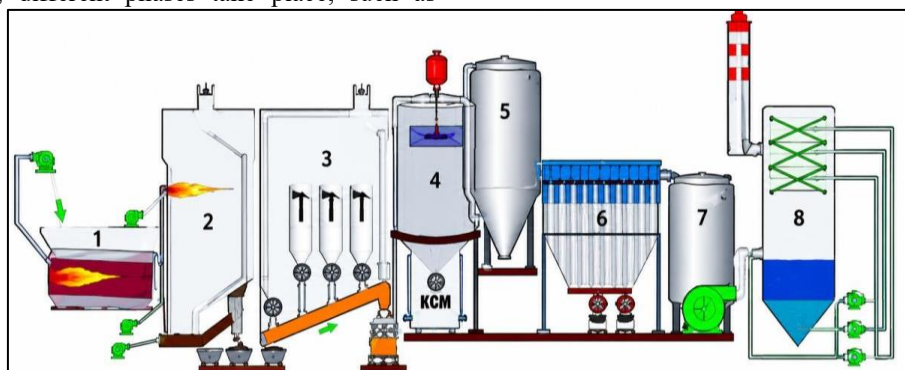


Fig. 2: Plastic Waste Incineration [8]

C. Recycling

Along with different methods of recycling that is primary, secondary, etc plastic waste management is broadly classified into different categories depending upon the types of processes we adopted as shown in fig. no [3] above are:

1) Mechanical Recycling

- 2) Thermolysis
- 3) Chemical Depolymerization
- 4) Biological Recycling[2]

This section highlights recent technological advances in the field, including mechanical recycling, thermolysis, chemical de-polymerization and biological recycling.

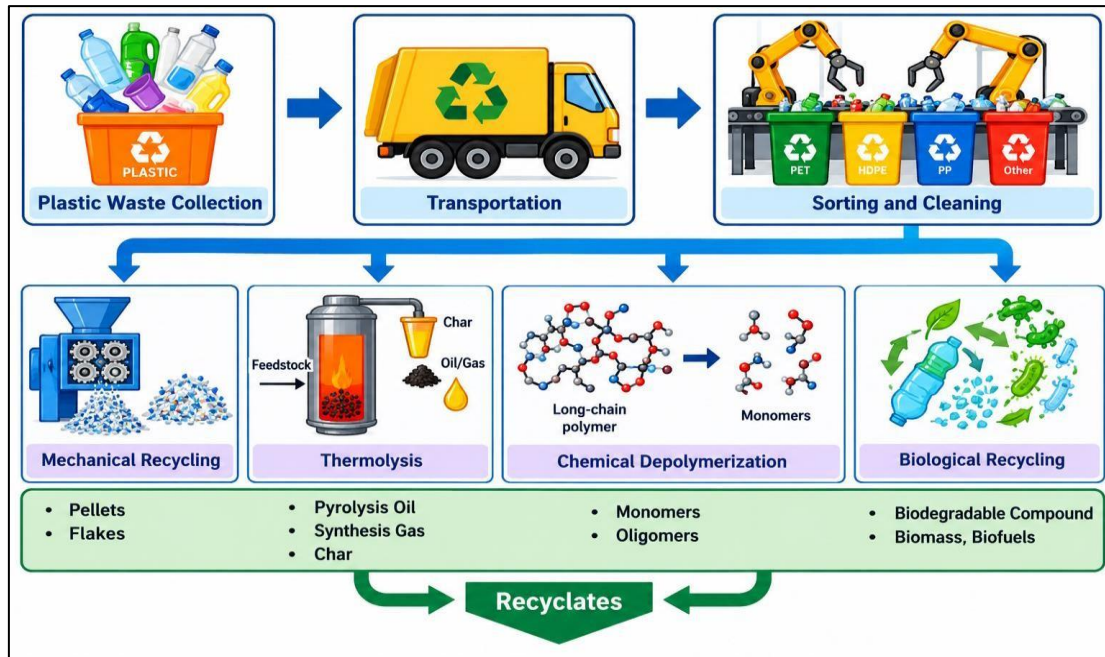


Fig. 3: Classification of Plastic Recycling Methods [2]

1) *Mechanical Recycling:*

Particularly developed country where large infrastructure and selective waste collection is available then mechanical recycling process is generally adopted. The procedure starts with collecting and sorting plastic waste based on its

composition and colour. Subsequently, the sorted plastics are washed to remove contaminants, labels and adhesives and then shredded or ground into smaller pieces. These fragments are melted and extruded to form pellets or flakes, which serve as raw materials for new plastic products.

