International Journal of Environmental Science and Technology (2023) 20:5895–5912
https://doi.org/10.1007/s13762-022-04079-x

REVIEW

Plastic waste recycling: existing Indian scenario and future opportunities

R. Shanker[2] · D. Khan[2] · R. Hossain[1] · Md. T. Islam[1] · K. Locock[3] · A. Ghose[1] · V. Sahajwalla[1] · H. Schandl[3] · R. Dhodapkar[2]

Received: 13 December 2021 / Revised: 23 February 2022 / Accepted: 4 March 2022 / Published online: 2 April 2022

Abstract

This review article aims to suggest recycling technological options in India and illustrates plastic recycling clusters and reprocessing infrastructure for plastic waste (PW) recycling in India. The study shows that a majority of states in India are engaged in recycling, road construction, and co-processing in cement kilns while reprocessing capabilities among the reprocessors are highest for polypropylene (PP) and polyethylene (PE) polymer materials. This review suggests that there are key opportunities for mechanical recycling, chemical recycling, waste-to-energy approaches, and bio-based polymers as an alternative to deliver impact to India's PW problem. On the other hand, overall, polyurethane, nylon, and polyethylene terephthalate appear most competitive for chemical recycling. Compared to conventional fossil fuel energy sources, polyethylene (PE), polypropylene (PP), and polystyrene are the three main polymers with higher calorific values suitable for energy production. Also, multi-sensor-based artificial intelligence and blockchain technology and digitization for PW recycling can prove to be the future for India in the waste flow chain and its management. Overall, for a circular plastic economy in India, there is a necessity for a technology-enabled accountable quality-assured collaborative supply chain of virgin and recycled material.

Keywords Informal and formal sector · Biological recycling · Chemical recycling · Mechanical recycling · Digitization · Blockchain technology

Introduction

Plastic has evolved into a symbol of human inventiveness as well as folly which is an invention of extraordinary material with a variety of characteristics and capacities. Although India is a highly populated country, it is ranked 12th among the countries with mismanaged plastics but it is expected that by the year 2025, it will be in 5th position (Neo et al. 2021). Therefore, recycling or upscaling, or reprocessing of PW has become the urgency to curb this mismanagement of plastics and mitigate the negative impacts of plastic consumption and utilization from the environment. However, this resource has not been given the required attention it deserves after post-consumer use. Recycling or reprocessing of PW usually involves 5 types of processes based on the quality of the product manufactured upon recycling of the waste, namely upgrading, recycling (open or closed loop), downgrading, waste-to-energy plants, and dumpsites or landfilling, as shown in Fig. 1 (Chidepatil et al. 2020). Usually, the PW is converted into lower-quality products such as pellets or granules, or flakes which are further utilized in the production of various finished products such as boards, pots, mats, and furniture (Centre for Science and Environment (CSE) 2021).

Plastics have a high calorific value, with polymer energy varying from 62 to 108 MJ/kg (including feedstock energy) which is much greater than paper, wood, glass, or metals (with exception of aluminum) (Rafey and Siddiqui 2021).

Editorial responsibility: Maryam Shabani.

✉ D. Khan
k.debishree@neeri.res.in

1 Centre for Sustainable Materials Research and Technology, SMaRT@UNSW, School of Materials Science and Engineering, UNSW Sydney, Sydney, NSW 2052, Australia

2 Council of Scientific and Industrial Research-National Environmental Engineering Research Institute (CSIR-NEERI), Nehru Marg, Nagpur 440 020, India

3 Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Australian National University, Canberra, ACT 2601, Australia

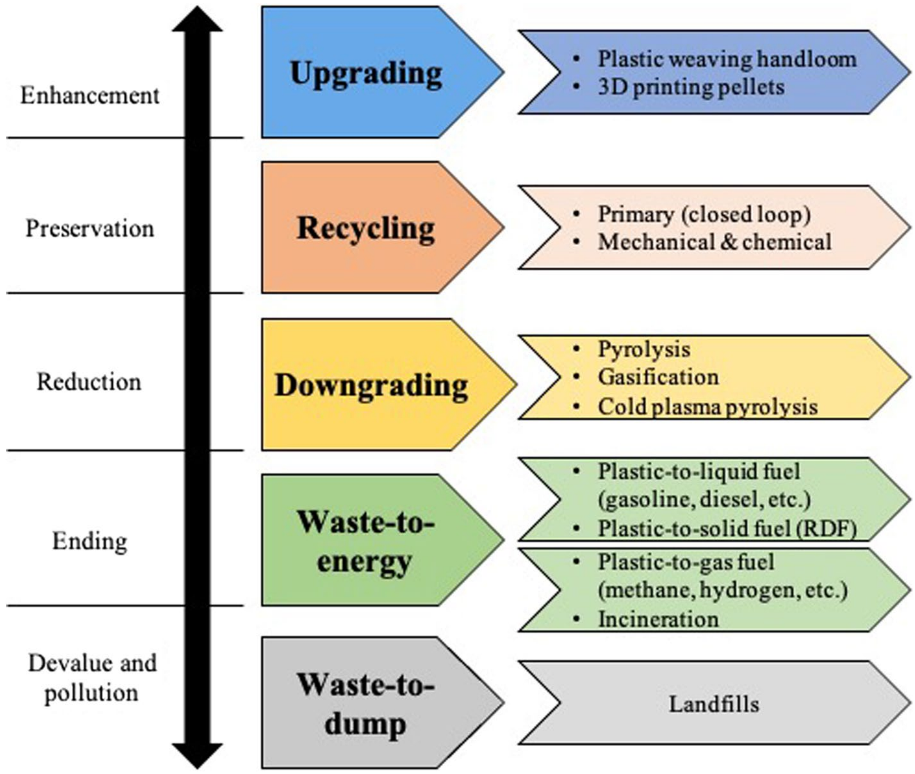

Fig. 1 Different processing pathways for plastic waste (modified from Chidepatil et al. 2020)

PW mishandling is a significant concern in developing nations like India due to its ineffective waste management collection, segregation, treatment, and disposal which accounts for 71% of mishandled plastics in Asia (Neo et al. 2021). Though there are numerous sources for PW the major fraction is derived from the post-consumer market which comprises both plastic and non-PWs and therefore, these wastes require to be washed and segregated accordingly for conversion into the homogenous mixture for recycling (Rafey and Siddiqui 2021). According to a study carried out by the Federation of Indian Chambers of Commerce and Industry (FICCI) and Accenture (2020), India is assumed to lose over $133 billion of plastic material value over the coming next 10 years until 2030 owing to unsustainable packaging out of which almost 75% of the value, or $100 billion, can be retrieved. This review article focuses on levers and strategies that could be put in place to transition India toward a circular economy for plastics. This involves two key areas, the first being reprocessing infrastructure in various states of India and the performance of the reprocessors in organized and unorganized sectors. The second key area for this study is an overview of the rapidly evolving area of plastic recycling technologies, including mechanical recycling, chemical recycling, depolymerization, biological recycling, and waste-to-energy approaches. A brief description of the technologies is provided and their applicability to the Indian context discussed along with the role of digitization in PW recycling.

Research motivation and scope of the article

The research on Indian PW and its recycling pathways according to the polymer types and its associated fates were studied along with the published retrospective and prospective studies. Due to COVID-19, there is an exponential increase in the PW and the urge to recycle this waste has become a necessity. Systematic literature studies from database collection of Web of Science (WoS) were performed with keywords such as "PW recycling technologies in India" OR "PW management in India" OR "plastic flow in India" from 2000 to October 2021 (including all the related documents such as review papers, research papers, and reports) which in total accounted for 2627 articles only. When the same keyword "plastic recycling" was searched without context to India, 5428 articles were published from 2000 to 2021 among which only 345 articles were published by Indian authors. Figure 2 shows the distribution of papers on PW and related articles over the years. However, the number of review articles remains very limited concerning published research papers and reports for the same. Review articles play a vital role in the substantial growth in the potential research areas for the enhancement of the proper management strategies in the respective domains. Recently, PW and its sustainable management necessity toward achieving a circular economy have attracted researchers, due to its detrimental effects on humans and the environment.

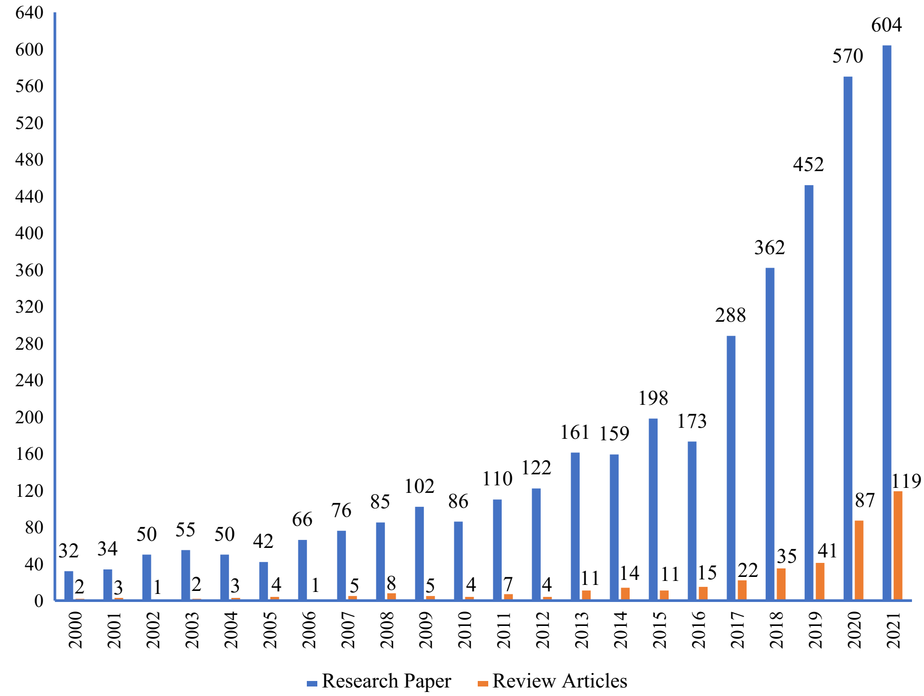

Fig. 2 Yearly distribution of papers related to plastic waste recycling from 2000 to October 2021

Reprocessing infrastructure and recycling rates for different types of plastics

Recycling rates of plastics vary between countries depending upon the types of plastic. Some polymers are recycled more than other types of polymers due to their respective characteristics and limitations. While PET (category 1) and HDPE (high-density polyethylene) (category 2) are universally regarded as recyclable, PVC (polyvinyl chloride) (category 3) and PP (category 5) are classified as "frequently not recyclable" owing to their chemical characteristics, however, they may be reprocessed locally depending on practical conditions. LDPE (low-density polyethylene) (category 4) is however difficult to recycle owing to stress failure, PS (category 6) may or may not be recyclable locally, and other types of polymers (category 7) are not recyclable due to the variety of materials used in its manufacturing (CSE 2021). About 5.5 million metric tonnes of PW gets reprocessed/recycled yearly in India, which is 60% of the total PW produced in the country where 70% of this waste is reprocessed in registered (formal) facilities, 20% by the informal sector and the rest 10% is recycled at household level (CSE 2020). The remaining 40% of PW ends up being uncollected/littered, which further results in pollution (water and land) and choking of drains (CSE 2019a). PW is dumped into landfills at a rate of 2.5 million tonnes per year, incinerated at a rate of over 1 million tonnes per year, and co-processed as an alternative energy source in blast furnaces at a rate of 0.25 million tonnes per year by cement firms (Rafey and Siddiqui 2021). Thermoset plastics (HDPE, PET, PVC, etc.), which are recyclable, constitute 94% of total PW generated, and the remaining 6% comprises other types of plastics which are multilayered, thermocol, etc. and are non-recyclable (CSE 2019b). Plastics such as PP, PS, and LDPE are partially recyclable but generally not recycled in India due to the economic unviability of their recycling processes (CSE 2020). Figure 3a shows the recycling rates of different kinds of plastics in India and Fig. 3b shows the percentage contribution of different recycling options in the Indian context.

