Regeneration and Recovery of Plastics

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Introduction

Metals, polymers and cements are the three major pillars in terms of applications in modern human civilization. In many applications plastics are easy to handle, resource-saving, non-toxic with esthetics. Although largescale production of plastics started in 1950s, we cannot imagine our modern life without plastics now. Plastic materials are strong, lightweight and moldable to produce a number of different types of articles like: protective packaging for various foods, product packaging for consumer and industrial goods, toys, mobile phones, lightweight and safety components in automobiles and aerospace industries, personal protective equipment and medical devices, insulation materials in buildings, materials for household and office furniture, pipeline transportation, and many other applications. The most widely known plastics are: Polyvinylchloride (PVC), Polystyrene (PS), Polyethylene terephthalate (PET), polyethylene(PE), low density (LDPE), linear low density (LLDPE), high density (HDPE) Polypropylene (PP) and polytetrafluoroethylene (PTFE or Teflon). Due to lightweight and high durability, plastics have replaced the use of metals, wood and cements and have revolutionized the standard of living. The replacement of metallic/wooden components in rail, road and air have resulted in light weight transportation with higher fuel efficiency, and reduced the dependency on non-renewable fossil fuels. The other major contributions of plastics are: the development of high-density data storage systems, laser systems for precise medical procedures, plastic tubing for the protection of optical fibers which allows the fast transfer of large quantities of data and the compact disks for the music industry and improve the quality of recordings. Use of plastics have helped in reducing the sizes and weights of laptop/desktop computers resulting in energy savings. Plastics can be used to meet the specific demands of electrical and electronic applications. The plastic foam insulation in refrigerators can save 17 times as much energy (Fisher *et al*., 2004). Production of plastics results in a higher need of hydrocarbon resources as well renewable polysaccharide based feedstocks with an increase in solid plastic waste (SPW) on the earth (**Fig. 1**).

Two Major Types of Plastics

(1) *Thermoplastics* which can be molded more than once with the application of heat: PVC, PE, LDPE, LLDPE, HDPE, PP, PET, PS, PTFE, High-impact polystyrene (HIPS), Acrylonitrile–butadiene–styrene (ABS), Styrene–acrylonitrile copolymer (SAN), Polymethyl methacrylate (PMMA), Thermoplastic elastomer (TPE), Polyoxymethylene (POM), Polybutylene terephthalate (PBT), Polycarbonate (PC), Polyamide (PA), Ethylene–vinyl alcohol copolymer (EVOH), Copolymer from ethylene and vinyl acetate (EVA), Polyphenylene oxide (PPO), Polyphenylenesulfide (PPS), etc., are widely used (**Fig. 2**).

(2) *Thermosets* which can be molded only once: Phenol–formaldehyde resin (PF), Melamine–formaldehyde resin (MF), Urea––formaldehyde resin (UF), Unsaturated Polyester (UP), Epoxy, Vinyl Esters, Silicone, Acrylic Resins etc., are widely used. Engineering plastics like ABS, PC, PA, PET, polysulphone (PSU), polyetherketone (PEK), polyetheretherketone (PEEK) and polyimides (PI) have high heat resistance, rigidity, chemical stability, flame resistance with high mechanical resistance. The above materials are widely used in electrical and electronic equipment due to the above properties. Again, fast changing technologies in the above two areas, a huge amount of disposable materials are produced (Tarantili *et al*., 2010). Engineering plastics market value is predicted to reach above $90 billion by 2020 (Chauhan *et al*., 2019). In 2018, worldwide production of plastics crossed 359 million metric tons, where the production from Europe was 62 million metric tons. China produces nearly more than one fourth of world production of plastics with a steady growth of its imports to United States (**Fig. 3**) (Plastics Europe, 2019).

Advantages and Disadvantages of Plastic Materials (Siddique *et al*., 2008)

(1) *Advantages:*

(a) Plastics can meet specific technical needs and has many applications.
(b) Low density of the plastics helps in reducing the cost of transportation.
(c) Safe and hygienic for food packaging.
(d) Durable and long-lasting.
(e) Water, chemical and impact resistant.
(f) Non-conductive to heat and electricity
(g) Production cost is comparatively cheaper than other materials for similar use.
(h) May be used in combination with aluminum foil, paper and adhesives.

 doi:10.1016/B978-0-12-820352-1.00045-6

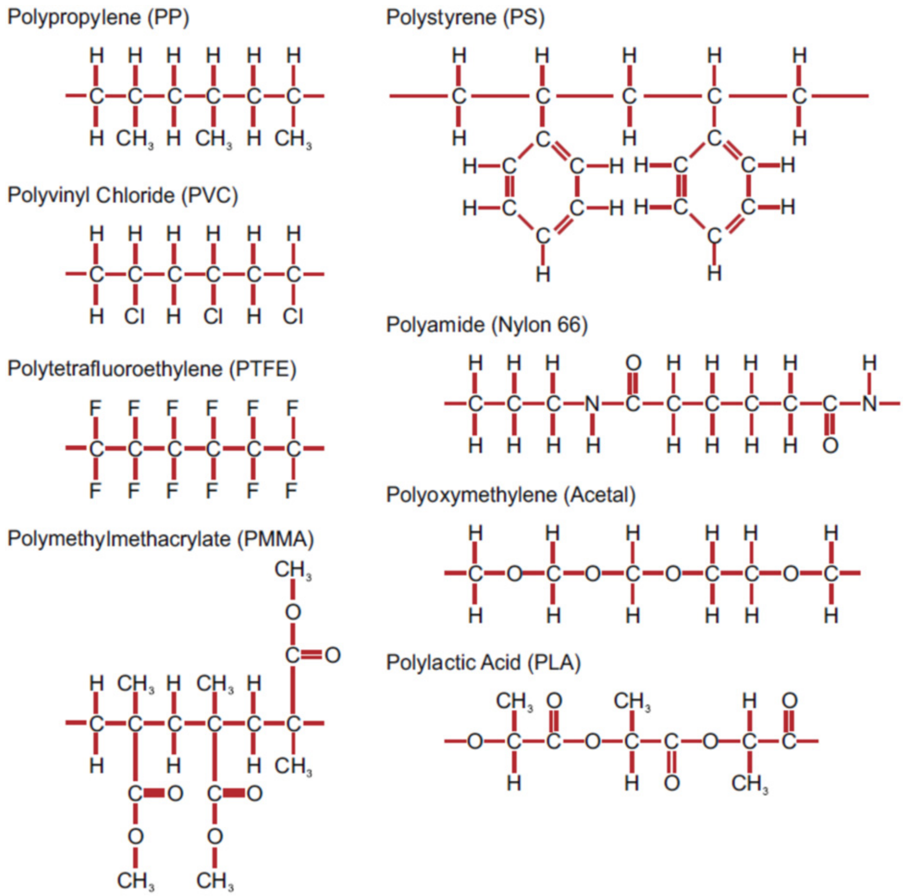

Fig. 1 Chemical structures of common plastics. Reproduced from Crawford, R.J., Martin, P.J., 2020. Plastics Engineering. Oxford: Butterworth-Heinemann; The Boulevard.

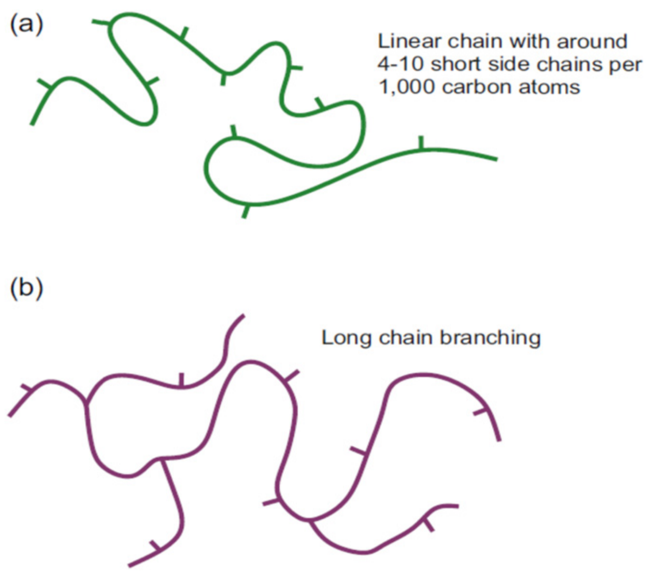

Fig. 2 Chain structure of polyethylene. Reproduced from Crawford, R.J., Martin, P.J., 2020. Plastics Engineering. Oxford: Butterworth-Heinemann; The Boulevard

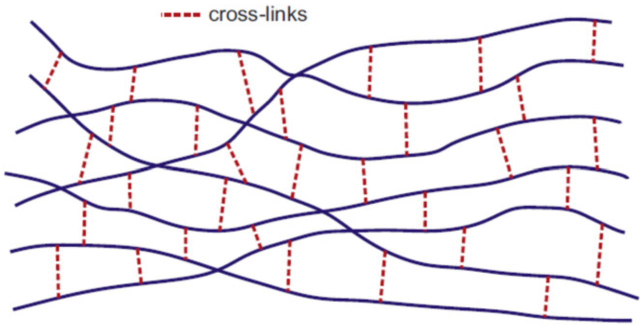

Fig. 3 Cross-linked structure of thermoset plastics. Reproduced from Crawford, R.J., Martin, P.J., 2020. Plastics Engineering. Oxford: Butterworth-Heinemann; The Boulevard

(i) Excellent esthetic appeal.