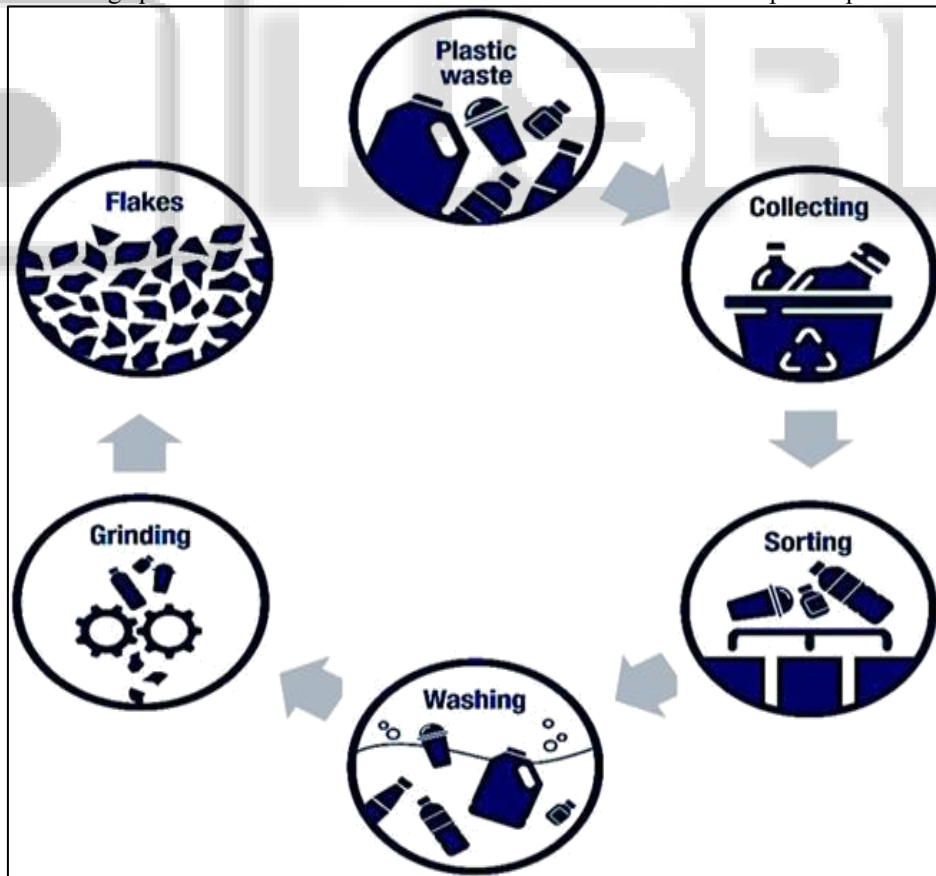


Fig. 4: Mechanical Recycling Process [2]

2) Chemical Recycling:

By using different chemical processes (Biological and Environment friendly) plastics like polyethylene(PE) and polypropylene (PP) are recycled.

Different chemical recycling processes are as follows:

- 1) Chemolysis
- 2) Pyrolysis
- 3) Gasification
- 4) Depolymerisation
- 5) Solvent Based purification