State-wise facilities and flows of PW

The total plastic generation in India by 35 states and union territories accounts for 34,69,780 tonnes/annum (~3.47 million tonnes/annum) in the year 2019–2020 (CPCB (Central Pollution Control Board) 2021). Plastic processing in India was 8.3 Mt in the 2010 financial year and increased to 22 Mt in 2020 (Padgelwar et al. 2021). Table 1 shows the state-wise PW generation, registered and unregistered plastic manufacturing/recycling units, and multiplayer manufacturing units across the country. Furthermore, the main recycling clusters in India are presented in Fig. 4, wherein Gujarat (Dhoraji, Daman and Vapi), Madhya Pradesh (Indore), Delhi and Maharashtra (Malegaon, Mumbai (Dharavi and Bhandup), Solapur) are the main recycling hubs (Plastindia Foundation 2018). Recycling processes and disposal methods for PW vary substantially across the states in India given in Table 1. Details of some of the major infrastructure available in the states are described in the following subsection.

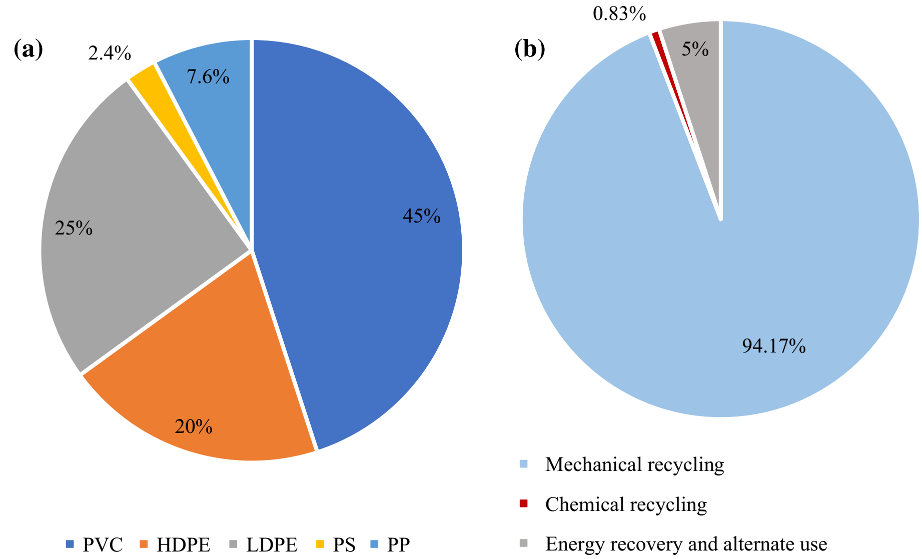

Fig. 3 **a** Recycling rates of different types of plastics in India (data extracted from CSE 2019b) and **b** percentage contribution of different recycling options in the Indian context (CSE 2021)

The door-to-door collection of solid waste is the most common practice for the collection of waste in almost all the states. Urban Local Bodies (ULBs) of some states like Goa, Himachal Pradesh, Maharashtra, Uttarakhand, and West Bengal are actively involved in the collection and segregation of waste (CPCB 2019; Goa SPCB 2020; MPCB 2020). Further after collection and segregation of waste, the PW is sent to various disposal (landfills) and recycling pathways (recycling through material recovery, road construction, waste-to-energy plants, RDF (refused derived fuel), etc.). Goa is the state where new bailing stations have been set up in addition to the existing facilities for the disposal of PW (Goa SPCB 2020). State like Kerala has taken the initiative for the installation of reverse vending machines (RVMs) for plastic bottles in supermarkets and malls whereas Maharashtra ensures 100% collection of waste with proper segregation and transport of PW where 62% of the waste is being reprocessed through different methods (Kerala SPCB 2020; MPCB 2020). Special Purpose Vehicles (SPVs) in Punjab have been effective for the collection of multilayered plastics (MLP) waste from different cities of the state and further being sent to waste-to-energy plants (Punjab Pollution Control Board (PPCB) 2018). Though almost all the states have imposed a complete ban on plastic bottles and bags, Sikkim was the first state who enforce the ban into the state which resulted in the reduction in its carbon footprint (MoHUA 2019). Many states such as Puducherry, Odisha, Tamil Nadu, Telangana, Uttar Pradesh, and West Bengal send their PW for reprocessing in cement kilns (CPCB 2019). Some states like Telangana have taken the initiative for source segregation of the waste from the households by separating the bins into dry and wet waste bins whereas the mixed waste is sent for further processing for road construction or in cement industries (Telangana State Pollution Control Board (TSPCB) 2018). Along with all these facilities in different states, several informal and unregistered recyclers are also contributing to their best to combat PW mismanagement.

Formal and informal sectors in India and their performance

The informal sector currently contributes 70% of PET recycling in India (Aryan et al. 2019). Approximately 6.5 tonnes to 8.5 tonnes per day of PW is collected by itinerant waste buyers (IWBs) and household waste collectors in India, out of which 50–80% of PW is recycled (Nandy et al. 2015). Kumar et al. (2018) mentioned that the average PW collected by a waste picker and an IWB was approximately 19 kg/d and 53 kg/d, respectively. According to ENF (2021), there are approximately 230 formal PW reprocessors in India, who can recycle various types of the polymer as shown in Fig. 5. However, the organized and unorganized sectors play a vital role in the reprocessing of plastics in India. Table 2 shows the distribution of organized and unorganized sectors along with the percentage growth in India. Most of the operations are currently related to mechanical recycling producing granules/pellets and flakes. In 30 states/UTs, there are 4953 registered units with 3715 plastic manufacturers/producers, 896 recyclers, 47 compostable manufacturing, and 295 multilayered packaging units however, 823 unregistered units have been reported from different states (CPCB 2021). However, data on reprocessing capability (material processed in terms of tonnes/year) of the individual recyclers are not readily available. With the limited data, it varies from 2500 to 3000 tonnes/year whereas capacity for processing various PW varies from 600 to 26,250 tonnes/year (ENF 2021).

Table 1 Plastic generation, plastic manufacturing, and recycling units in different states in India and status of plastic recycling and disposal in different states

States/UT	Plastic generation (tonnes/annum)	Registered plastic manufacturing/recycling units	Unregistered plastic manufacturing/recycling units	Multilayer manufacturing units	Possible recycling and disposal methods involved
Andaman and Nicobar	386.85	–	–	–	Recycling, Road construction
Andhra Pradesh	46,222	Manufacturing units—131 Compostable units—1	–	–	Recycling, Road construction, Co-processing in cement kilns
Arunachal Pradesh	2721.17	–	–	–	No information
Assam	24,970.88	Manufacturing units—18	–	5	Road construction, Co-processing in cement kilns
Bihar	4134.631	Manufacturing/Recycling units—8	Producers—225 Brand owners—203 Recyclers—36	–	No information
Chandigarh	6746.36	Recycling units—7	–	–	RDF processing plant
Chhattisgarh	32,850	Manufacturing units—8 Recycling units—8	–	–	Recycling, Co-processing in cement kilns, Waste-to-energy plant
Daman Diu & Dadra Nagar Haveli	1947.7	343	–	–	No information
Delhi	230,525	Producers—840	–	–	Waste-to-energy plant
Goa	26,068.3	Manufacturing units—35 Compostable unit—1	–	1	Recycling, Co-processing in cement kilns, Sanitary landfills
Gujarat	408,201.08	Manufacturing/Recycling units—1027 Compostable units—12	–	10	Co-processing in cement kilns
Haryana	147,733.51	Manufacturing units—69 Compostable unit—1	–	28	Road construction
Himachal Pradesh	13,683	No information	24	79	Road construction, Co-processing in cement kilns, Waste-to-energy plants
Jammu & Kashmir	74,826.33	259	45	–	No information
Jharkhand	51,454.53	Manufacturing units—59	–	–	Road construction, Co-processing in cement kilns, Reverse Vending Machines
Karnataka	296,380	Manufacturing/Recycling units—163	91	–	Recycling, Co-processing plants
Kerala	131,400	Manufacturing units—1266 Producers—82 Recycling units—99 Compostable unit—1	–	–	Recycling
Lakshadweep	46	–	–	–	Recycling
Madhya Pradesh	121,079	Manufacturing and Recycling units—164 Compostable unit—1	–	22	Recycling, Road construction, Co-processing in cement kilns
Maharashtra	443,724	Recycling units—62 Compostable manufacturing units—6	42	–	No information
Manipur	8292.8	Manufacturing units—4	–	–	No information
Meghalaya	1263	4	–	–	Road construction
Mizoram	7908.6	–	–	–	Recycling

Table 1 (continued)