(2) *Disadvantages*:

(a) Plastic manufacturing uses potentially harmful chemicals like colorizing materials.
(b) Phthalates may be released when plastic toys are sucked by children.
(c) The presence of toxic chemicals, exposure to plastics may result in birth defects, tumors, cancer and immune system disorders.
(d) Thermosetting plastics can be molded only once.
(e) Widely used plastic items such as food packaging become waste within a short time after purchase.
(f) Most of the plastics are non-degradable, long time is required to degrade, may take up to hundreds of years.
(g) The disposal of plastics may have environmental impact on plankton through to whales. Plastics need to undergo environmental risk assessment before its use in some cases.
(h) Space requirement for landfill by plastics waste is a major environmental problem.

Regeneration and Recovery of Plastics

In addition to reducing the amount of plastic waste requiring disposal, regeneration and recovery of plastics are more desirable due to the following reasons:

(1) Conservation of non-renewable fossil fuels: plastic production uses 8% of the world's oil production, 4% as feedstock and 4% during manufacture.
(2) Reduced consumption of energy.
(3) Reduced amounts of solid waste going to landfill can also reduce the municipal solid wastes.
(4) Reduced emissions of carbon-dioxide (CO_2), nitrogen oxide (NO) and sulfur-dioxide (SO_2).

Regeneration of plastics means conversion of plastics with the formation of new monomers, oligomers or petrochemicals. The process of recovering resource from waste for reuse or reprocessing is known as recovery which includes collection, sorting and aggregation of materials. Pyrolysis methods are generally used for synthesis gas, production by means of gasification or of partial oxidation. With the invention of modern technologies, collection and separation of various types of wastes, proper regeneration and recovery of the plastics could help in saving a sizable amount money for the exchequer. There is a direct impact on the economy for the regenerated and recovered plastics which cannot be ignored (**Fig. 4**).

Presently, nearly 95% of packaging plastics are discarded after only a single use. Since plastic waste generally contaminated by many non-plastic materials like paper, glass, metal, cloth and wood, the separation of plastic from such contaminants is labor intensive. The problem can be solved by proper use of separate bins for plastics, papers, metals and food waste. Besides the above, only plastic waste may even contain heterogeneous polymeric components. Recent developments of new processes for such as direct incineration via one or two stage combustion with production of monomers can reduce the volume of plastic solid waste. These processes indirectly reduce the use of oil and gas required for the production of virgin plastics (Al-Salem *et al.*, 2009; Singh *et al.*, 2017).

Physical methods of recovery do not change chemical structures and properties of the plastics, where direct mechanical crush methods are used. During chemical recovery methods plastics are decomposed or by pyrolysis they produce monomers as regenerated products. Since chemical methods are costly, landfilling is the easier option. In many cases, burning of plastics are also carried out, but due to environment pollution such practices are prohibited in many places. Mechanochemical methods are used for regeneration of thermosetting phenolic plastics. It has been found that by the above method after the destruction of the molecular structure, reactive groups are produced with decrease in the crosslinking density with improvement in plasticity of the regenerated products (Wu *et al.*, 2014). It has been found that plastics can be effectively regenerated with the production of monomers. Out of various paths of regeneration processes of plastic wastes, the identical parent plastics can be produced using

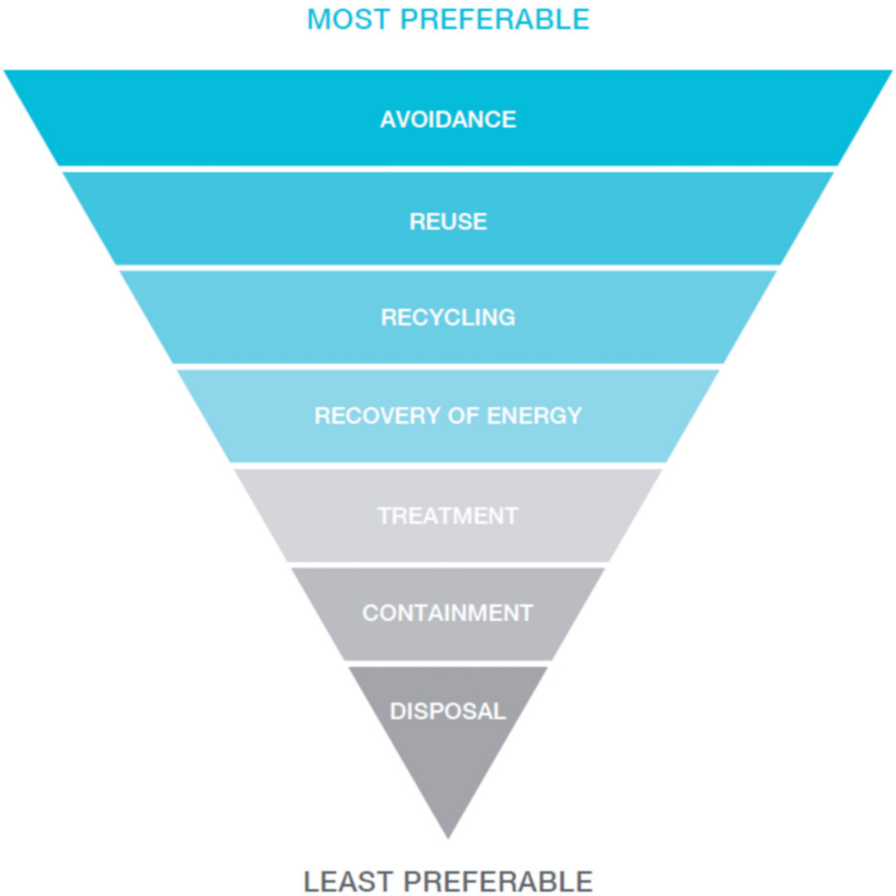

Fig. 4 Waste hierarchy. See Relevant Websites section.

chemical regeneration process. This process can also reduce the demand for the feedstocks for plastics in the market (Oku, 2005). In many plastic packaging we may find some identification codes which are shown in the figure below (**Fig. 5**):

Due to differences in melting and processing temperatures and the lack of compatibility, the quality of the products made from mixed plastics is reduced quite considerably (**Figs. 6–11**) (**Table 1**).

In 2018, 29.1 million tonnes of plastic waste were collected in the EU28 + NO/CH in order to be treated. Plastic waste exports outside the EU have decreased by 39% from 2016 to 2018.

Different Paths for Plastics Recovery

SPW recycling, treatment and recovery are very common in the plastic industry. The primary recycling is the re-extrusion process, and mechanical recycling as the secondary process has been described with advantages and disadvantages. It has been observed that the solid plastic waste for mechanical recycling process needs to have similar properties of commercial grade plastics for improved recovery of plastic waste. Tertiary or the chemical treatments of waste plastic are the thermo-chemical treatment methods which are more sustainable, produce the monomers or the feedstocks by pyrolysis methods. The quaternary treatment technologies are the incineration or combustion technologies which burn the SPW along with the municipal solid waste burning and hence, it is one of the energy recovery processes (Ragaert *et al.*, 2017; Singh *et al.*, 2017).

(1) *Primary recovery*: This is the reprocessing of the scraps and by-products of the same plastic material produced during the processing of finished products or extrusion process. This method of recycling is also known as re-extrusion process.
(2) *Secondary recovery or mechanical recovery*: Reprocessing scrap plastics by physical means into plastic recyclates or products. This process has been commercialized in 1970s. In this process the SPW is converted into powders, or flakes, or pellets resulting in volume reduction which depends on the components present in the SPW. This process also involves in size reduction (pellets, flakes or powders), contaminant separation (separation of paper, metals and dusts using cyclone), floating (separation based on density differences in a floating tank) and finally washing, drying and palletization. This process is the best for a single component SPW like industrial scraps and homogeneous post-consumer plastics recovery. Mechanical recovery mostly follows the methods of recovery of plastics where no change in chemical structures and properties takes place and plastics are used directly after mechanical crush or

Fig. 5 Packaging codes by Society of Plastics Industry.

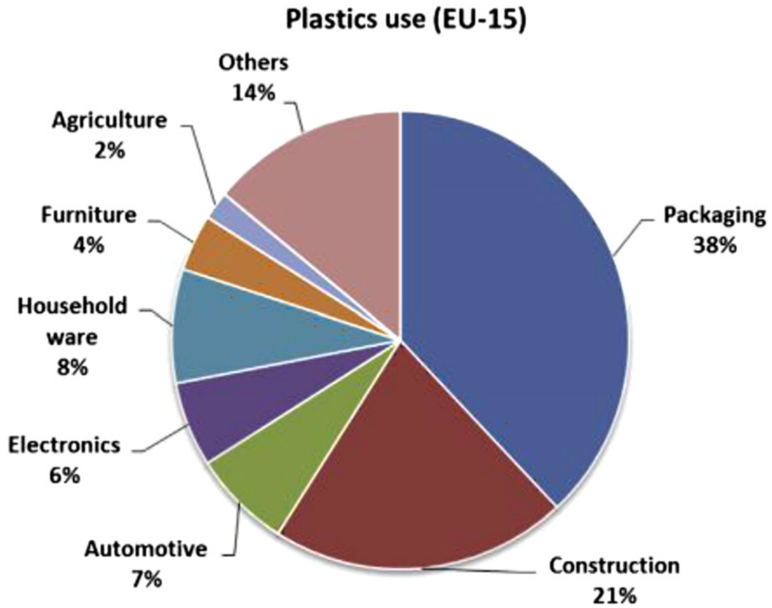

Fig. 6 Major applications of plastics in the European Union (EU-27) in 2011. Reproduced from Plastics Europe, 2012. Plastics – the facts 2012. An Analysis of European Plastics Production, Demand and Recovery for 2011. Plastics Europe Association of Plastics Manufacturers. Brussels. Available at: www.plasticseurope.org.