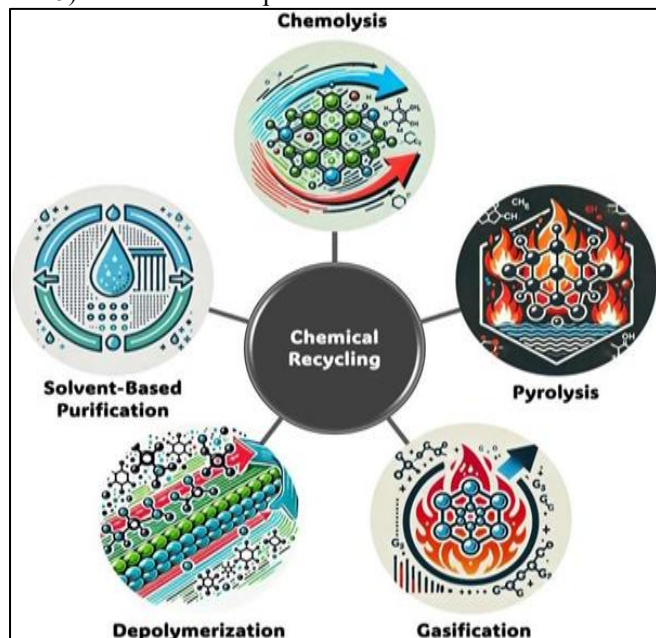


Fig. 5: Chemical Recycling Processes [2]

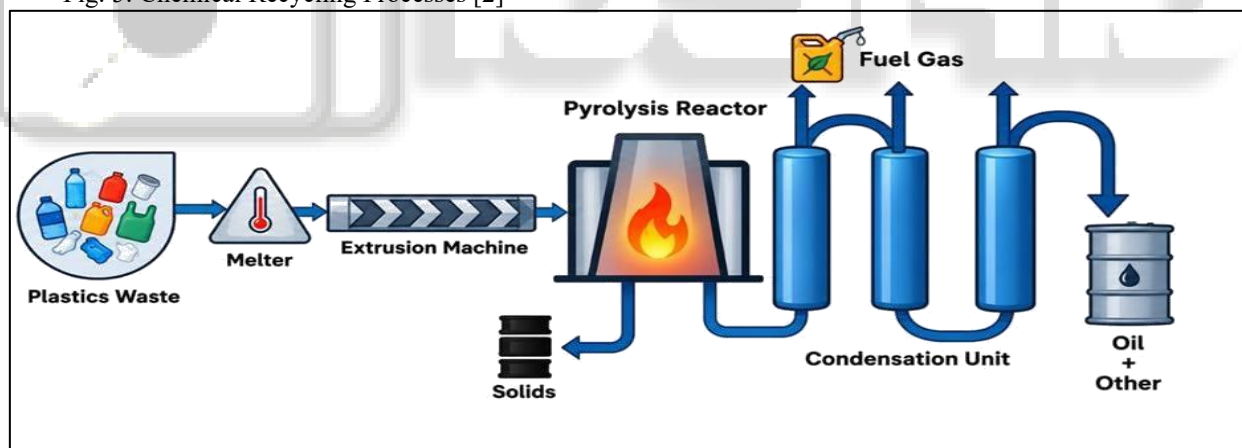


Fig. 6: Pyrolysis Process for Plastic Waste [2]

B. Solvolysis / Depolymerization:

Solvolysis, sometimes called molecular disassembly, uses chemical agents to break down plastic polymers into their original monomer building blocks. Same as that of Pyrolysis, it also uses high heat to breakdown monomers under a different solvolysis type, mainly chemolysis, Hydrolysis, ethanolysis, glycolysis, Aminolysis, between the temperature to 80-280 °C for recovering the monomers, but due to some chemicals involve like Terephthalic acid, which is not much more popular. Unlike pyrolysis, which relies on high heat, solvolysis degrades plastics like PET at lower temperatures by targeting and splitting specific bonds in the polymer chain.

II. ADVANCE CHEMICAL RECYCLING

A. Pyrolysis:

Under the high-pressure heating with oxygen-free environment, plastic is broken down into lighter components with the help of a catalyst, called as Pyrolysis. The intense heat causes a molecule to change through hydrogen transfer with decarboxylation, with the release of CO₂, is the limitation of the incineration process. It is a process that uses heat to break down (300–900 °C), basically suited for PET plastic polymers into smaller molecules. By heating plastics under high pressure with a catalyst in an oxygen-free environment, their molecular chains split into lighter compounds. For PET plastics, pyrolysis often results in random chain breaking, creating chemicals of different sizes. However, the intense heat can cause molecular changes through hydrogen transfer and decarboxylation, which releases CO₂, potentially increasing emissions and complicating the process. This makes PET less suitable for pyrolysis. The method typically involves heating large polymer chains to 300–900 °C in an inert gas setting to break them into smaller pieces, producing valuable products like liquid fuels and combustible gases for energy.⁵⁸ It works especially well for hydrocarbon-based plastics like polyethylene (PE), polypropylene (PP), and PET. (1) Random chain breaking (fragmentation), (2) splitting at the chain ends (Depolymerization), (3) forming bonds between chains (network formation), and (4) stripping off side groups (chain-stripping). Each polymer's unique molecular structure determines which of these pathways it follows during decomposition.