States/UT	Plastic generation (tonnes/annum)	Registered plastic manufacturing/recycling units	Unregistered plastic manufacturing/recycling units	Multilayer manufacturing units	Possible recycling and disposal methods involved
Nagaland	565	Manufacturing units—4	–	–	Recycling, Road construction
Odisha	45,339	Manufacturing units—13	–	3	Co-processing in cement kilns
Punjab	92,890.17	Manufacturing/Recycling units—187 Compostable units—2 Material Recovery Facility—169	48	4	Recycling
Puducherry	11,753	Manufacturing/Recycling units—49 Compostable unit—1	–	4	Road construction, Co-processing in cement kilns
Rajasthan	51,965.5	Manufacturing units—69	–	16	No information
Sikkim	69.02	–	–	–	No information
Tamil Nadu	431,472	Manufacturing units—78 Recycling units—227	–	3	Recycling, Road construction, Co-processing in cement kilns
Telangana	233,654.7	Manufacturing/Recycling units—316	–	2	Recycling, Road construction, Co-processing in cement kilns
Tripura	32.1	Manufacturing units—26 Recycling units—4	–	2	No information
Uttarakhand	25,203.03	Manufacturing/Recycling units—33 Compostable units—2	15	28	Recycling
Uttar Pradesh	161,147.5	Manufacturing units—99 Recycling units—16 Compostable units—4	23	63	Road construction, Co-processing in cement kilns, Waste-to-energy plant, Production of fibers and raw materials
West Bengal	300,236.12	Manufacturing/Recycling units—157 Compostable unit—1	–	9	Road construction

Data sources: (Central Pollution Control Board 2019; Central Pollution Control Board 2021; CSE 2020; Goa State Pollution Control Board 2020; Tamil Nadu Pollution Control Board 2020; Haryana State Pollution Control Board 2020; Jammu and Kashmir State Pollution Control Board 2018; Kerala State Pollution Control Board 2020; Maharashtra Pollution Control Board 2020; Uttarakhand Pollution Control Board 2019; Uttar Pradesh Pollution Control Board 2021)

In the Indian context, the scale of operation and quantity of material handled by the formal sector is insignificant when compared to the informal sector (Nallathambi et al. 2018). However, data on the contribution of the informal sector in PW recycling in India are very limited (Kumar et al. 2018). Formal recycling is constrained to clean, separated, pre-consumer waste in a few places in India, even if the states have efficient recycling technology and resources, as in Gujarat and Maharashtra (TERI 2021). At present, the total numbers of organized and unorganized recycling units in India are 3500 and 4000, respectively (Satapathy 2017). The formal recyclers face challenges in providing supply security for reprocessed plastic materials as the current supply is dominated by informal recyclers (TERI 2021). In recovering consumer waste (including PW), the informal sector and households play a vital role in the waste collection; approximately 6.5–8.5 Mt of PW are collected by these entities, which is about 50–80% of the plastic produced (Nandy et al. 2015). PW collection, dismantling, sorting, shredding and cleaning, compounding, extrusions (pellet making) and new product manufacturing are the key activities done by the informal sector PW supply chain in India (WBCSD 2017).

Among the formal recyclers, Banyan Nation has implemented a proprietary washing technology to remove ink and markings from PW in the mechanical recycling process (Banyan Nation 2020). The recycler has integrated plastic recycling technology with data intelligence (real-time

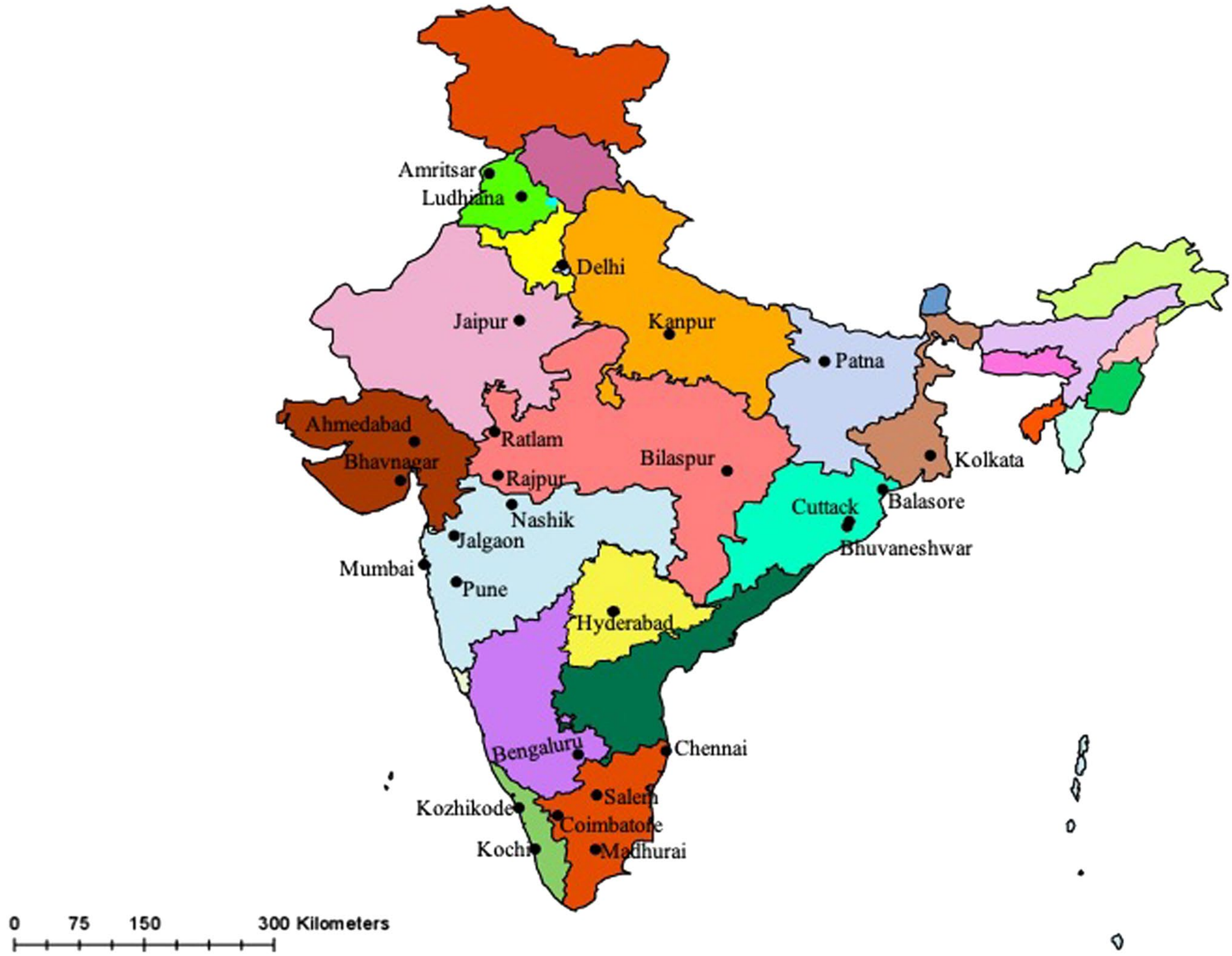

Fig. 4 Plastic recycling clusters in India (Plastindia Foundation 2018)

Fig. 5 Number of reprocessors according to polymer types in India (ENF 2021). (Abbreviations: ABS: Acrylonitrile butadiene styrene; HIPS: High impact polystyrene; LLDPE: Linear low-density polyethylene; PA: Polyamide; PBT: Polybutylene terephthalate; SAN: Styrene acrylonitrile; POM: Polyoxymethylene; PMMA: Poly(methyl methacrylate); TPE: Thermoplastic elastomer)

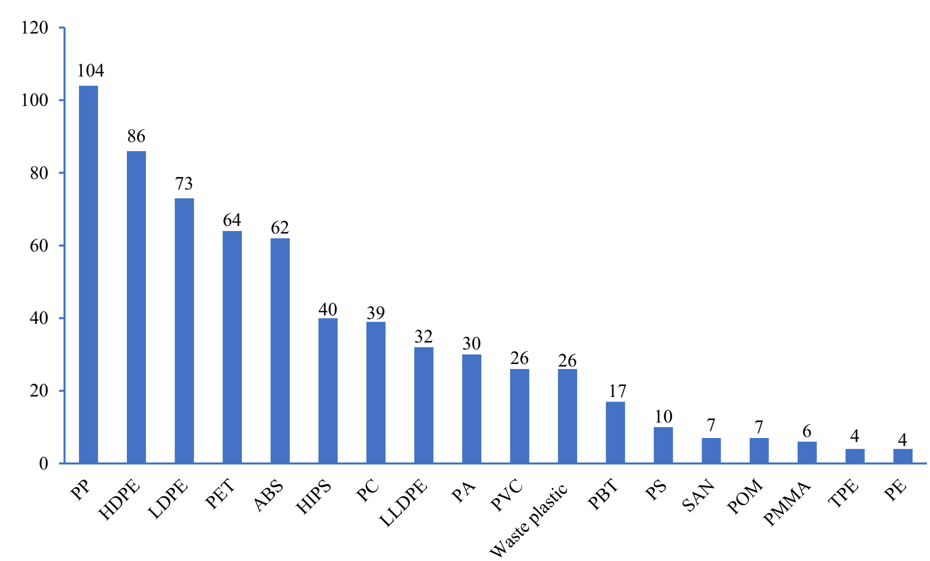

Table 2 Distribution of organized and unorganized plastic recycling units in India (Plastindia Foundation 2019)

Parameters	2018 report	2019 report	Percentage growth
No. of organized recycling units	3500	100	– 93%
No. of unorganized recycling units	4000	10,000	60%
Direct manpower	600,000	100,000	– 83%
Indirect manpower (including ragpickers)	1 million	1–1.5 million	50% (concerning upper limit)
Amount of plastic waste recycled	5.5 million metric tonnes	6 million metric tonnes	8.3%

location of informal sector PW collectors and their capacity for waste processing), which has enhanced its performance in high-quality waste collection and recycling (Banyan Nation 2020). The informal sector is largely involved in recycling PET bottles (mainly collection and segregation). Horizontal turbo washers and aglow machines are widely used in PE granule production by the informal sector (Aryan et al. 2019). The Alliance of Indian Waste Pickers comprises 30 organizations in 24 cities of the country, working in collaboration with waste pickers, acknowledging their contribution, and urging for them to be integrated into the waste management system. For the informal sector, a proper collection network, linking GPS (Global Positioning System) to points of segregation, and tracking vehicles should be considered in a consolidated framework (Jyothsna and Chakradhar 2020).

The organized/formal and unorganized/informal sectors are not discrete and do not vie for waste; instead, they are interdependent and coherent as the formal recyclers can operate because the informal sector performs the onerous task of conveying utilizable PW to the formal sector in the form of aggregates, pellets, flakes and, in a few instances, even the finished product. Since formal commodities are the ones who purchase their final goods, the informal sector relies on the formal sector. Furthermore, the informal sector's financial capability and ability to invest in infrastructure and equipment to manufacture goods on their own are restricted and therefore both communities have a mutual relationship (CSE 2021).