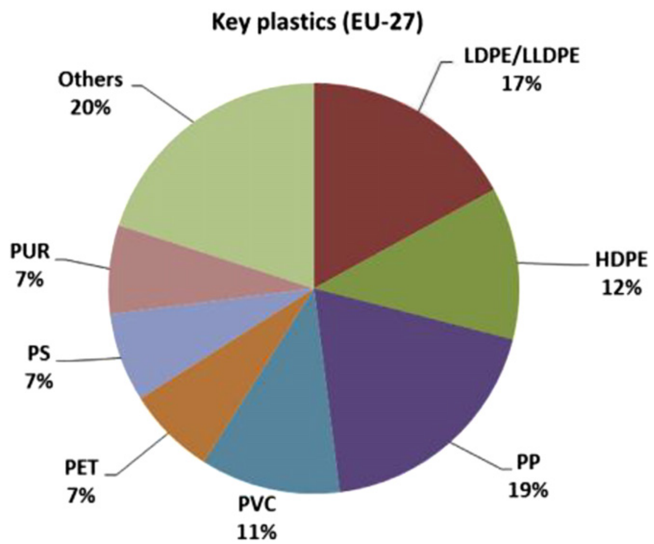

Fig. 7 Major types as used in the European Union (EU-27) in 2011. Reproduced from. Plastics Europe, 2012. Plastics – the facts 2012. An Analysis of European Plastics Production, Demand and Recovery for 2011. Plastics Europe Association of Plastics Manufacturers. Brussels. Available at: www.plasticseurope.org.

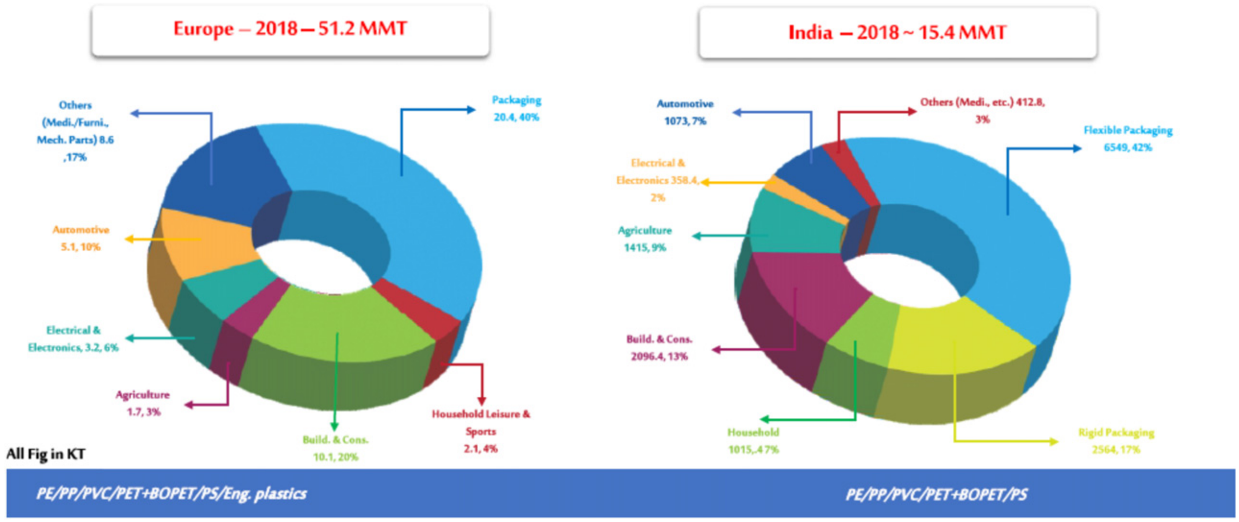

Fig. 8 Major sector wise plastics consumption India vs. Europe. See Relevant Websites section.

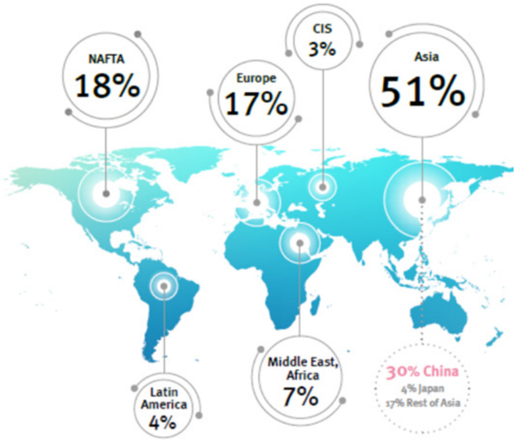

Fig. 9 Distribution of global plastic production 2018. Reproduced from Plastics Europe, 2019. Plastics – the facts 2019. An analysis of European Plastics Production, Demand and Recovery for 2018. PlasticsEurope Association of Plastics Manufacturers. Report. Brussels. Available at: www.plasticseurope.org.

adhesive bonding. Besides low operational costs and easy operational methods, mechanical recovery rate is low with limited applications (Al-Salem *et al.*, 2009; Hopewell *et al.*, 2009; Ragaert *et al.*, 2017; Singh *et al.*, 2017; Gu *et al.*, 2017).

(3) *Tertiary recovery or chemical feedstock recovery*: Also known as chemical recycling where the chemical structures of the SPW components are depolymerized by pyrolysis to produce oil and gas fractions in presence of air at high temperature (Ragaert *et al.*, 2017). Catalytic cracking, steam degradation and liquid–gas hydrogenation are also commonly used in tertiary recycling of SPW for the production of various monomers. Condensation polymerized plastics like nylons polyesters, and polyurethanes are suitably converted to monomers by glycolysis, methanolysis, and hydrolysis processes. Whereas addition of polymerized plastics like vinyls, acrylics, fluoroplastics, and polyolefins are difficult to reprocess. These wastes may be sorted out and mixed with respective virgin resins after they are powdered and blended with virgin plastics for remolding into finished goods or using suitable compatibilisers to make recycled products. Fluidized bed pyrolysis provides excellent heat and mass transfer between the particles and has been found to be most suitable for the chemical processing of the mixed plastic wastes. It has been reported that using fluidized bed pyrolysis, 25%–45% of product gas with a high heating value and 30%–50% of an oil rich in aromatics could be recovered (Kaminsky, 1995). While Comparing with virgin polyester, chemically recovered fibers provide lower desired physicochemical characteristics. Although, chemically recycled fibers can be applied in a wider range of applications than mechanically recycled fibers, mechanically recycled plastics provides better environmental impacts than chemical recycled plastics (Shen *et al.*, 2010).

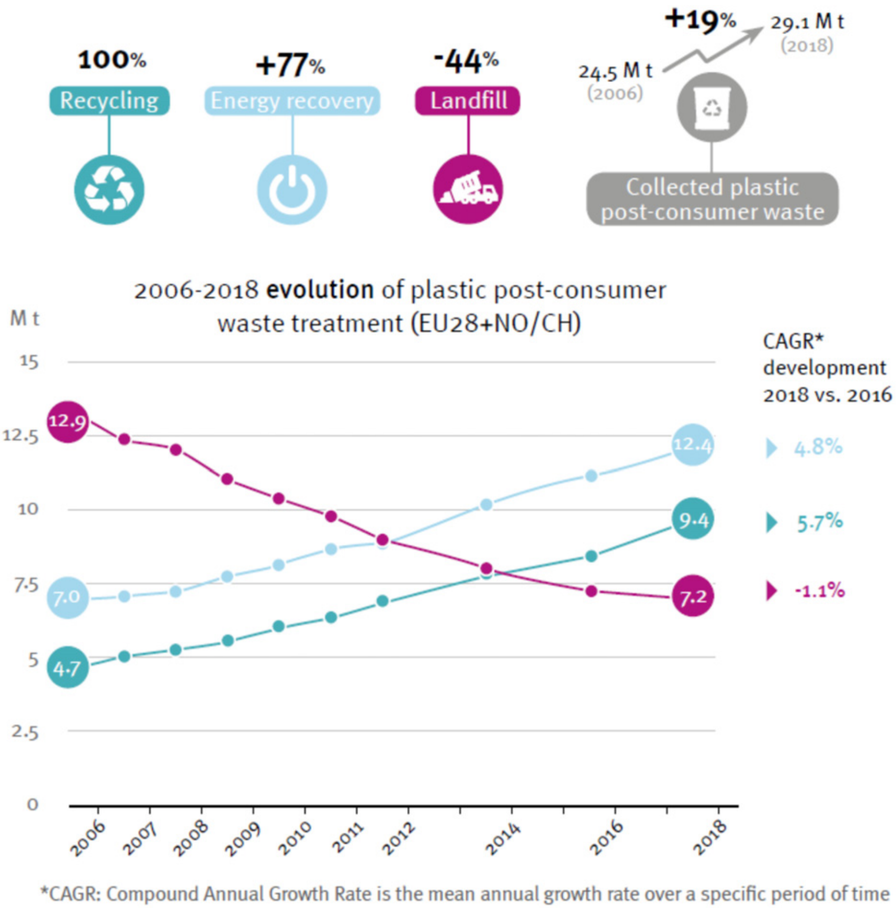

Fig. 10 Amount of plastic waste recycling in Europe. Reproduced from Plastics Europe, 2019. Plastics – the facts 2019. An analysis of European Plastics Production, Demand and Recovery for 2018. PlasticsEurope Association of Plastics Manufacturers. Report. Brussels. Available at: www.plasticseurope.org.

Fig. 11 Plastic postconsumer waste treatment in 2018. Reproduced from Plastics Europe, 2019. Plastics – the facts 2019. An analysis of European Plastics Production, Demand and Recovery for 2018. PlasticsEurope Association of Plastics Manufacturers. Report. Brussels. Available at: www.plasticseurope.org.