There are several solvolysis methods, each producing different end products. This process allows for rebuilding polymers, such as turning PET back into terephthalic acid.

Chemolysis, another term for solvolysis or depolymerization, chemically breaks plastics down into monomers at temperatures between 80–280 °C.^{8,63} The efficiency of recovering monomers depends heavily on the type of plastic, which makes processing mixed waste tricky. Because of this, chemolysis isn't as widely used as traditional recycling methods. Still, some countries and companies take advantage of its unique benefits, using specific chemical processes like glycolytic, methanolytic, hydrolytic, or alcoholic decomposition.

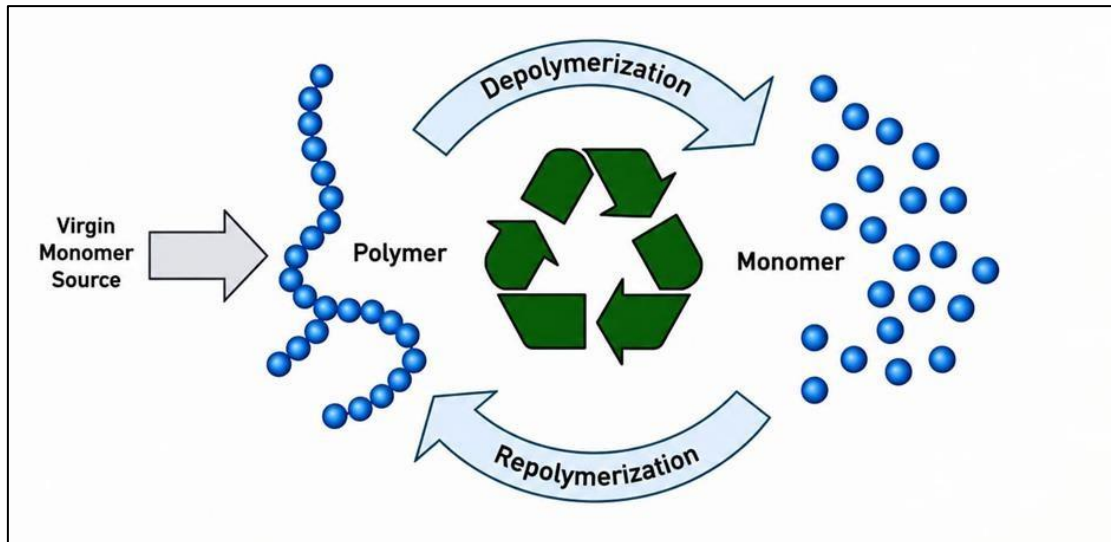


Fig. 7: Solvolysis / Depolymerization Process [2]

C. Gasification:

Besides Pyrolysis, Incineration, Solvolysis Gasification is a heat offering methods to breakdown a plastic waste and converting it into syngas which is a mixture of gases like CO₂, CH₄, Water vapours etc. These gases are condensable and non-condensable obtain at the working temperature of 1200- 1500 °C. Gasification is another way to break down materials using heat, offering a solid alternative to methods like pyrolysis and hydrocracking. It works by turning raw materials into syngas a mix of gases like carbon dioxide, water vapor, and methane through reactions with oxygen at high temperatures.⁶⁴ Industries use various gasification techniques, such as the Texaco, Akzo, and Battelle systems.^{65,66} The Texaco method is particularly popular.