Overview on plastic recycling technologies and their applicability to India

From waste to material recovery, PW recycling can broadly be categorized into mechanical recycling, chemical recycling, biological recycling, and energy recovery (Al-Salem et al. 2017). The most preferable type of recycling is primary recycling because of its contamination-free feature which further facilitates a smaller number of operating units resulting in the optimal amount of consumption of energy supply and resources which is further followed by secondary recycling (mechanical recycling) for recycling PW (CSE 2021). However, processing difficulties and the quality of recyclates are the main drivers for seeking alternative approaches (Ragaert et al. 2017). Comparatively, tertiary recycling or chemical/feedstock recycling is a less favored alternative because of high production and operational costs, as well as the lack of scalable commercial technology in India whereas quaternary recycling which involves energy recovery, energy from waste, or valorization of PW, is least preferred due to uncertainty around propriety and prominence of the technology, and the negative potential to convert land-based pollution to water and air pollution, but anyhow more preferable than dumping into the landfill (Satapathy 2017; CSE 2021). Figure 6 shows the categorization of the recycling process of PW.

Recycling technologies

Mechanical recycling (MR)

Mechanical recycling (also known as secondary, material recycling, material recovery, or back-to-plastics recycling) involves physical processes (or treatments) that convert PW into secondary plastic materials. It is a multistep process typically involving collection, sorting, heat treatment with reforming, re-compounding with additives, and extruding operations to produce recycled material that can substitute for virgin polymer (Ragaert et al. 2017; Faraca and Astrup 2019). It is conventionally capable of handling only single-polymer plastics, such as PVC, PET, PP, and PS. It remains one of the dominant recycling techniques utilized for post-consumer plastic packaging waste (PlasticsEurope 2021). There are various key approaches to sorting and separating PW for MR, including zig-zag separator (also known as an air classifier), air tabling, ballistic separator, dry and wet gravity separation (or sink-float tank), froth flotation, and electrostatic separation (or triboelectric separation). There are also some newer sensor-based separation technologies available for PW which include plastic color sorting and near-infrared (NIR) (Ministry of Housing & Urban Affairs (MoHUA) 2019). Fig. S1 of the supplementary material

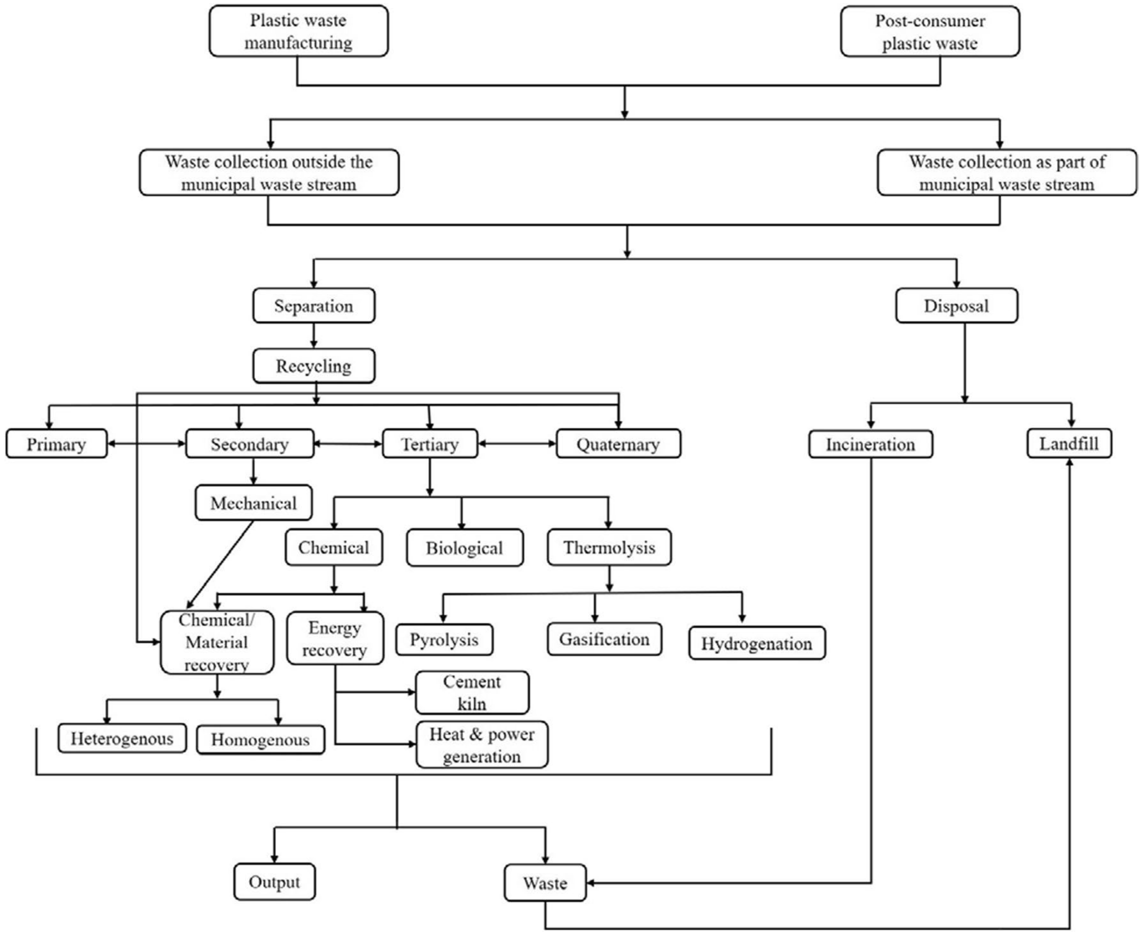

Fig. 6 Plastic waste flow and recycling categorization (Modified from FICCI 2016; Sikdar et al. 2020; Tong et al. 2020)

shows the overall mechanical reprocessing infrastructure for plastics.

After the collected plastics are sorted, they are melted down directly and molded into new shapes or are re-granulated (with the granules then directly reused in the manufacturing of plastic products). In the re-granulation process, plastic is melted down after being shredded into flakes, then processed into granules (Dey et al. 2020).

Degradation and heterogeneity of PW create significant challenges for recyclers involved in mechanical recycling as in many cases, recycled plastics do not have the same mechanical properties as virgin materials and therefore, several challenges emerge while recycling mono and mixed PW. Furthermore, difficulties in developing novel technologies to remove volatile organic compounds to improve the quality of recycled plastics is one of the key technological challenges in mechanical recycling (Cabanes et al. 2020). Different polymers degenerate under their specific characteristics such as oxidation, light and heat, ionic radiation, and hydrolysis where thermal–mechanical degradation and degradation during lifetime are the two ways by which it occurs while recycling or reprocessing of PW (Ragaert et al. 2017). Faraca and Astrup (2019) also state that models to predict plastic performance based on the physical, chemical, and technical characteristics of PW will be critical in optimizing these processes. Other than technical challenges, the mechanical recycling process possesses social and economic challenges such as sorting of mixed plastics, lack of investments and legislation, and quality of recycled products (Payne et al. 2019).

Chemical recycling

Chemical recycling, tertiary recycling, or feedstock recycling refers to the transformation of polymers into simple chemical structures (smaller constituent molecules) which can be utilized in a diverse range of industrial applications and/or the production of petrochemicals and plastics (Bhagat et al. 2016; Jyothsna and Chakradhar 2020). This type of recycling directly involves fuel and chemical manufacturers (Bhagat et al. 2016). Pyrolysis, hydrogenation, and gasification are some of the chemical recycling processes (Singh and Devi 2019). The food packaging sector could be the main industry to utilize outputs from the chemical recycling process (BASF 2021).

When molecules, combustible gases, and/or energy are generated in a thermal degradation process, molecules, combustible gases, and/or energy are generated as multi-stream outputs whereas layered and complex plastics, low-quality mixed plastics, and polluted plastics are all viable targets for chemical/feedstock recycling (CSE 2021). From an operational standpoint, utilizing residual chars and no flue gas clean-up requirements are the main advantages, while from an environmental point of view, reduction in landfilling coupled with reduced GHGs (green-house gases) and CO_2 (carbon dioxide) emissions are added benefits. Ease of use in electricity and heat production and easily marketed products are some of the financial advantages of pyrolysis (Al-Salem et al. 2010). Plasma pyrolysis is a state-of-the-art technology in which thermo-chemical properties are being integrated with pyrolysis (MoHUA 2019). Fig. S2 of the supplementary material shows the chemical valorization of waste plastics. Although, cost and catalyst reuse capability in pyrolysis processes need further investigation (TERI 2020). Due to high energy requirements and the low price of petrochemical feedstock compared to monomers developed from waste plastics, chemical recycling is not yet common at an industry scale (Schandl et al. 2020).

Processing of mixed waste remains a difficult task due to the intricacy in the reactions where different types of polymers reflect completely distinct spectra following degradation pathways (Ragaert et al. 2017). The presence of PVC in the waste stream possesses another problem due to its density and removal of hydrochloric acid (HCl) from products and thus resulting in incomplete segregation (Ragaert et al. 2017). Other than this, lack of stable waste supply, suitable reactor technology, and presence of inorganics in the waste stream possess challenges in the chemical recycling of the plastics (Payne et al. 2019). Lack of investments, production of by-products and metal-based catalysts systems contribute to other significant difficulties in the chemical valorization of waste plastics (Cabanes et al. 2020; Kubowicz and Booth 2017).

Depolymerization Depolymerization of the plastics is the result of chemical processing where various monomer units are recovered which can be reused for the production of new plastics manufacturing or conversion into their raw monomeric forms through processes such as hydrolysis, glycolysis, and alcoholysis (Bhandari et al. 2021; Mohanty et al. 2021). This process is often used to recover monomers from a recoverable resin's grade to that of virgin resin such as PET, polyamides such as nylons, and polyurethanes with excellent results, as well as the possibility to restore a significant resource from commodities that are difficult to recycle commercially (MoHUA 2019). This is the process by which the plastic polymers are converted into sulfur-free liquid power sources through chemical recycling where these power sources facilitate energy recovery from PWs (Bhandari et al. 2021). According to the studies carried out on depolymerization of mixed waste plastics, it has been reported that even a small quantity, for instance, 1 mg of these plastics can yield 4.5 to 5.9 cal of energy with a little amount of energy consumption of 0.8–1 kWh/h and therefore, this process can yield additional convenience for the high-quality recycling which is recently being used for the PET (Bhandari et al. 2021; Ellen MacArthur Foundation 2017; Wołosiewicz-Głąb et al. 2017). In the anoxic conditions and the presence of specific catalytic additives, the depolymerization is accomplished in a specially modified reactor where 350 °C is the highest reaction temperature which is converted to either liquid RDF or different gases (reutilized as fuel) and solids (reutilized as fuel in cement kilns) (MoHUA 2019).