Table 1 Approximate percentages of different plastics present in PSW from household refuse

Mixed plastic percentage from household wastes	
Name of plastic material	Approximate%
Polyethylene	55
Polypropylene	15
Polyvinyl chloride	11
Polystyrene	9
Expanded polystyrene (foamed materials such as fast food packaging)	3
Remainder (various)	7

Note: Goodship, V., 2007. Introduction to Plastics Recycling. Shrewsbury, Shropshire: Smithers Rapra Technology Limited Shawbury.

(4) *Quaternary recovery or process engineered fuel*: This process consists of conversion of pre consumer or post-consumer plastics into an industrial fuel that meets market specifications. When all the material recovery processes from the SPW fails due to economic reasons, they are burned to produce heat energy converted to hot water, steam and electricity. During thermal recycling of plastics, energy derived from plastics along with other high caloric waste streams is used as fuel. Thermal decomposition is a costlier process with environment pollution when some toxic gaseous components are liberated into the atmosphere (Al-Salem *et al.*, 2009).

(5) *Landfilling with waste plastic*: This may be the last option with relatively less environmental pollution (Rebeiz and Craft,1995; Siddique *et al.*, 2008) (**Fig. 12**).

Recent Developments in Plastic Regeneration and Recovery

Value recovery from plastics waste by pyrolysis using molten salts: A low temperature (420–480°C) pyrolysis using molten salts has been carried out in the laboratory. The pyrolysis products obtained are light oils, aromatics, paraffin waxes and monomers of high economic value. Although the process is capital intensive, small units of capacity one tonne per day is viable (Bertolini and Fontaine, 1987).

Thermal degradation of mixed plastic waste: Using Hamburg Pyrolysis Process, mixed plastic waste with less than 1% chlorine content can be processed to produce nearly 48 wt% of oil containing benzene, toluene, xylenes and styrene with calorific value of around 50 MJ/Kg. The products can be used as feedstock for petrochemical productions. The chlorine and the heavy metals are obtained from the residue have calorific value of about 40 MJ/Kg (Kaminsky *et al.*, 1996).

Recovery of plastics using froth flotation: Froth flotation has been used to recover plastics from municipal solid waste. Since inorganic minerals possess high-energy surfaces, strong adsorption of inorganic minerals by solutes stabilizes the electrical forces for flotation. Whereas, due to low-energy surfaces of plastics, solutes do not get adsorbed and electrical stabilizing forces are not formed for flotation (Alter, 2005).

Rapid characterization of plastics using laser-induced plasma spectroscopy (LIPS): A compact laser-induced plasma spectrometer has been developed for instant identification of post-consumer plastics by LIPS. A software package consisting of data acquisition and data processing has also been developed. Nearly 90%–99% reliable identification of almost all analysed plastics has been reported for on-line, real-time analysis of recycling materials (Anzano *et al.*, 2006).

Alkaline hydrothermal treatment of brominated high impact polystyrene (HIPS-Br) for bromine and bromine-free plastic recovery: During the debromination of high impact polystyrene (HIPS-Br), Br can be recovered as KBr from aqueous solution after treatment. The plastic can be recovered as individual pellets with similar molecular weight as initial HIPS-Br. Debromination with only water is carried out when very low amounts of HIPS-Br is present (Brebu *et al.*, 2006).

Recycling of cable plastics: A life cycle assessment of different recycling alternatives for cable plastic waste are mechanical recycling, chemical recycling and energy recovery or incineration process. The recycling of plastics from Sweden in China the options are: open burning in granulation and energy recovery, and cable stripping. From an environmental point of view, recycling of plastics from Sweden in China is worse (Lindahl and Winsnes, 2005).

A goal programming approach for plastic recycling system in Thailand: A mixed integer goal programming (MIGP) has been developed as a multi objective recycling program for proper planning of solid plastic recycling in Thailand. Reduction in total cost, increase in the amount of plastic recovery and raising the desired plastic materials in recycling process are the major objectives of the above study. To get the targeted amount of recycled plastic and the desired plastic materials, the total budgeted costs are required (Wongthatsanekorn, 2009).

Plastic wastes recovery using free-fall triboelectric separator: A simple triboelectric separator used for PVC and PE wastes separation. Experimental studies carried out in the laboratory and it has been found that the degree of purity of the separated materials depends on the characteristics of the materials to be separated, the applied potential difference between the electrodes, rotational speed of the separator tube, material of the tube, and diameter and inclination of the tube (Bendimerad *et al.*, 2009).

Plastic waste management and uncertainties in a life cycle perspective: The aim of the European Union waste management policy is to reuse and recycle of the materials for increasing the material efficiency. Various waste management options are discussed for the environmentally beneficial processes with life cycle assessment studies. Identification of the main methodological considerations for the plastic waste management including uncertainties are discussed (Lazarevic *et al.*, 2010).

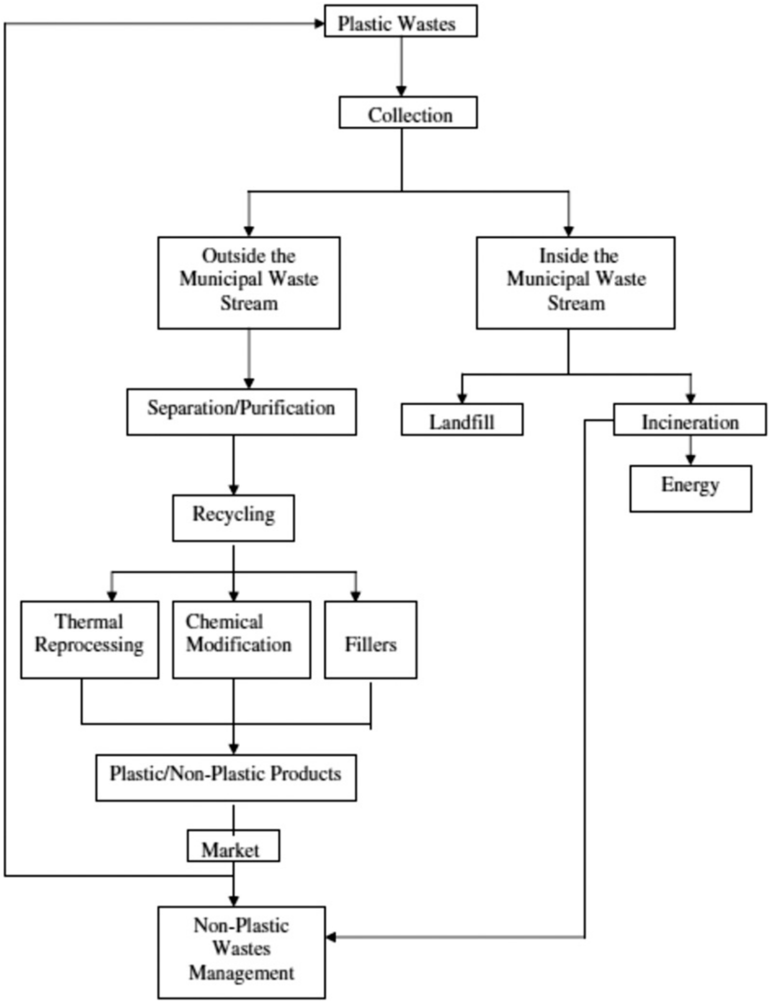

Fig. 12 Plastic waste management process. Reproduced from Rebeiz, K.S., Craft, A.P., 1995. Plastic waste management in construction: Technological and institutional issues. Resources, Conservation and Recycling 15, 245–257.

Separation of packaging plastics by froth flotation: Froth flotation process for the separation of post-consumer polyethylene terephthalate(PET) from other packaging plastics with similar density consisting of 85% PET, 2.5% PVC (polyvinyl chloride) and 11.9% PS (polystyrene)has been reported. Treatment with a combination of alkali and surfactant followed by froth flotation in a continuously operated pilot plant can improve the separation producing a concentrate grade with 97.2% PET, 1.1% PVC and 1.1% PS (Carvalho *et al.*, 2010).

Recycling of high-density polyethylene to fuel: The pyrolysis of plastic wastes is carried out to produce hydrocarbon fractions like gasoline, kerosene and diesel. HDPE, LDPE, PP, PS, PVC, PET, PA, PUR, etc., are used as feedstocks for the pyrolysis, where the polyolefins and polystyrenes are found to be successfully degraded to hydrocarbon fractions. The pyrolysis in advanced reactors results in successful degradation of HDPE to middle distillates using suitable catalysts (Kumar *et al.*, 2011).

Recycling of plastics from cable waste: A commercial process PlastSep has been reported where the cable plastic waste can produce polyolefin and PVC rich fractions. Copper and aluminum can be separated from the plastic fractions and be recycled with 99.5% yield (Boss *et al.*, 2011).

Catalytic pyrolysis of plastic wastes: A commercial synthetic zeolite (ZSM-5, Zeolyst International) and waste red mud have been used as catalysts for pyrolysis of solid waste plastic consisting of both virgin and recycled plastics. The use of catalysts shows its influence in the recycled product quality and yields. ZSM-5 promotes low molecular weight gas production and higher aromatic containing liquids at 440°C from the feed containing polyolefinic feedstock. On the other hand, red mud mainly containing Fe_2O_3, Al_2O_3 and TiO_2 produces a higher yield of gases and a greater proportion of aromatics in the liquids at 500°C. The above catalytic pyrolysis may be another economical way of regeneration and recovery of solid plastic waste (López *et al.*, 2011).

Waste plastic recycling in Japan: Japan has enforced their Packaging and Recycling Law from 2000. Mechanical and thermal recycling methods are carried out along with the life cycle assessment for PET plastic waste. Thermal decomposition of waste plastic or gasification of waste plastic for ammonia production is found to be the most effective method to reduce the environmental effect for the sustainable development (Kamo, 2011).