This approach involves two main steps: liquefaction and entrained-low gasification. In the liquefaction phase, plastics are heated and broken down into tiny particles, producing both condensable gases (which can turn into liquids) and non-condensable gases, along with a thick synthetic crude. The non-condensable gases are reused as an energy source, while the condensed vapors and oil move on to the gasification unit. This unit operates at scorching temperatures of 1200– 1500 °C, using steam and oxygen, and includes a purification step to remove harmful contaminants like hydrogen fluoride and chloride. The end result is purified synthesis gas, mostly made up of hydrogen and carbon monoxide, with small amounts of carbon dioxide, water vapor, methane, and trace gases

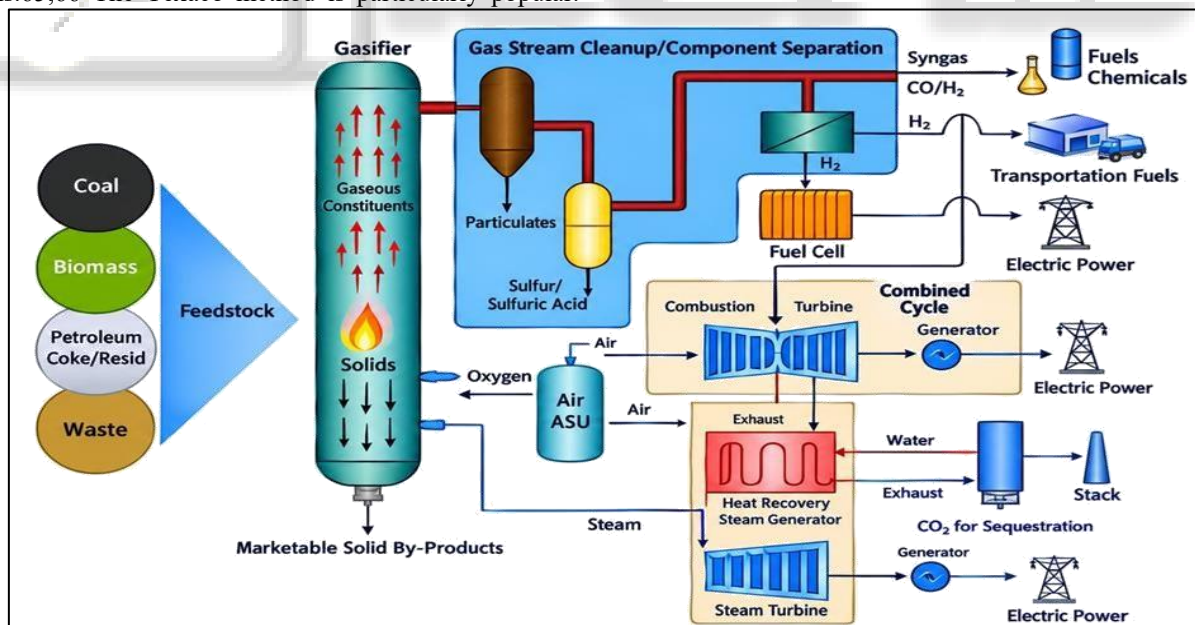


Fig. 8: Gasification of Plastic Waste [2]

III. ADVANTAGES, DISADVANTAGES AND FUTURE SCOPE

Advanced plastic waste recycling technologies offer several advantages for effective plastic waste management. They can process difficult, mixed, and contaminated plastics that are

not easily handled by conventional mechanical recycling. Technologies such as pyrolysis, gasification, and depolymerization can convert plastic waste into useful products including fuels, hydrocarbons, monomers, chemical feedstocks, and syngas. These technologies can support

resource recovery, reduce dependence on landfill and incineration, and contribute to circular-economy practices. Advanced sorting, automation, artificial intelligence, and improved separation systems can further improve the identification and processing of different plastic types [2,5,7].

Despite these advantages, advanced recycling technologies have several disadvantages and challenges. They generally require high capital investment, specialized equipment, and significant energy input. Thermal processes such as pyrolysis and gasification operate at high temperatures, while chemical recycling involves complex reaction, separation, and purification processes. Mixed and contaminated plastic waste, additives, multilayer materials, and variations in waste composition can make processing difficult. Pyrolysis may also produce a mixture of products that requires further processing. Biological recycling is still developing, with challenges related to reaction rates, polymer compatibility, and large-scale implementation. Effective operation also requires suitable collection, transportation, sorting, and processing infrastructure [2,5,7].