Energy recovery Gasification of PW is performed via reaction with a gasifying agent (e.g., steam, oxygen, and air) at high temperatures (approximately 500–1300 °C) to produce synthetic gas or syngas. This can subsequently be utilized for the production of many products, or as fuel to generate electricity, with outputs of a gaseous mixture of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), and methane (CH_4) via partial oxidation (Heidenreich and Foscolo 2015; Saebea et al. 2020). The amount of energy derived from this process is affected by the calorific input of PW where polyolefins tend to display higher calorific values. Table 3 shows calorific values of various plastic polymers and conventional fuels for comparison. Due to flexibil-

Table 3 The calorific value of popular plastics and conventional fuels (Zhang et al. 2021)

Fuel	Calorific value (MJ/kg)
Polyethylene	43.3–47.7
Polypropylene	42.6–46.5
Polystyrene	41.6–43.7
Polyvinyl chloride	18.0–19.0
Polyethylene terephthalate	21.6–24.2
Polyamide	31.4
Polyurethane foam	31.6
Methane	53
Gasoline	46
Kerosene	46.5
Petroleum	42.3
Heavy oil	42.5
Household plastic solid waste mixture	31.8

ity, robustness, and advantageous economics, gasification along with pyrolysis is a leading technology for chemical recycling. Characterization of PW is essential for developing optimal process design, particularly for HDPE, LDPE, PP, PS, PVC, and PET (Dogu et al. 2021). CSIR-IIP, India (Council of Scientific and Industrial Research-Indian Institute of Petroleum) and GAIL, India (Gas Authority of India Ltd.) in collaboration, have been successful in producing fuel and chemicals from PW where PE and PP plastics have been converted to diesel, petrochemicals, and gasoline. 1 kg of these plastics can yield 850 ml of diesel, 500 ml of petrochemicals, and 700 ml of gasoline, along with LPG (CSIR-IIP 2018) where the process ensures 100% conversion with no toxic emissions and is suitable for both small- and large-scale industries (CSIR-IIP 2018).

Biological recycling

Biological recycling or organic recycling involves the breaking of PW with the intervention of microorganisms such as bacteria, fungus, or algae to produce biogas (CO_2 for aerobic processes and CH_4 for anaerobic processes). PW may be recycled biologically through two methods namely aerobic composting and anaerobic digestion (Singh and Ruj 2015). An enzymatic approach for biodegradation of PET is considered an economically viable recycling method (Koshti et al. 2018). Table S1 in the supplementary data shows microorganisms responsible for the PW degradation process which could be utilized in the biological recycling process. Blank et al. 2020 reported that non-degradable plastics such as PET, polyethylene (PE), and polystyrene (PS) can be converted to biodegradable components such as polyhydroxyalkanoates (PHA) using a combination of pyrolysis and microbiology, which is an unconventional route to a circular economy. Polyaromatic hydrocarbons, polyhydroxy valerate (PHV) and polyhydroxyalkanoate (PHH), polylactide (PLA), and other aliphatic polyesters are biodegradable, whereas many aromatic polyesters are highly impervious to microbial assault (Singh and Ruj 2015). Fig. S3 of supplementary data shows an overview of the biodegradation of plastics.

Oxo-degradable plastics which is one of the major classes of bioplastics that possess challenges due to rapid breakage into microplastics when conditions (sunlight and oxygen) are favorable (Kubowicz and Booth 2017). The behavior of specific polymers interrupts their degradation into monomers due to which the microbial activity is ineffective for non-hydrolyzable manufactured polymers as the activity of the microorganisms responsible for the degradation differs concerning the environmental conditions (Ali et al. 2021). Other challenges include the consumption of energy for recycling and time for degradation of the generated microplastics along with socioeconomic challenges such as more time and capital investment and lack of resources (Kubowicz and Booth 2017). Collection and separation of bio-PW and a lack of effective policy contribute to some other barriers related to bio-based polymers and recycling.

Techno-economic feasibility of different recycling techniques

The techno-economic feasibility study provides a medium to analyze the utilization (raw materials, resources, energy, etc.) and end-of-life trail for different recovery pathways for the conversion of PW by qualitative and quantitative approaches in technical and financial aspects (Briassoulis et al. 2021a). The association of technical and economic prospects of reprocessing technologies and related products' market tends to have a compelling impact on the formation of policies to reduce PW. Hence, the techno-economic feasibility study is essential for the effective management of PW. The disparity in melting points and treatment technologies contributes to the major challenge for the recycling of mixed/multilayered plastic packaging waste which affects the quality of the recycled product (Larrain et al. 2021). Table 4 shows different parameters for techno-economic feasibility for recycling technologies. Though techno-economic feasibility study facilitates the understanding inadequacy prevails in terms of sustainability. This is overcome by Techno-Economic Sustainability Analysis (TESA) which studies alternative methods for feedstock alteration, common environmental criteria (such as mass recovery efficiency, the impact of additives, and emissions from recycling facility), and pathways for recycling and end-of-life of plastic products (Briassoulis et al. 2021b).

Utilization of PW and recycled products in India and contribution of major players toward plastic sustainability

Post-consumer PW can be utilized to produce several products after recycling, such as laying roads, use in cement kilns, pavement blocks, tiles, bricks, boards, and clothes. Due to good binding properties, when PW is in a high-temperature molten state, it can be utilized in road laying (Rokade 2012). Mixing PP and LDPE in bituminous concrete significantly increases the durability and fatigue resistance of roads (Bhattacharya et al. 2018). Various industries based in different locations of the country utilizes PP, HDPE, and LDPE waste plastics to produce reprocessed granules and further use them in the production of chairs, benches, dustbins, flowerpots, plastic pellets, mobile stands, etc. Few informal recyclers produce eco-friendly t-shirts and napkins from PET waste bottles whereas some recyclers convert PW to office accessories, furniture, and

Table 4 Techno-economic feasibility parameters for recycling technologies (Briassoulis et al. 2021a; CSE 2021; ElQuliti 2016; Fivga and Dimitriou 2018; Ghodrat et al. 2019; Larrain et al. 2021; NITI Aayog- UNDP 2021; Singh and Ruj 2015; Volk et al. 2021)

	Feasibility parameters	Mechanical	Chemical	Biological for bioplastic
TECHNOLOGICAL	Type of polymer	PET, HDPE, LDPE,	PET, PP, PVC, PE, PS, laminated plastics, low-quality mixed plastics	Bio-PET, bio-PE, bio-PP, etc.
	Energy requirements	300–500 kW/month for 30–50 tonnes/month	1200–1500 kW for 80–100 kg PW/hour (depends on type of technology and polymer type)	40 TJ–1500 TJ (terajoule)
	Temperature requirement	100–250 °C	Pyrolysis—300–900 °C Plasma pyrolysis—1730–9730 °C Gasification—500–1300 °C	130–150 °C
	Biodegradability	Non-biodegradable	Non-biodegradable	Mostly biodegradable (PHA, PHV, PHH, PLA)
	Raw materials cost	Rs. 6–40/kg	Rs. 6–40/kg	Rs. 10–30/kg
ECONOMICAL	Quality of processed materials	Depending on polymer type	Depend on type of technology and polymer type	High-quality compostable bio-polymer
	Cost of recyclates	Rs. 20–150/kg (depends on type of polymers and quality of recycled products)	Rs. 20–40/l (diesel/fuel)	Oxo-degradable plastics—Rs. 90–120/kg Biodegradable films/bags—Rs. 400–500/kg
	Recycling facilities in India (units)	7000–10,000	15–25	5–10
	Cost requirements (Operating and capital costs)	50–60 lakhs/annum	50–65 lakhs for 1 TPD (tonnes per day) plant	1–2 crores/annum

decorative garden items. Recycle India Hyderabad, in 2015, built houses, shelter bus stops, and water tanks with PW bottles. Further, under this initiative, thousands of chips packets were weaved into ropes, tied to metal frames, and used to create dining tables. Shayna Ecounified Ltd., Delhi, with the CSIR-National Physical Laboratory, Delhi, converted 340 tonnes of HDPE, LDPE, and PP waste plastics to 11 lakh tiles and has commercialized them to other cities such as Hyderabad, and companies such as L'Oréal International and Tata Motors. Further, few recyclers convert PW such as milk pouches, oil containers, shower curtains, and household plastics to poly-fuel (a mixture of diesel, petrol, etc.). Few of them collect PET waste and recycle it into clothes, automotive parts, battery cases, cans, carpets, etc. There are several other non-government organizations (NGOs), companies, and start-ups that are involved in the recycling of PW and its conversion to different types of products, even after post-consumer use.

Using shredded PW, in 2015–16, the National Rural Road Development Agency laid around 7,500 km of roads in India. In 2002, Jambulingam Street in Chennai was constructed as the first plastic road in India (TERI 2018). Plastic fibers can replace common steel fibers for reinforcement. Fire-retardant composites with a wide scope of applications could be developed by blending recycled plastics with fly ash (TERI 2020). HDPE, PVC, LDPE, PP, and PS have yielded conflicting performance measures, which require further investigation into the performance of the pavement, methods of improving compatibilization between plastic and asphalt, and economic and environmental implications of the process.

For the reduction in packing, costs and rising issues related to PW and packaging, FMCGs (fast-moving consumer goods) industries have teamed up with the Packaging Association of Clean Environment (PACE), have primarily emphasized immediate benefits including a reduction in size and resource consumption where these changes have promoted the usage of flexible packaging and pouches over rigid packaging forms. Major FMCG companies like Hindustan Unilever (HUL), Nestlé, and P&G have assured that they will reduce the use of virgin plastics in packaging to half the amount by the year 2025 (PRI 2021). To promote the utilization of recycled plastics, HUL incorporated recycled PET and recycled HDPE in the manufacturing of personal care products (Condillac and Laul 2020). Other companies like L'Oréal and Henkel had successfully eliminated PVC in 2018 along with the reduced use of cellophane to 5.5% in 2019 and reduction in the utilization of carbon black packaging to make carbon-free toilet cleaners, respectively (PRI 2021). Beverage companies like PepsiCo, Coca-Cola India, and Bisleri which use a large quantity of PET bottles, have collaborated with several recyclers to upcycle the PW products for the production of new recycled utilities such as clothes and bags (Condillac and Laul 2020). Similarly, other companies like Marico and Dabur are also actively involved in reducing the use of virgin plastics in its packaging and for the implementation of a recycling initiative where Marico in collaboration with Big Bazaar is providing incentives to the customers for dropping their used plastic bottles in the stores and Dabur is also competing in the race to become among first Indian FMCG company to be plastic-free (Condillac and Laul 2020). On the other side, apart from taking initiatives by various FMCG companies, a lot of efforts is being done for the innovation toward plastic-free packaging materials and therefore, Manjushree Technopack (Bengaluru, India) launched its first plant for the production of post-consumer recycled polymer up to 6000 metric tonnes/year to these industries. Other than this, Packmile, a packaging company is producing no plastic alternative such as kraft paper (which is biodegradable and recyclable) for Amazon India (Condillac and Laul 2020).