Dissolved air flotation on separation of waste: Dissolved air flotation method has been used to separate waste plastics containing acrylonitrile butadiene styrene (ABS) and polystyrene (PS). Wetting agents like tannic acid and terpinol as frother are used for improved separation of the above plastics. The purity and recovery rate of waste PS in the floated products were 90.12% and 97.45%, respectively, and the purity and recovery rate of waste ABS in the depressed products are 97.24% and 89.38%, respectively (Wang *et al.*, 2012).

Plastic recycling in Rio de Janeiro: Field research with visits to plastic recyclers, dealers, recycling cooperatives sorting plants, selective garbage programs and urban waste dumps shows that polyolefins and PET packaging plastic materials are the most abundant plastic materials dumped in Duque de Caxias and Rio de Janeiro City which have the highest plastic recycling capacity (jointly 60%) in the Metropolitan area of Rio de Janeiro. The recycled plastics mostly have low aggregate value. Selective garbage separation is the key to get quality products during plastic recycling at a lower cost (Pacheco *et al.*, 2012).

Solid waste management and plastic recycling in Qatar: In Qatar, the second major waste component of MSW is the plastic waste. The life cycle assessment (LCA) shows that the recycling of plastic wastes is the best solution for the municipal plastic waste. The total amount of municipal solid waste generation, storage, collection and disposal along with major the constituents of the above waste in Qatar shows that nearly 2,000,000 tons per day of solid municipal is accumulated for landfill and composting which is considered to be the most appropriate waste disposal techniques in Qatar. This may reduce the environmental impact by reducing the Global Warming Potential (GWP) and Human Toxicity Potentials (HTP) indicators (Al-Maaded *et al.*, 2012).

Municipal solid waste characteristics and potential of plastic recovery in Malaysia: The MSW at Bakri Landfill, Malaysia mainly contains food waste, plastic and paper. The total amount of the above three components is approximately 55% of the total MSW. The MSW containing the plastics waste is contaminated with paper and soil which amounts to nearly 35 tonnes per day. To recover high quality of recovered plastic, removal of the above contaminants is essential. The solid waste generation in the city is presently very high and needs further attention to its recovery (Kalanatarifard and Yang, 2012).

Recycling and recovery of post-consumer plastic solid waste in Europe: Plastics are mostly non-biodegradable and only 1%–3% of the hydrocarbon content of it degrades during nearly 100 years (Al-Salem *et al.*, 2009). Due to the high volume to weight ratio, recycling of plastics is not attractive. Collection, transportation, recycling, reprocessing, and the virgin feedstock price have an impact on the ultimate cost of the recycled/recovered plastics (Ambrose *et al.*, 2002). Since landfill by plastic waste is no longer a viable option, mechanical and thermal recycling processes are the two options where the first option is suitable for a homogeneous plastic waste. A mixed plastic waste needs to be treated and pyrolysis is the most suitable option where feedstocks may be produced. Incineration may be another option where burning of waste plastics can produce heat energy where plastics possess calorific value ranging from 30 to 40 MJ/kg. Besides the various technical options available, several European directives and US legislation related to plastic wastes management needs to be considered (Brems *et al.*, 2012).

Preparation of nanocomposites: Addition of nano fillers like nano clay, $CaCO_3$, carbon nano tubes(CNTs), SiO_2, mica and graphene are found to be an efficient technique for recycling of polymers such as PP, HDPE, PVC, etc., composites and blends. The application of compatibilisers for recycling of blends and composites are reported to be more useful for the recycled polymers with improved properties, low-weight, ease of processing, and low cost (Zare, 2013).

Recycling of bioplastics, their blends and bio composites: The mechanical recycling of bioplastics, their blends and thermoplastic bio-composites has been reviewed. During mechanical recycling, due to the presence of shear stress, heat, oxygen, UV light, residual catalyst and water, the recycled products are degraded along with the changes in their physic-chemical properties, stability and functional qualities. High quality extruded and recycled products are difficult to get from the above process (Soroudi and Jakubowicz, 2013).

Recycling of waste from polymer materials: Polymeric wastes form polyethylene, polypropylene, and polystyrene along with their blends and composites has been carried out using the mechanical and chemical recycling concepts. Mechanical recycling is preferred to the chemical recycling where the waste is subject to complex chemical treatments. During mechanical recycling, addition of a small amount of virgin polymers to the waste from same or other polymers in the presence of suitable compatibilisers have improved the properties of the recycled products (Hamad *et al.*, 2013).

Characterization of polyolefin packaging waste: Pre-concentrate of mixed Romanian household waste obtained by hand picking. To recover high-purity polyolefins from complex wastes at low cost, Magnetic Density separation (MDS) and Hyperspectral Imaging (HSI) based approach have been reported (Bakker *et al.*, 2009; Serranti *et al.*, 2011). To distinguish the polymer manufacturing methods (injection molding or blow molding) by flake physical properties and finally to perform all the required characterization and identification by hyperspectral imaging has been carried out. It has been observed that, polyolefins from packaging wastes can be recycled by density separation. Hyperspectral imaging based procedures have been also applied to set up quality control actions for recycled products (Hu *et al.*, 2013).

Technical specifications for mechanical recycling of agricultural plastic waste: Some of the agricultural plastic waste of film categories contains significant amount of dirt. During the recycling process of the above film waste, the film becomes curled resulting in plugging the extruder filter and hence, it has been found to be difficult to recycle such plastic wastes, and the recycling of thin agriculture needs to be pelletized or flaked. For valorising the waste stream, LabelAgri-Waste collection a unique shipping format for APW across Europe has been carried out (Briassoulis *et al.*, 2013).

Tribo-electrostatic separation for granular plastic waste recycling: Incineration of municipal solid waste containing plastics may produce many toxic components like polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), polychlorinated dioxins (PCDs) and polychlorinated dibenzofurans (PCDFs) in the fly ash. The above compounds may cause carcinogenesis, teratogenesis and mutagenesis (Chung *et al.*, 2010). Tribo-electrostatic separation for the granular plastic waste

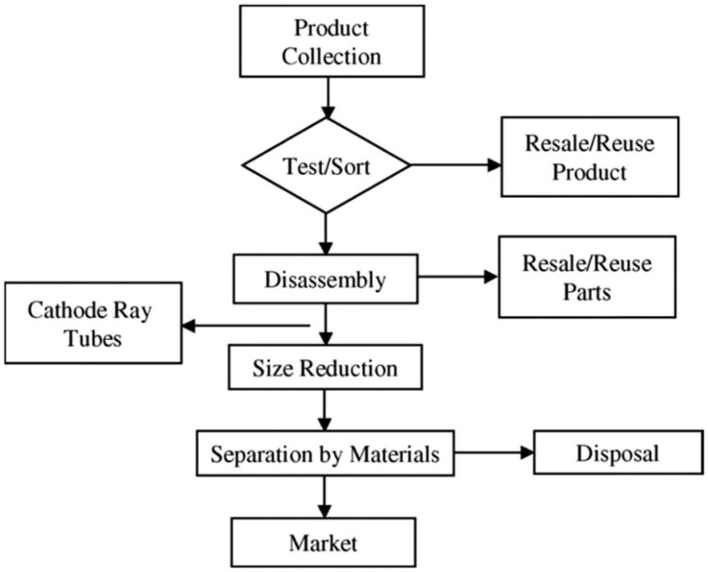

Fig. 13 Schematic diagram for the recycling of electronic products. Reproduced from Kang, H.Y., Schoenung, J.M., 2005. Electronic waste recycling: A review of U.S. infrastructure and technology options. Resources, Conservation and Recycling 45, 368–400.

has been reported for separation of plastic waste, development and effectiveness of various devices have been discussed (Wu *et al.*, 2013).

Wastes of electrical and electronic equipment: Glass, plastics, and metals found in e-waste. For glass, glass-to-glass recycling and glass-to-lead recycling technologies and the recovery processes for copper, lead, and precious metals such as silver, gold, platinum, and palladium are different from recovering plastics using chemical recycling, mechanical recycling, and thermal recycling methods (Kang and Schoenung, 2005). Chopped electric wires or printed-board circuits may be processed for recovery using electrostatic separation methods (Li *et al.*, 2008). Although electrostatic forces can control the motion of charged particles resulting in electrostatic precipitation, electrostatic powder coating and electrostatic separation, the electrostatic separation of fine particles such as powder and micrometric-size particles is still less efficient due to the aerodynamic forces. The efficiency depends on several factors including the high-voltage level, the rotating speed of the disks, the fluidization rate, the total mass of the fluidized bed and the composition ratio of the granular mixture. The analytical methods need to be used to develop a correlation between the particle system, the particle properties, and the chargeability adapted (Landauer and Foerst, 2018; Bouhamri *et al.*, 2019). The recycling of a mixture of polycarbonate and polyamide plastics from waste electrical and electronic equipment using electrical and electronic equipment has been reported. Initially separation is carried out using a tribo-aero-electrostatic separator. Tribo-aero-electrostatic separated granular waste is being subsequently treated in two free-fall electrostatic separators. The tribo-aero-electrostatic separator and the free-fall electrostatic separator are the upper and lower sections of the same installation. The purity of the products has been verified using a program of image processing in MATLAB. A very high purity separation (roughly 95% for both PC and PA) at a recovery rate higher than 70% has been reported (Aksa *et al.*, 2013) (**Fig. 13**).

Use of recycled plastics in wood plastic composites: When the waste plastics are collected from various sources, their performance varies due to their exposure to various environmental conditions and recycling/reprocessing cycles. Wood plastic composites may be a promising material to be manufactured using waste plastic as one of the major feedstocks. The physical and mechanical properties of waste and recycled plastics have been discussed (Najafi, 2013).