The future scope of plastic waste recycling is focused on developing more efficient, selective, economical, and environmentally sustainable technologies. Further research is required in advanced sorting, artificial intelligence, catalytic depolymerization, improved pyrolysis reactors, solvent recovery, enzyme-based recycling, and integrated mechanical-chemical systems. Emerging electrochemical and photocatalytic approaches may provide additional methods for plastic waste conversion. Future development should also focus on reducing energy consumption, improving the treatment of mixed and contaminated waste, increasing the quality of recovered products, and reducing catalyst and solvent requirements. Standardized techno-economic analysis and life-cycle assessment can help in comparing different recycling technologies. Integration of advanced recycling with efficient collection, segregation, preprocessing, supportive regulations, and circular-economy practices will be important for large-scale and sustainable plastic waste management [2,5].

IV. CONCLUSION

Plastic waste is a major environmental problem because it is generated in large quantities and remains in the environment for a very long time. Globally, only about 9% of plastic waste was ultimately recycled in 2019, showing the limitations of present recycling systems. In India, the estimated plastic recycling rate was about 25% in 2020–21, according to the India Plastics Pact based on available government data.

The data presented in this study also highlights the serious persistence of plastic waste: plastic bags, straws, cups, water bottles and toothbrushes can require decades to hundreds of years to degrade.

Therefore, depending only on conventional disposal methods is not sufficient. Moreover, existing recycling methods are not suitable for every type of plastic, particularly contaminated, mixed or difficult-to-process waste.

Hence, advanced plastic-waste recycling technologies such as mechanical recycling, thermolysis/pyrolysis, chemical depolymerization and

biological recycling are important for improving plastic waste management. These technologies can help recover useful materials and reduce the amount of plastic sent to landfill or released into the environment. However, their effectiveness depends on the type and quality of plastic waste, energy requirements, processing cost and available infrastructure.

The present project therefore focuses on studying the behaviour and performance of different plastic wastes under cryogenic conditions, with the aim of understanding their response and identifying possibilities for improved recycling and waste-management practices. Overall, the study highlights the need for advanced recycling technologies, proper waste segregation, efficient collection systems and sustainable plastic-waste management to reduce the long-term environmental impact of plastic waste.

REFERENCES

- [1] J. Hopewell, R. Dvorak, and E. Kosior, "Plastics recycling: challenges and opportunities," *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 364, no. 1526, pp. 2115–2126, 2009.
- [2] O. O. Alabi, T. O. Akande, O. J. Gbadeyan, and N. Deenadayalu, "Advanced technologies for plastic waste recycling: examine recent developments in plastic waste recycling technologies," *RSC Advances*, vol. 15, pp. 40541–40568, 2025.
- [3] J. E. Sonke, A. Koenig, T. Segur, and N. Yakovenko, "Global environmental plastic dispersal under OECD policy scenarios toward 2060," *Science Advances*, vol. 11, no. 16, eadu2396, 2025.
- [4] M. Tacker, T. Hafner-Kuhn, A. Gstöhl, E. Nduagu, E. Vozzola, T. W. Roux, and R. Auras, "Life cycle assessment of polyethylene packaging and alternatives on the European market," *Cleaner Environmental Systems*, vol. 17, p. 100270, 2025.
- [5] M. Alaghemandi, "Sustainable Solutions Through Innovative Plastic Waste Recycling Technologies," *Sustainability*, 2024, 10401.
- [6] A. S. Pottinger et al., "Pathways to reduce global plastic waste mismanagement and greenhouse gas emissions by 2050," *Science*, 2024, pp. 1168–1173.
- [7] P. G. C. Nayanathara Thathsarani Pilapitiya et al., "The world of plastic waste: A review," *Cleaner Materials*, 2024.
- [8] Nagy, Á., Kuti, R., "The Environmental Impact of Plastic Waste Incineration," *AARMS – Academic and Applied Research in Military and Public Management Science*, 15(3), 231–237, 2016. DOI: 10.32565/aarms.2016.3.3.