Role of digitization in PW recycling

As the amount of waste is increasing by each successive year, technology-driven methods can be established for communities to reduce, reuse and recycle PW in an eco-friendly manner. In light of this, Recykal (in south Indian city Hyderabad), a digital technology firm developed an end-to-end, cloud-based fully automated digital solution for efficient waste management by tracking waste collection and promoting recycling of non-biodegradable. Its services assist in the formation of a cross-value channel coalition and the connection of various stakeholders such as waste generators (commercial and domestic users), waste collectors, and recyclers, assuring that transactions between the organizations with 100% transparency and accessibility (Bhadra and Mishra 2021). The quantities of waste received per day have risen from 20 to 30 kg in the months following to over 10,000 to 15,000 kg recently and offer incentives based on the quality of recycled products (Bhadra and Mishra 2021). One such Android-based application is proposed and developed by Singhal et al. (2021), for efficient collection by pick-up or drop facility incorporated in the software. Segregation, as well as methods for recycling different types of plastics, are also suggested and in return, the users are rewarded with the e-coupons accordingly (Singhal et al. 2021).

For improvement in plastic recycling, a variety of techniques have been used and blockchain is one among them, and it holds promise for enhancing plastic recycling and the circular economy (CE). A distributed ledger, or blockchain, is made up of certain immutable ordered blocks which prove to be an excellent approach to commence all of their customers' transactions under the same technology (Khadke et al. 2021). One such approach is the introduction of Swachh-coin for the management of household and industrial waste, and their conversion into usable high-value recoverable goods such as paper, steel, wood, metals, and electricity with efficient and environmentally friendly technologies (Gopalakrishnan and Ramaguru 2019). This is a Decentralised Autonomous Organization (DAO) that is controlled unilaterally via blockchain networks which utilize a combination of techniques such as multi-sensor driven AI to establish an incremental and iterative chain that relies on information transferred between multiple ecosystem players, analyzes these inputs, and offers significant recommendations based on descriptive algorithms which will eventually make the system entirely self-contained, economical, and profitable (Gopalakrishnan and Ramaguru 2019). The purpose of AI in this multi-sensor infrastructure purpose is to limit unpredictability and facilitate efficient and reliable separation by training the system to identify and distinguish them appropriately (Chidepatil et al. 2020). Most businesses favor blockchain technology because of its decentralized architecture and low trading costs along with the associated benefits of accessibility, availability, and tamper-proof structures (Khadke et al. 2021; Wong et al. 2021).

Discussion

India is a major player in global plastic production and manufacturing. Technology, current infrastructure, and upcoming strategies by the Indian government are combined to provide detailed suggestions for policymakers and researchers in the area of achieving a circular economy. The most important barrier in Indian PW management is the lack of source segregation of the waste. As in many other countries, mechanical recycling is the leading recycling route for India's rigid plastics. The influence of thermomechanical deterioration should be avoided to get high-quality recycled material with acceptable characteristics. The development of advanced quality measurement techniques for technology such as nondestructive, cost-effective methods to assess the chemical structure and mechanical performance could be key to overcoming the obstructions. For instance, the performance of MR can be partially improved through simple packaging design improvements, such as the use of a single polymer instead of a multilayer structure. Furthermore, PS and PVC could be replaced with PP for the packaging film market. There are also issues with depolymerization selectivity and activity, ability, and performance trade-offs that may need to be addressed before these methods have wide applicability. Based on our assessments, Indian policymakers should consider PET, polyamide 6 (PA 6), thermosetting resins, multilayer plastic packaging, PE, PS, PP, and fiber-reinforced composites for chemical recycling.

As chemical recycling is innovation-intensive, assessing economic feasibility is the main challenge for developing countries like India. Overall, PUR, nylon, and PET appear most competitive for chemical recycling. The more problematic mixed waste streams from multilayer packaging could be more suited for pyrolysis along with PE, PP, PS, PTFE (polytetrafluoroethylene), PA, and PMMA (poly(methyl methacrylate)). Substantial investment is required for hydrocracking which can deal with mixed plastics. Better guidance on the correct chemical recycling technology for each Indian PW stream may require technology readiness level (TRL) assessments as proposed by Solis and Silveira (2020), which require an increased number of projects and data available on the (chemical) process optimization. Compared to conventional fossil fuel energy sources, PE, PP, and PS are the three main polymers with higher calorific value, making them suitable for energy production. There are some challenges, however, with this technology, such as the identification of specific optimal biodiesel product properties which can be addressed using techniques such as LCA (life cycle assessment) and energy-based analysis. As the practical module of the Indian PW management rules explicitly shows the route to oil production from waste, this may indicate a focus on this technology for the country in the future as chemical recycling accounts for only 0.83% (as shown in Fig. 3b) among all the recycling technologies. Although a relatively high cost is associated with bio-polymers at present, it is expected that production costs will reduce due to economies of scale in the coming years. There are already numerous bioplastic food packaging materials in the market. Since food packaging constitutes a large portion of PW in India, a significant impact could be made for the country if it is switched to more sustainable bio-based polymers. In India, the J&K Agro Industries Development Corporation Ltd, in collaboration with Earth soul, has introduced the first bioplastic product manufacturing facility, with 960 tonnes per year production capacity whereas Truegreen (Ahmedabad) can manufacture 5000 tonnes per year. Some of the major manufacturing plants in India are Biotech bags (Tamil Nadu), Ravi Industries (Maharashtra), Ecolife (Chennai). Recently, plant-based bio-polymer has been introduced by an Indian company named Hi-Tech International (Ludhiana) to replace single-use and multi-use plastic products such as cups, bottles, and straws, which is India's only compostable plastic which implies that plastics produced from this bio-polymer will initiate its degeneration within 3–4 months and can completely disintegrate after 6 months and also, a biodegradable plastic made is converted to carbon dioxide and the remaining constituents transforms into water and biomass (Chowdhary 2021). However, there are several challenges associated with this technology. Improvements are required to sort bioplastic from other PW types to avoid waste stream contamination. There is also a need for optimization of anaerobic digestion parameters to ensure the complete degradation of these materials. From the Indian perspective, feedstock type with their respective infrastructure availability and interactions between sustainability domains is critical for policymaking issues as most of the recycling sectors are operated by informal sector workers. Commercialization of laboratory-based pyrolysis and gasification of bioplastic streams should be developed. Due to contaminated collection, there is limited recyclability in other PW streams, which should be considered as part of bio-based PW management. Though India recycles 60% of the total waste generated and its recycling methods are quite effective in solving the problem of increasing PW in India, there are still some major challenges or barriers linked with it. For more efficient management of all the PW produced, stakeholders need to understand and tackle the challenges faced to curb plastic pollution in the country. Different types of recycling technologies have their respective associated challenges and barriers (including technological and social) which need to be addressed as mentioned in Table S2 of the supplementary data.

Recycled plastics and the products made from these plastics are often expensive from the virgin plastics and therefore compete for their place in the market. The reason behind this is the easy availability of raw materials (which are waste from the petroleum industry) for the production of virgin plastics. Other than this, even after mentioning that 60% of the PW is being recycled, a massive amount of this waste is found littered and unrecycled in the environment which contradicts the percentage of recycling as there is a lack of relevant and accurate data for the same. Furthermore, Goods and Services Tax (GST) also plays a vital role to build market linkages between recycled and virgin products as the availability of recycled products is sporadic, the revenue or business model tends to collapse for these products and affects the recyclers if the PW is being exported where the GST rates decreased to 5% from 18% in 2017 (CSE 2021). The increased input costs due to GST and customs taxes are being transferred to secondary waste collectors by lowering the cost of recycled plastics. For instance, PET bottles were Rs. 20/kg before GST came in which decreased to Rs. 12/kg after GST imposition, milk packets price varied from Rs 12/kg to Rs 8/kg and similarly, the cost of HDPE dropped by 30% post-GST (CSE 2021). With the introduction of GST in the plastic value and supply chain, the informal sectors are facing huge losses due to the availability of scrap at cheaper costs. Therefore, the current GST structure has affected the most fragile and vulnerable section of the plastic supply value chain.

Enormous studies have been carried out related to different techniques for recycling for various types of polymers, very limited research is available on the techno-economic feasibility of these technologies and therefore, this could provide a wide scope for the relevant research in India. Other than this feasibility study, there is a broad range of opportunities and possibilities to explore and analyze the technologies in India concerning sustainability (involving environmental and social parameters) through TESA.

Several published reports claim that India recycles 60% of the total PW generated annually which is the highest among other countries such as Germany and Austria with more than 50% recycling. India's recycling is mostly contributed by the informal sectors but has not been documented accurately by the governing bodies of the country. Moreover, information on the recycling rate of 60% varies with different sources and creates disparity and ambiguity of the data. As depicted in Fig. 3b, India recycles 94.17% of waste plastics through mechanical recycling, while 0.93% is chemical or feedstock recycling and 5% for energy recovery and alternative uses such as making roads, boards, and tiles. Compared with chemical recycling, mechanical recycling is the most popular technique due to ease of operation and low-cost expenditure as compared to feedstock or chemical recycling in which high finances and operational costs are involved along with the lack of availability to ascendable technology. Landfill dumping is sometimes favored due to improper segregation of waste and ease of operation by agencies employed by ULBs. Other than mechanical and chemical recycling, bioplastics are the emerging alternative for PW in India but lag due to improper legislation, high cost, and unawareness of the segregation of these types of plastics. This can be facilitated if eco-labeling and a proper coding system are introduced. Though these recycling technologies are widely used for reprocessing the PW, elimination of plastics from the environment is still a far-fetched dream and merely adds a few more years into the end-of-life of the plastics. Therefore, there is a need for affirmative legislation and strict guidelines for the use of recycled products and the exploration of alternatives in different sectors. Active involvement of the informal sectors and inclusive growth can be ensured as their livelihood is dependent on PW.