Regeneration and recycling of waste thermosetting plastics: During mechanical and thermal processing, molecular structure and chemical properties of phenolic resins changed due the breakdown of the cross-linked structure. As a result, a lot of mechanically active groups are formed and the crosslink density is decreased. Reshaping of phenolic resin and polypropylene blend composites are produced. Mechanical testing results shows that phenolic resin improves the recycling rate. The tensile strength and bending strength of samples are found to be high (Wu *et al.*, 2014).

The recovery potential of plastic wastes obtained from landfill mining: Incineration or treating as residue derived fuels for recovering energy has been found to be the most practical way to process landfill mining plastic wastes under the normal cleaning techniques. A typical old landfill of 24 years of storage in central China, the plastics waste contains $10.62 \pm 5.12\%$ of the total stored wastes in the old landfill, among which, 69.13% contains plastic bags (white PE plastic bags accounted for 11.34%; colored PE plastic bags 29.77%; other plastic bags 28.02%), and 30.87% are other plastics (including PP, PVC, PS, etc.). Since it is difficult to remove all impurities present on plastic surfaces of the excavated plastic bags, mechanical or chemical methods using pyrolysis or gasification or hydrogenation are not suitable. The most suitable method for recycling such plastic wastes to recover the energy out of such wastes is incineration (Zhou *et al.*, 2014).

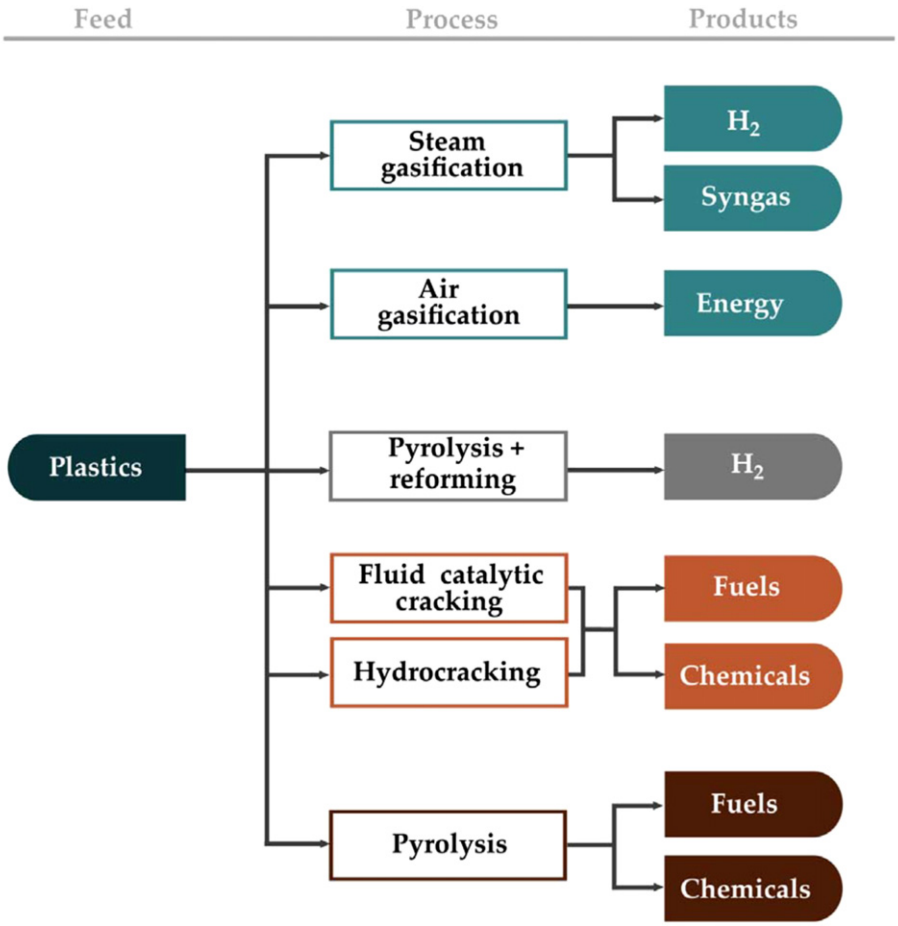

Fig. 14 Schematic diagram for chemical valorization of waste plastics. Reproduced from Lopez, G., Lopez, G., Artetxe, *et al.*, 2018. Recent advances in the gasification of waste plastics. A critical overview. Renewable and Sustainable Energy Reviews 82, 576–596.

Selective floatation of polycarbonate and polystyrene waste plastics: Separation of polycarbonate(PC) plastic waste from a mixture of PC and polystyrene (PS) has been carried out using selective floatation process. The wettability of PC surface has been modified by ammonia treatment where PC is obtained as the floated product and PS as the submerged product. The purity of PC in the submerged product and PS in the overflowed product is found to be up to 98.21% and 99.53%, respectively. The above process is claimed to be cheaper compared to other separation processes for waste PC and PS mixture (Wang *et al.*, 2016).

Implications of the presence of phthalates in plastics recycling: "Phthalates" or phthalic acid esters are widely used as plasticisers in plastics production, with polyvinyl chloride (PVC). It has been observed that phthalate contents in plastic items disposed in residual or source-segregated waste are same. The insignificant difference between household residual waste plastics (RWP) and source-segregated waste plastics (SSWP) of recycled household plastics (RHP) suggest that phthalates are not removed following plastics recycling. In such cases there may be the chances of the presence of phthalates during the recycling process which may result in phthalate spreading and accumulation of phthalates. No significant phthalate contents are detected neither in the virgin nor in the recycled industrial plastic waste. Detection of significant phthalate content indicates that phthalates are added in the later stages of manufacturing (labeling, gluing, etc.) or the samples of the household waste plastics are contaminated by other articles with higher phthalate content (e.g., PVC) (Pivnenko *et al.*, 2016).

Thermal and catalytic pyrolysis of plastic solid waste: Treatment of plastic solid waste (PSW) has been carried out using pyrolysis in oxygen free atmosphere resulting in no dioxins production, reducing carbon monoxide and dioxide emissions. The pyrolysis has produced a wide range of feedstock or as energy and has minimized the dependency on oil and gas, besides solving the landfilling problem. For both thermal and catalytic pyrolysis, the operating parameters like temperature, pressure, residence time are quite flexible for any desired product mixture production (Al-Salem *et al.*, 2017).

Recycling of plastic solid waste and future applications: Various recycling methods for plastic solid waste (PSW) has been discussed in detail along with their identification and separation techniques for PSW including froth flotation and magnetic density separation. Effects of various reinforcements like sand, fiber, ash, rice husk, wood husk, metal powder etc., on the virgin and recycled HDPE/LDPE/Nylon has also been reviewed (Singh *et al.*, 2017).

Mechanical and chemical recycling of solid plastic waste: Mechanical recycling, separation, froth flotation, magnetic density separation and X-ray detection etc., including thermo-mechanical or lifetime degradation and the immiscibility of plastic blends in

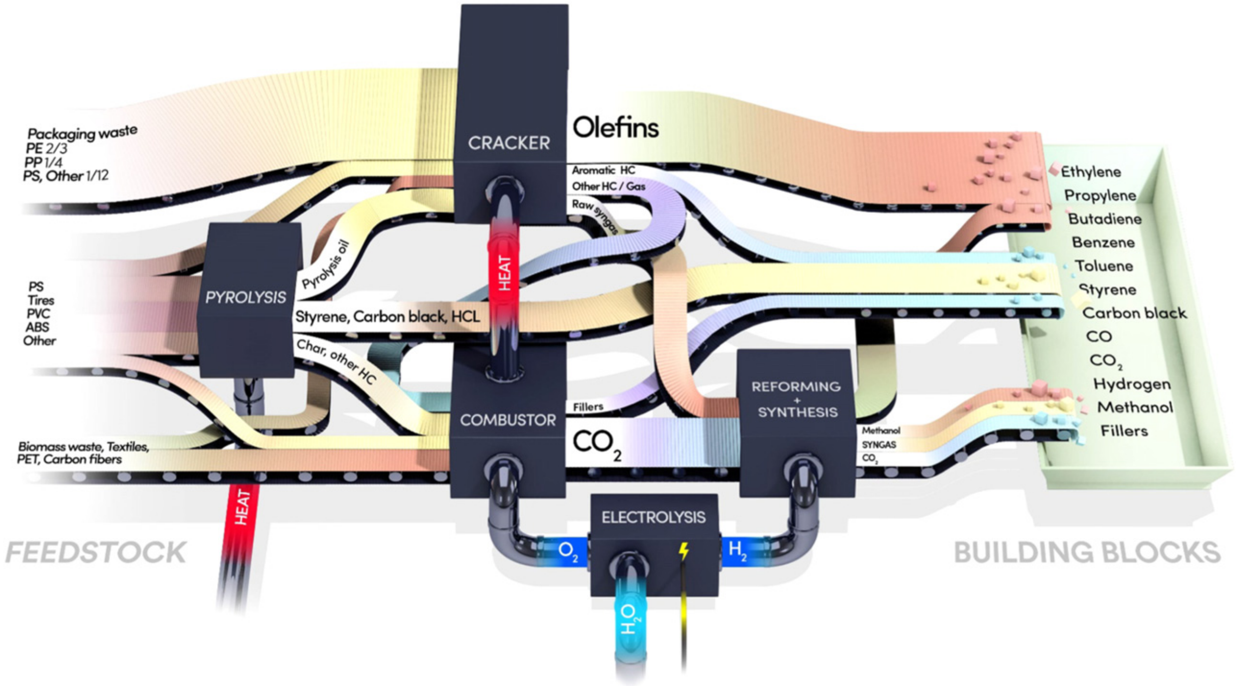

Fig. 15 Schematic diagram thermochemical recycling of plastics nearly 100% carbon recovery. Reproduced from Thunman H., Vilches, T.B., Seemann, M., *et al.*, 2019. Circular use of plastics-transformation of existing petrochemical clusters into thermochemical recycling plants with 100% plastics. Materials and Technologies 22, e00124.

SPW have been discussed. In chemical recycling the conversion of plastics into smaller molecules can produce fuels or virgin plastics with almost identical performance as the virgin monomers. A number of chemical recycling processes like chemolysis, pyrolysis, fluid catalytic cracking, hydrocracking, gasification etc., have been reviewed and found that chemical recycling process may be preferentially used for heterogeneous and contaminated SPW. The contaminations present in waste has been found to affect the product quality which directly controls economics of the recycled materials (Ragaert *et al.*, 2017).

Plastic waste to liquid oil through catalytic pyrolysis using natural and synthetic zeolite catalysts: Catalytic pyrolysis of plastic wastes containing PE, PS, PP, and PET has been carried out using both natural and synthetic zeolite catalysts which produced styrene, ethylbenzene, benzene, azulene, naphthalene, and toluene with a few aliphatic hydrocarbon compounds. GCMS and FTIR analyzes are used for the characterization of the pyrolysis products. It has been observed that the pyrolysis products may be used as value-added products after proper refining or blending with commercial fuels (Miandad *et al.*, 2017).

Separation and recovery of glass, plastic and indium from spent liquid crystal displays (LCD) panels: Recovery of valuable fractions like plastic, glass and indium by physico-mechanical pre-treatments for dismantling of spent LCDs has been discussed. Wet and dry processes are followed for the recovery where the recovery is found to be 20%, 15% and 40% by weight of the feeding panels as plastic, glass and indium concentrate respectively from the wet process, and in the dry process, only two fractions are separated and around 11% and 85% by weight are recovered as plastic and glass/indium mixture (Ferella *et al.*, 2017).

Plastic flexible films waste management: Based on the quality and the applications of the recycled materials, clean and homogeneous post-industrial and post-consumer plastic waste is recycled through closed-loop or open-loop mechanical processes. The closed loop mechanical recycling process method shows minimum material degradation. Due to the availability of selective waste collection routes, the post-consumer wastes from agricultural and packaging sectors are recycled through open-loop mechanical recycling. The presence contaminations in the waste adversely affects the quality of recycled plastics which has necessitated upgradation of washing the wastes before processing. Due to insufficient sorting technologies, the recycling of household flexible packaging is lowest. Only a limited number of Life Cycle Assessment (LCA) on the above type of waste management has been reported (Horodytska *et al.*, 2018).

Gasification of waste plastics: Several gasification of waste plastics has been performed at pilot scale units. The success of any commercial plastic valorization process depends on its ability to process plastic wastes with high impurity contents. The co-gasification of plastics with coal and biomass valorization route has been found to have more process flexibility. Pyrolysis and in-line reforming processes found to produce syngas and hydrogen free of tar (Lopez *et al.*, 2018) (**Fig. 14**).

Recycling of polystyrene based plastics: Recycling of polystyrene based plastics has been reviewed including the various separation methods used before recycling for such materials (Thakur *et al.*, 2018).

Solvent-based separation and recycling of waste plastics: Separation and recovery of plastics by various solvent extraction methods has been used selectively. Distillation methods for the recovery of plastics after dissolution resulted in degradation of the recovered monomers. The selection of proper solvent and purification techniques are the most challenging. As the solid plastic waste is

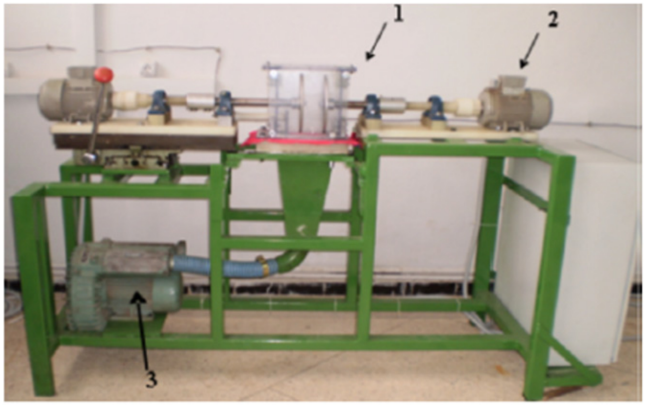

Fig. 16 The tribo-electrostatic separator: (1) Separation chamber/Electrodes; (2) Motor; (3) Air compressor. Reproduced from Bouhamri, N., Zelmat, M.E., Tilmatine, A., 2019. Micronized plastic waste recycling using two-disc tribo-electrostatic separation process. Advanced Powder Technology 30, 625–631.

mixture of different type of plastics, the recovered products widely vary in qualities and properties. Besides the above, there are several disadvantages including the use of hazardous solvents and higher cost of the solvents limits the usage of the above process (Zhao *et al.*, 2018).

Circular use of plastics-transformation of existing petrochemical clusters into thermochemical recycling plants: For the transformation of plastic waste (PW) into a thermochemical recycling plant for 100% recovery of plastics, the following sequence has been followed: (1) partially feedstock replacement (45% on carbon basis) by PW; (2) total replacement by PW; (3) the process undergoes electrification; and (4) 100% carbon recovery in the form of monomers or permanent storage by oxy-combustion, carbon capture and storage. Using thermochemical recycling, the technical solution and the process economics for closing the material cycle of plastics has been studied. The above process can handle any type of plastic waste (sorted or mixed) with close to 100% carbon recovery (Thunman *et al.*, 2019) (**Fig. 15**).

Utilization and recycling of end of life plastics for iron and steel industry: It has been observed that recycling of plastics in high-temperature materials processing like the iron and steel industry, out of 7% CO_2 emissions, nearly 30% of the carbon footprint is reduced using the waste plastics compared to other carbon sources, in addition to energy savings. During magnesia production, which is high carbon footprint process, plastics also greatly reduce the emissions and contributes to energy (Devasahayam *et al.*, 2019).

Delineating the plastic waste status in the State of Qatar: State of Qatar is one of the highest waste generating countries of the world and for last few years it has been producing nearly 1.4 kg/person/d during the past years. Out of the total MSW nearly 13%–14% plastics are present may be recovered. The challenges and opportunities for such waste management in the state of Qatar has been analysed using SWOT analysis (Hahladakis and Aljabri, 2019).

Dissolution and recovery of waste expanded polystyrene: From the waste expanded polystyrene (WEP), expanded polystyrene has been recovered using commercial essential oils for dissolution. The WEP and the recovered expanded polystyrene including the oil used for the recovery are characterized using various instrumental methods of analysis. The recovery process has been claimed to be cheaper and environment friendly (Gil-Jasso *et al.*, 2019).

Micronized plastic waste recycling: Recently, triboelectrostatic separation of a mixture of granular pure virgin micronized white polyvinylchloride particles (WPVC) and gray polyvinylchloride(GPVC) particles containing a small percentage of carbon of average size 100 μm has been carried out experimentally. It has been observed that the separation is efficient and the efficiency of the process depends on the rotating speed of the disc, the fluidization rate, the total mass of the fluidized bed and the composition ratio of the granular mixture and applied potential difference (Bouhamri *et al.*, 2019) (**Fig. 16**).

Environmental Aspects

Plastics are generally not bio-degradable and pollutes air and water, mixes with food chain effecting humans and animals. The plastic bags which are used for an average of 12 min can persist in the environment for half a millennium. The leaching of chemicals from plastics and then transfer of such chemicals to wildlife and humans are very common. Due to absence of light and cold atmosphere, the degradation rates of waste plastics in the deep sea is very slow. Waste plastics pollute the shorelines and the deep sea where shoreline debris contains nearly 50%–80% waste plastics. The ingestion of the plastic debris by an albatross has been reported where the plastic debris is of an aeroplane which crashed nearly 60 years ago (Barnes *et al.*, 2009; Thompson *et al.*, 2009). Marine plastic wastes get converted to microplastics due to photo-oxidation and thermal degradation during natural weathering processes (Wright *et al.*, 2013).

Scarcity of landfilling space and its cost has made waste utilization as an attractive alternative to landfilling by discarded tires, plastic, glass, steel, burnt foundry sand, and coal combustion by-products (CCBs). Waste plastics in concrete not only makes it