Conclusion

The circular economy is a regenerative model which requires the participation of accountable stakeholders. There should be continuous interaction among stakeholders to share current practices dealing with PW as part of the plastic economy. It was found that there was incomplete and indistinct reporting on PW generation from individual states. Information exchange via technology application should eventually be an integral part of the PW management value chain. Thus, generation estimation is an essential task to set targets for resource recovery and recycling, which connects the "global commitment" element of the circular plastic economy and waste minimization. Being part of the global commitment to "reducing, circulating and innovating" under the "plastic pact," a national target could be set and a mechanism is developed. In setting a national target, the "dialogue mechanism" would further invigorate inter-and multidisciplinary research and policy directions. Consumer behavior is an essential task as the end-users share equal responsibilities as the producer circular economy. Waste management is a complex multi-actor-based operational system built on knowledge, technologies, and experience from a range of sectors, including the informal sector. Indigenous innovation and research at a regional scale, such as in Gujarat, Andhra Pradesh, and Kerala, has set an example of a circular plastic economy and would help in developing a further regional circular plastic economy. Efficient recycling of mixed PW is an emerging challenge in the Indian recycling sector. As plastic downcycling and recycling is an energy-intensive process, energy supply from renewable energy sources such as solar and wind energy can potentially reduce the CO_2 emissions produced. The recovery and recycling of substantial volumes of PW need emerging technological and specialized equipment, which in turn necessitates a considerable capital investment. Informal sectors being prominent in waste management may be deprived of recognition, technology, and scientific understanding but their skills, knowledge, and experience can be utilized in the value chain of plastic flow. Also, there is a need to formalize the informal sectors with proper incentivization and other benefits as they play a major role in plastic flow in India. Additionally, there are no policies or rules for the treatment of the residues from the result of recycling technologies and their production units, which needs to be addressed as the number of waste residues depends on the quantum of waste and technique incorporated. Universities, research organizations, and most importantly, polymer manufacturers and most important policymakers should collaborate in renewable energy integration and process optimization.

Further detailed assessment using LCA should be performed in this regard to identify the optimized solutions. Extended producer responsibility (EPR) and other policy mechanisms would be integrated sooner or later; however, one of the fundamental aspects is being part of the circular economy. Although segmented, it is believed that the informal sector is very innovative, and they could also be technologically enabled. New app development and PW collection campaigns through digitalization could increase non-contaminated sources of PW. Specific manufacturing sectors such as flexible packaging, automobiles, electrical, and electronics should look at the plastic problem through the lens of resource efficiency and climate change (CO_2 and GHGs) perspectives. The sectors should develop innovative solutions so that recycled plastics can be re-circulated within the sectors where they will be the leading consumer.

Though there are a lot of available data on different types of recycling of plastics and the state-wise flow of plastics there is no proper information on different types of plastic polymers and their respective flow in the value chain in different states/UTs. There is a need for the fortification of recycling different technologies for different polymers and for this purpose, the multi-sensor-based AI and blockchain technology can prove effective in segregation and recycling of the PW in a more environmentally friendly manner which should be implemented in all parts of the country for efficient PW management. Furthermore, the amount of PW can only be controlled by the replacement of new virgin plastics and existing plastics with the desired recycled plastics along with citizen sensitization. Overall, for a circular plastic economy in India, there is a necessity for a technology-enabled, accountable quality-assured collaborative supply chain of virgin and recycled material.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13762-022-04079-x.

Acknowledgments The authors wish to thank all who assisted in conducting this work.

Author contributions All the authors contributed to the study conception and design. Conceptualization and writing of the draft were done by Riya Shanker, Dr. Debishree Khan, Dr. Rumana Hossain, Anirban Ghose, and Md Tasbirul Islam. The draft was revised and edited by Katherine Locock with the supervision of Dr. Heinz Schandl, Dr. Rita Dhodapkar, and Dr. Veena Sahajwalla. All the authors have read and approved the final manuscript.

Funding The authors acknowledge project funding for "India – Australia Industry and Research

Collaboration for Reducing Plastic Waste" from CSIRO, Australia, through contract agreement.

Declarations

Conflict of interest The authors declared that they have no conflict of interest.

Ethical approval There is no ethical approval required.

References

Al-Salem SM, Antelava A, Constantinou A, Manos G, Dutta A (2017) A review on thermal and catalytic pyrolysis of plastic solid waste (PSW). J Environ Manag 197:177–198. https://doi.org/10.1016/j.jenvman.2017.03.084

Al-Salem SM, Lettieri P, Baeyens J (2010) The valorization of plastic solid waste (PSW) by primary to quaternary routes: From re-use to energy and chemicals. Prog Energy Combust Sci 36:103–129. https://doi.org/10.1016/j.pecs.2009.09.001

Ali SS, Elsamahy T, Al-Tohamy R, Zhu D, Mahmoud Y, Koutra E, Sun J (2021) PWs biodegradation: mechanisms, challenges and future prospects. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2021.146590

Singh AP, Devi AS (2019) PW management: a review. Retrieved from http://ijasrm.com/wp-content/uploads/2019/05/IJASRM_V4S5_1488_233_237.pdf

Anon (2020) Strategies for sustainable plastic packaging in India. FICCI & Accenture. Retrieved from https://ficci.in/spdocument/23348/FICCI-Accenture-Circular-Economy-Report1.pdf

Aryan Y, Yadav P, Samadder SR (2019) Life cycle assessment of the existing and proposed PW management options in India: a case study. J Clean Prod 211:1268–1283. https://doi.org/10.1016/j.jclepro.2018.11.236

Banyan Nation (2020) Recycling and monitoring PW Flow in the city. ASCI J Manag 49:73–76

BASF (2021) Chemical recycling of PW. Retrieved from https://www.basf.com/in/en/who-we-are/sustainability/we-drive-sustainable-solutions/circular-economy/chemcycling.html

Bhadra U, Mishra PP (2021) Extended producer responsibility in India: evidence from Recykal, Hyderabad. J Urban Manag 56:280. https://doi.org/10.1016/j.jum.2021.07.003

Bhagat S, Bhardawaj A, Mittal P, Chandak P, Akhtar M, Sharma P (2016) Evaluating PW disposal options in Delhi using multicriteria decision analysis. Inst Integr Omics Appl Biotechnol 7:25–35

Bhandari NL, Bhattarai S, Bhandari G, Subedi S, Dhakal KN (2021) A review on current practices of plastics waste management and future prospects. J Inst Sci Technol 26(1):107–118. https://doi.org/10.3126/jist.v26i1.37837

Bhattacharya RS, Chandrasekhar KMV, Deepthi PR, Khan A (2018) Challenges and opportunities: plastic management in India. https://www.teriin.org/sites/default/files/2018-06/plastic-waste-management_0.pdf

Blank LM, Narancic T, Mampel J, Tiso T, O'Connor K (2020) Biotechnological upcycling of PW and other non-conventional feedstocks in a circular economy. Curr Opin Biotechnol 62:212–219. https://doi.org/10.1016/j.copbio.2019.11.011

Briassoulis D, Pikasi A, Hiskakis M (2021) Recirculation potential of post-consumer/industrial bio-based plastics through mechanical recycling-Techno-economic sustainability criteria and indicators. Polym Degrad Stab 183:109217

Briassoulis D, Pikasi A, Hiskakis M (2021) Organic recycling of post-consumer/industrial bio-based plastics through industrial aerobic composting and anaerobic digestion-Techno-economic sustainability criteria and indicators. Polym Degrad Stab 190:109642. https://doi.org/10.1016/j.polymdegradstab.2021.109642

Cabanes A, Valdés FJ, Fullana A (2020) A review on VOCs from recycled plastics. Sustain Mater Technol 25:e00179. https://doi.org/10.1016/j.susmat.2020.e00179

Central Pollution Control Board (2019) Annual report for the year 2018–2019 on implementation of PW management Rules. Retrieved from https://cpcb.nic.in/uploads/plasticwaste/Annual_Report_2018-19_PWM.pdf

Chidepatil A, Bindra P, Kulkarni D, Qazi M, Kshirsagar M, Sankaran K (2020) From trash to cash: how blockchain and multi-sensor-driven artificial intelligence can transform circular economy of PW? Adm Sci 10(2):23. https://doi.org/10.3390/admsci10020023

Condillac R, Laul C (2020) Megatrend: reducing plastic usage across FMCG value chain. Retrieved from http://bwhealthcareworld.businessworld.in/article/Megatrend-Reducing-Plastic-Usage-across-FMCG-Value-Chain/24-07-2020-300857/

CPCB Annual Report 2019–2020 (2021). Retrieved from https://cpcb.nic.in/uploads/plasticwaste/Annual_Report_2019-20_PWM.pdf

Centre for Science and Environment (CSE) (2019a). The plastics factsheet 1. https://cdn.cseindia.org/attachments/0.57139300_1570431848_Factsheet1.pdf

Centre for Science and Environment (CSE) (2019b) The plastics factsheet 3. https://cdn.cseindia.org/attachments/0.97245800_1570432310_factsheet3.pdf

CSE (2020) Managing PW in India: challenges and Agenda. Retrieved from https://www.cseindia.org/content/downloadreports/10352

CSE (2021) Plastic recycling decoded. Retrieved from https://www.cseindia.org/plastic-recycling-decoded-10885.

CSIR-IIP (2018) https://www.iip.res.in/waste-plastics-to-fuel-and-petrochemicals/

Dey A, Dhumal CV, Sengupta P, Kumar A, Pramanik NK, Alam T (2020) Challenges and possible solutions to mitigate the problems of single-use plastics used for packaging food items: a review. J Food Sci Technol. https://doi.org/10.1007/s13197-020-04885-6

Dogu O, Pelucchi M, Van de Vijver R, Van Steenberge PHM, D'Hooge DR, Cuoci A, Mehl M, Frassoldati A, Faravelli T, Van Geem KM (2021) The chemistry of chemical recycling of solid PW via pyrolysis and gasification: State-of-the-art, challenges, and future directions. Prog Energy Combust Sci 84:100901. https://doi.org/10.1016/j.pecs.2020.100901

Ellen MacArthur Foundation (2017) The new plastics economy: rethinking the future of plastics and catalysing actions. Retrieved from https://ellenmacarthurfoundation.org/the-new-plastics-economy-rethinking-the-future-of-plastics-and-catalysing

ElQuliti SAH (2016) Techno-economic feasibility study of waste-to-energy using pyrolysis technology for Jeddah municipal solid waste. Int J Power Eng Energy 7(1):622–635

ENF (2021) Plastic recycling plants in India. https://www.enfrecycling.com/directory/plastic-plant/India

Principles for Responsible Investments (PRI) (2021) Engaging on plastic packaging: Fast Moving Consumer Goods. Retrieved from https://www.unpri.org/plastics/engaging-on-plastic-packaging-fast-moving-consumer-goods/7919.article

Faraca G, Astrup T (2019) PW from recycling centers: characterization and evaluation of plastic recyclability. Waste Manag 95:388–398. https://doi.org/10.1016/j.wasman.2019.06.038