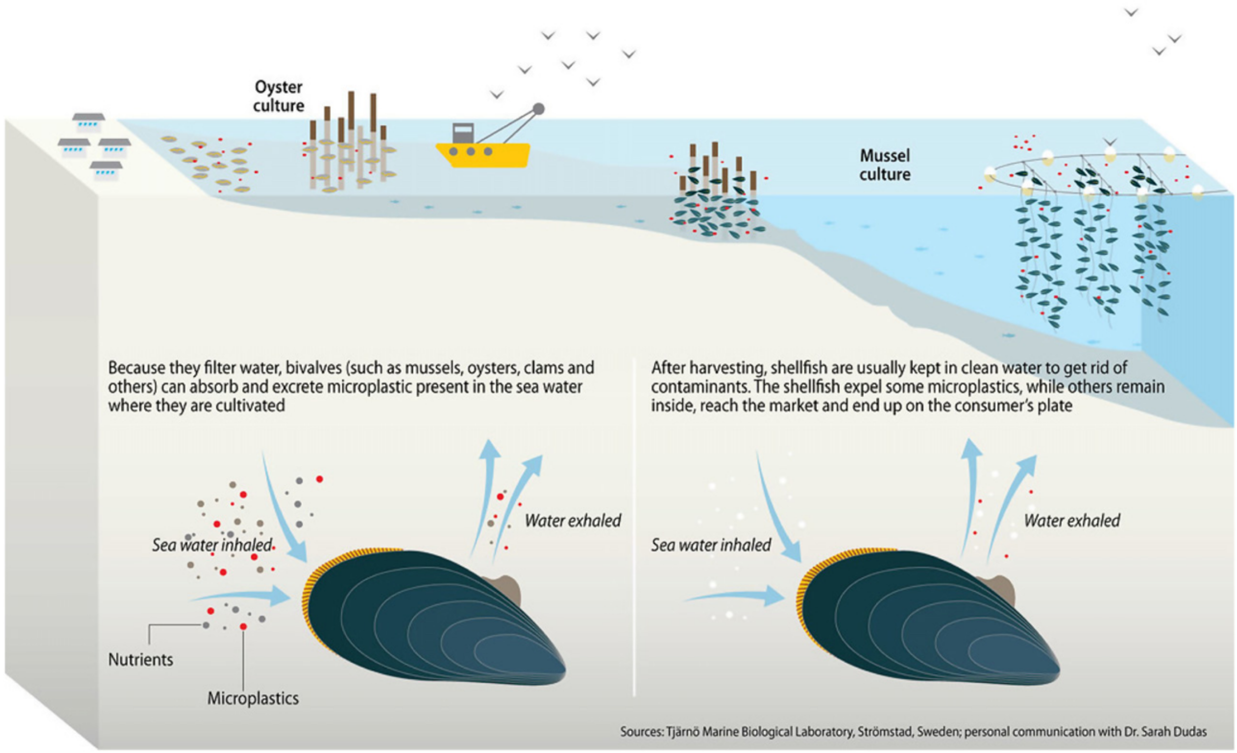

Fig. 17 How microplastics could end up on a consumer's plate. See Relevant Websites section.

economical, but also helps in reducing disposal problems. The effect of recycled and waste plastic depends on its bulk density, air content, workability, compressive strength, splitting tensile strength, modulus of elasticity, impact resistance, permeability, and abrasion resistance (Siddique *et al.*, 2008).

Life cycle assessment (LCA) is a method to assess the total environmental impacts of a product in all of its life cycle stages, including resource extraction, materials processing, manufacturing, transport, use, and end-of-life disposal. The environmental impacts associated with the alternatives for PSW technologies for the various recycling systems along with regenerating and energy recovery processes are used to analyze recycling options and the environmental effects. LCA is found to be most suitable for evaluating the overall environmental effects for regeneration and energy recovery from plastic solid waste for Shanghai (Zhou *et al.*, 2015).

Various pyrolysis methods of converting plastic waste like thermal and catalytic pyrolysis, microwave-assisted pyrolysis and fluid catalytic cracking to produce fuels like gasoline and diesel with high calorific value have been studied. The quality of the liquid fuel is mainly influenced by the type of catalysts used. Catalysts that possess lower acidity shows higher conversion to gasoline and diesel and helps in promoting a sustainable environment. Dissolution of plastic waste in a compatible solvent prior to catalytic pyrolysis may improve the conversion processes (Wong *et al.*, 2015).

LCA on environmental impacts of waste plastics from agricultural wastes, solid plastic wastes and the plastic wastes from the dismantled parts of electric and electronic equipment has been carried out for mechanical processing of recycling methods. The modifiers contribute more than the additives to the environmental impacts of recycled composites. Sensitivity analysis has been carried out to find that collecting network contribute very small environmental impact, whereas centralisation contributes a lot in reducing overall environmental impacts (Gu *et al.*, 2017).

Microplastics contamination throughout the marine environment results in widespread toxicity and epidemiology when they are ingested by fish and shellfish and pose concern when they accumulate and retain microplastics (Smith *et al.*, 2018). Long-term ingestion of contaminated sea foodstuffs with plastic contamination in the food chain may cause serious toxicity due to a leaky gut or a permeable blood-brain barrier (Waring *et al.*, 2018) (**Fig. 17**).

End-of-life (EOL) treatments for postconsumer plastic films are used to identify the key parameters affecting the environmental impacts of film waste. Recycling of plastic film waste is found to be more advantageous than landfilling or incineration for the environment. From sensitivity analysis it has been reported that increase in the mass fraction of films in waste significantly improves the environmental benefits of recycling. The recycling rate at the material recovery facility, utilization rate, and incinerator waste-to-energy ratio are the key parameters governing the life cycle environmental impacts of plastic film EOL treatments (Hou *et al.*, 2018).

In ballast waters multiple drug-resistant human pathogens through co-selection mechanisms are developed and spread. These are the sources and vectors for toxic chemicals, pathogenic bacteria, harmful algal bloom (HAB)-forming dinoflagellates, metals, and antibiotics across the continents through ballast water and may pose a serious threat to human health due to higher incidences of bacterial disease outbreaks and HABs (Naik *et al.*, 2019).

Polybrominated diphenyl ethers (PBDEs) and hexabromocyclododecane (HBCDD) are widely used in plastic products such as soft furnishings, building insulation foams, and electrical and electronic equipment(EEE). In high impact polystyrene (HIPS) for electrical applications Penta-BDE, Octa-BDE and Deca-BDE are generally used besides their applications in fabric and soft furnishing. For the treatment of polyurethane foam for transport, upholstery, mattresses, textiles, in circuit boards, packaging, and textiles, Penta-BDE is widely used in Ireland. Octa-BDE is also used in hard plastic acrylonitrile butadiene styrene (ABS) casings, HIPS and EEE. The Irish indoor air indoor dusts containing the above materials necessitates the health implications of such exposure to human beings (Wemken *et al.*, 2019).

Carcinogenic, neurotoxic additives are used in plastic products remain in the waste polluting the air, land and water and affect the land and marine food chains. Besides carbon and silica as reinforcing materials, vinyl chloride, dioxins, benzene, phthalates, brominated flame retardants, formaldehyde, and bisphenol-A and various other plasticizers are widely used as additives for plastics production. Many commercial products including food packaging, perfumes, cosmetics, toys, flooring materials, computers, compact disks and medical devices, can represent a significant content of the plastic. The above additives remain in the plastic wastes while they are recycled or used for landfilling. Regeneration of monomers from such wastes may be another option to segregate such additives by chemical or thermal methods of recycling/regeneration. Nearly 10% of the waste plastics are recycled and the rest of them are incinerated producing various toxic gases which are vented into the atmosphere causing air pollution (Manzoor *et al.*, 2020).

Environmental evaluation of plastic waste management along with sensitivity analysis has been carried out where five scenarios are defined and modeled with a life cycle assessment approach using the EASEWASTE model with four different scenarios. It has been observed that none of them is explicitly found to be the best for the above four options (Rigamonti *et al.*, 2014).

Biopolymers help in reducing the consumption of non-renewable energy and reduction in global warming. The environmental impact of each of the three biodegradable biopolymers: poly (lactic acid) (PLA), poly(hydroxyalkanoates) (PHAs), and starch-based polymers have been studied. A comparative study of the above renewable biopolymers with petrochemical based polymers shows that, despite some unfavorable impacts due to geographical location, biopolymers are superior to petrochemical derived polymers (Yates and Barlow., 2013).

Plastic waste has been piling up all over the world as people have started using more disposable packaging under Covid 19 lockdowns. Lot of plastic wastes are now being generated hence, creating more problems for recyclers.

It has also been reported that the coronavirus remains active on plastic even after 72 h, while on cardboard and copper it remains active only for 24 h (Brock, 2020).

Economics and Sustainability

Sustainable development requires the management of waste by reducing, reusing and recycling of materials. Packaging industry consumes a lot of plastics and they are thrown after one time use only. These type of short-live applications of plastics are not sustainable. Hence, when plastics are regenerated and recovered, rapidly declining fossil fuels consumption is reduced and helps in sustainable use of plastic products, reduces the economic pressure on the plastic industry, and contributes to sustainable development (Mwanza and Mbohwa, 2017).

For end of life (EOL) of plastics we need an efficient collection system, particularly for engineering plastics like ABS and PC. For economic viability, recycling needs to be very vigorous to perform the entire EOL of electronic products and the plastic materials. Nearly 87 wt% of the plastics in EOL electronics contains HIPS, ABS, and polyphenylene ether(PPE). It is impractical to try recycling all plastics from EOL electronics. The remaining plastics can be economically recycled using chemical feedstock recycling processes, or energy recovery systems. Based on local or regional considerations, landfilling may be the last available option (Fisher *et al.*, 2004). The recycling of e-waste from mobile phones through voluntary or mandatory take-back and collection programs is economical for the recovery of a limited number of its metallic components. Copper and precious metals contain 95% of the metal value of mobile phones which depends on the amount of gold in mobile phones and its market value (Geyer and Blass, 2010). The recycling of solid waste and municipal solid waste are the key drivers for sustainable development of post-consumer packaging plastic waste recycling systems. Application of the above drivers at different situations in developed and developing economies have been identified (Mwanza and Mbohwa, 2017).

Conclusions

For an effective regeneration and recovery of plastics segregation of waste is essential. It can help us to properly utilize the potential of the plastic waste. Separate bins for different types of wastes may greatly help in such waste segregation, their further processing and management.

Reuse of plastics is controversial. Many people favor one time use of plastic materials due to hygienic reasons, others may support the reuse of it for economic reasons.

Recovery and regeneration of plastic waste can reduce the consumption of non-renewable fossil fuels as feedstock and lower the impact on environment pollution. Recently, regeneration and recovery of waste plastics have been increasing worldwide with better way of collecting, segregating and proper processing of the waste. International quality certification with a transparent monitoring process may lead to plastic regeneration and recovery an attractive industry with high quality of plastic products in near future.

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