FICCI (2016) Indian plastic industry: challenges & opportunities. Retrieved from https://www.slideshare.net/TSMG-Chemicals/indian-plastic-industry-challenges-opportunities

Fivga A, Dimitriou I (2018) Pyrolysis of PW for production of heavy fuel substitute: a techno-economic assessment. Energy 149:865–874. https://doi.org/10.1016/j.energy.2018.02.094

Ghodrat M, Alonso JA, Hagare D, Yang R, Samali B (2019) Economic feasibility of energy recovery from waste plastic using pyrolysis technology: an Australian perspective. Int J Environ Sci Technol 16(7):3721–3734. https://doi.org/10.1007/s13762-019-02293-8

Goa State Pollution Control Board (2020) Annual report for FY 2019–2020 on implementation of PW (Management and Handling) Rules, 2016 as amended 2018. Retrieved from http://goaspcb.gov.in/Media/Default/uploads/Annual%20Report%20Plastic%202019-20.pdf

Gopalakrishnan P, Ramaguru R (2019) Blockchain-based waste management. Int J Eng Adv Technol 8(5):2632–2635

Haryana State Pollution Control Board (2020) Annual report under PW management rule for the year 2019. Retrieved from https://hspcb.gov.in/content/plasticwaste/ARPWM19-20/ARPWM19-20.pdf

Heidenreich S, Foscolo PU (2015) New concepts in biomass gasification. Prog Energy Combust Sci 46:72–95. https://doi.org/10.1016/j.pecs.2014.06.002

Indian Plastics Industry Report, PlastIndia Foundation (2019). Retrieved from https://www.plastindia.org/plastic-industry-status-report.php

Jammu and Kashmir State Pollution Control Board (2018) Annual report 2017–2018. Retrieved from http://jkspcb.nic.in/WriteReadData/userfiles/file/BMW/0.jpg

Jyothsna TSS, Chakradhar B (2020) Current scenario of PW management in India: way forward in turning vision to reality. In: Urban mining and sustainable waste management. Springer, Singapore, pp 203–218

Kerala State Pollution Control Board (2020) Annual report 2019–2020. Retrieved from https://www.keralapcb.nic.in/cmsadmin/fileUploads/Annual%20Report%20PWM%20Rules%202019%20-%202020.pdf

Khadke S, Gupta P, Rachakunta S, Mahata C, Dawn S, Sharma M, Dalapati GK (2021) Efficient plastic recycling and re-molding circular economy using the technology of trust-blockchain. Sustainability 13(16):9142. https://doi.org/10.3390/su13169142

Koshti R, Mehta L, Samarth N (2018) Biological recycling of polyethylene terephthalate: a mini-review. J Polym Environ 26:3520–3529. https://doi.org/10.1007/s10924-018-1214-7

Kubowicz S, Booth AM (2017) Biodegradability of plastics: challenges and misconceptions. https://doi.org/10.1021/acs.est.7b04051

Kumar A, Samadder SR, Kumar N, Singh C (2018) Estimation of the generation rate of different types of PWs and possible revenue recovery from informal recycling. Waste Manag 79:781–790. https://doi.org/10.1016/j.wasman.2018.08.045

Larrain M, Van Passel S, Thomassen G, Van Gorp B, Nhu TT, Huysveld S, Billen P (2021) Techno-economic assessment of mechanical recycling of challenging post-consumer plastic packaging waste. Resour Conserv Recycl 170:105607. https://doi.org/10.1016/j.resconrec.2021.105607

Maharashtra Pollution Control Board (2020) Annual report 2019–2020. Retrieved from https://www.mpcb.gov.in/sites/default/files/plastic-waste/PWMAnnualreportMPCB201920.pdf

Ministry of Housing & Urban Affairs (MOHUA) (2019) PW management issues, solutions & case studies. Retrieved from http://164.100.228.143:8080/sbm/content/writereaddata/SBM%20Plastic%20Waste%20Book.pdf

Mohanty A, Borah RK, Fatrekar A, Krishnan S, Vernekar A (2021) Stepping towards benign alternatives: sustainable conversion of PW into valuable products. Chem Commun. https://doi.org/10.1039/D1CC03705F

Nallathambi M, Prasad G, Samuel, S (2018) Life cycle inventories of plastic recycling—India. Retrieved from https://www.ecoinvent.org/files/sectorial_report_sri_plastics_report.pdf

Nandy B, Sharma G, Garg S, Kumari S, George T, Sunanda Y, Sinha B (2015) Recovery of consumer waste in India—a mass flow analysis for paper, plastic and glass and the contribution of households and the informal sector. Resour Conserv Recycl 101:167–181. https://doi.org/10.1016/j.resconrec.2015.05.012

Neo ERK, Soo GCY, Tan DZL, Cady K, Tong KT, Low JSC (2021) Life cycle assessment of PW end-of-life for India and Indonesia. Resour Conserv Recycl 174:105774. https://doi.org/10.1016/j.resconrec.2021.105774

NITI Aayog-UNDP Handbook on Sustainable Urban PW Management (2021) Retrieved from https://www.niti.gov.in/sites/default/files/2021-10/Final_Handbook_PWM_10112021.pdf

Padgelwar S, Nandan A, Mishra AK (2021) PW management and current scenario in India: a review. Int J Environ Anal Chem 101(13):1894–1906. https://doi.org/10.1080/03067319.2019.1686496

Payne J, McKeown P, Jones MD (2019) A circular economy approach to PW. Polym Degrad Stab 165:170–181. https://doi.org/10.1016/j.polymdegradstab.2019.05.014

PlasticsEurope (2021) Recycling and energy recovery. Retrieved from https://plasticseurope.org/#:~:text=Mechanical%20recycling%20of%20plastics%20refers,chemical%20structure%20of%20the%20material.&text=It%20is%20currently%20the%20almost,99%25%20of%20the%20recycled%20quantities.

Plastindia Foundation (2018) Report on The Indian Plastics Industry. Retrieved from https://plastindia.org/pdf/Indian-Plastics-Industry-Report-2018-2.pdf

Punjab Pollution Control Board (2018) Annual report 2018. Retrieved from https://ppcb.punjab.gov.in/Attachments/Plastic%20Waste/PlasticCPCB.pdf

Rafey A, Siddiqui FZ (2021) A review of PW management in India—challenges and opportunities. Int J Environ Anal Chem. https://doi.org/10.1080/03067319.2021.1917560

Ragaert K, Delva L, Van Geem K (2017) Mechanical and chemical recycling of solid PW. Waste Manag 69:24–58. https://doi.org/10.1016/j.wasman.2017.07.044

Rokade S (2012) Use of waste plastic and waste rubber tyres in flexible highway pavements. In: International conference on future environment and energy, IPCBEE, vol 28

Saebea D, Ruengrit P, Arpornwichanop A, Patcharavorachot Y (2020) Gasification of PW for synthesis gas production. Energy Rep 6:202–207. https://doi.org/10.1016/j.egyr.2019.08.043

Satapathy S (2017) An analysis of barriers for plastic recycling in the Indian plastic industry. Benchmark Int J 24(2):415–430

Schandl H, King S, Walton A, Kaksonen AH, Tapsuwan S, Baynes TM (2020) National circular economy roadmap for plastics, glass, paper and tyres. Australia's National Science Agency, CSIRO, Australia

Sikdar S, Siddaiah A, Menezes PL (2020) Conversion of waste plastic to oils for tribological applications. Lubricants 8(8):78. https://doi.org/10.3390/lubricants8080078

Singh RK, Ruj B (2015) PW management and disposal techniques-Indian scenario. Int J Plast Technol 19(2):211–226. https://doi.org/10.1007/s12588-015-9120-5

Singhal S, Singhal S, Neha, Jamal M (2021) Recognizing &automating the barriers of plastic waste management – collection and segregation 8(4):775–779

Solis M, Silveira S (2020) Technologies for chemical recycling of household plastics—a technical review and TRL assessment. Waste Manag 105:128–138. https://doi.org/10.1016/j.wasman.2020.01.038

Chowdhary S (2021) Biopolymers: smart solution for solving the PW problem. Retrieved from https://www.financialexpress.com/industry/bio-polymers-smart-solution-for-solving-the-plastic-waste-problem/2267620/.

Tamil Nadu Pollution Control Board (2020) Annual report on PW management rules, 2016. Retrieved from https://tnpcb.gov.in/pdf_2019/AnnualRptPlasticwaste1920.pdf

Telangana Pollution Control Board (2018) Annual report 2017–18. Retrieved from https://tspcb.cgg.gov.in/CBIPMP/Plastic%20annual%20returns%202017-18.pdf

TERI (2020) PW management: turning challenges into opportunities. Retrieved from https://www.teriin.org/sites/default/files/2020-12/plastic-management_0.pdf

TERI (2021) Circular Economy for plastics in India: A Roadmap. https://www.teriin.org/sites/default/files/2021-12/Circular-Economy-Plastics-India-Roadmap.pdf

Tong Z, Ma G, Zhou D (2020) Simulating continuous counter-current leaching process for indirect mineral carbonation under microwave irradiation. J Solid Waste Technol Manag 46(1):123–131. https://doi.org/10.5276/JSWTM/2020.123

Uttar Pradesh Pollution Control Board (2021) Annual report 2019–2020. Retrieved from http://uppcb.com/pdf/Plastic-Annual_090321.pdf

Uttarakhand Pollution Control Board (2019) Annual report 2018–2019. Retrieved from https://ueppcb.uk.gov.in/files/annual_report_PWM.pdf

Volk R, Stallkamp C, Steins JJ, Yogish SP, Müller RC, Stapf D, Schultmann F (2021) Techno-economic assessment and comparison of different plastic recycling pathways: a German case study. J Ind Ecol. https://doi.org/10.1111/jiec.13145

WBCSD (2017) Informal approaches towards a circular economy—learning from the plastics recycling sector in India. https://www.sustainable-recycling.org/wp-content/uploads/2017/01/WBCSD_2016_-InformalApproaches.pdf

Wołosiewicz-Głąb M, Pięta P, Sas S, Grabowski Ł (2017) PW depolymerization as a source of energetic heating oils. In: E3S web of conferences, vol 14. EDP Sciences, p 02044. https://doi.org/10.1051/e3sconf/20171402044

Wong S, Yeung JKW, Lau YY, So J (2021) Technical sustainability of cloud-based blockchain integrated with machine learning for supply chain management. Sustainability 13(15):8270. https://doi.org/10.3390/su13158270

Zhang F, Zhao Y, Wang D, Yan M, Zhang J, Zhang P, Chen C (2021) Current technologies for PW treatment: a review. J Clean Prod 282:124523. https://doi.org/10.1016/j.jclepro.2020.124523