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On technological solutions for recycling of polymer waste: A review

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Abstract. In the past few decades (after the industrial revolution) the pollution caused by polymers has become a matter of concern and recycling of polymers as a solution has attracted global attention. Several studies were conducted in the context of polymer recycling, but hitherto little has been reported on the impact of technological solutions for recycling polymer waste and its effect on the economy andenvironment. In the present study, different polymer recycling techniques have been outlined in a comprehensive manner along with the effect of recycling on the economy and environment. Also, bibliographic analysis was performed to understand possible research gaps.

1 Introduction

In the past four decades, polymers (both thermoplastic and thermosetting) have become an inseparable part of humanlife. These plastics have transformed human life in many ways. Plastic has unique properties like cost effectiveness, lightweight, corrosion resistance and easeof manufacture. These qualities have enhanced theproduction of plastics dramatically [1, 2]. As per reportedliterature, more than 8400 metric tons (MT) of plastic hasbeen produced till today. Also, a huge amount of 6300 MT (approx.) of plastic waste has been generated. Approximately 12% of total plastic have been incinerated, 9% of which has been recycled and 79% was accumulated in landfills or neutral environment [3-5]. Shortly, if this trend continues for the next 10 to15 years, the eco-system will be unable to cope with the amount of plastic being produced. It has been reported that plastic waste is very harmful to the environment and to marine life [4, 5]. More than 12.7 million MT of plastic enters oceans per year and is supposed to increase for the next 20-30 years [6]. The great Pacific garbage patch has become the greatest threat to marine life. This patch consists of more than 80,000 tons of waste plastic and it has been spread over 1.6 million square kilometers. The majority of this patch consists of ghost fishing nets (discarded fishing nets),plastic bags, polyethene tetrathionate (PET) bottles, caps, and single-use plastic waste. 8% of the patch consists of microplastics. This plastic waste is responsiblefor toxifying seawater thus destroying their aquatic life [7]. It gets ingested by aquatic animals and destroys their natural habitat [4-7].

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The world is moving towards a circular economy. Theleakage of plastic in the terrestrial and aquatic environment should be precisely controlled [8]. It should be done by improving after-collection and enhancing storage facilities. Strict government regulations and more innovation for plastic alternatives are required. Paris Agreement is one of the recent initiatives taken by the United Nations to join countries together on the issue of greenhouse gas emissions and environmental pollution. Asof the year 2020, a total number of 169 countries have signed this pact. There is a strict need to develop carbon-neutral alternatives to decrease greenhouse gas emissions [2].

Furthermore, recycling plastic is one of the solutions for the reduction of plastic waste. The recycling of plasticcan be divided into several types: primary, secondary, tertiary, and quaternary [9-14]. Someimportant points of mechanical recycling (primary, secondary) are screening, shape separation, magnetic separation, electrical-conductivity-based separation, and density separation. Some researchers have developed acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) based filament from their waste through primary and secondary recycling. Generally, two types of recycling methods are deployed: conventional recycling method and distributed recycling method [12,13]. In developing nations generally, the conventional recycling method is used. In this method, plastic waste is separated and then collected by scavengers and waste pickers after thatit is transported to a collection centre and reclamation facility [14-16]. On the other hand, a distributed recycling system has numerous benefits over the conventional recycling system it consists of a shredder, extruder, sensing element, and control component. There are ampleadvantages of a distributed recycling system over the conventional/centralized recycling system. The substantial embodied (energy used in transport and waste collection) energy saving in the case of a distributed recycling system is more than 80%. It has been revealed from the study that 100 million MJ of energy can be conserved if high density poly ethylene (HDPE) is recycled with a distributed recycling system (in USA).

There has also been a significant reduction in greenhouse gas emissions. A novel path has been established for both developing and developed worlds with the least environmental impacts [17]. Tertiary recycling involves chemical-assisted mechanical recycling. Incineration is a type of quaternary process which is widely used for recycling. It is also termed as a thermal treatment process [9]. Incineration is also socially opposed as there is a release of toxic and hazardous gaseslike dioxin into the atmosphere [10,11].

In the previously reported studies, researchers have explored the way to deal with plastic waste and to supporta circular economy. The economic and environmentalfeasibility recycling approach to deal with waste plastic has been explored [18]. A mixed integrated linear programming model (MILP) was used as an evaluation tool for the local closed-loop recycling network. The MILP helps to evaluate polymer waste resource selection routes. It also helped with the means of selection of transport for each route. It helps in the decision-making process forfeasibility and evaluation [18]. One example of distributedrecycling additive manufacturing (DRAM) consists of mechanical grinding to fused granular fabrication then to the development of composite and finally to prototype development. Scrap and windshield wiper blades have been converted into biomedical products for finger- tip grip for hand prosthetics [19].

In recycling, the recycler has become the end-of-lifefacilitator. Recycler analyzes shares and exchanges information with the designer [20].In circular economy consumption of natural resources should be optimized. There should be an optimized transformation of production chains. Consumption patterns are transformed into a newly designed industrial system. The circular economy is restorative or regenerative by intention and design [21]. Linear recycling aspects such as recycling maintenance and composting require proper methods to increase circularity to take advantage of unexplored opportunities. There are ample amount of benefitsassociated with a circular economy which include material cost-saving, constant price, reduced environmental pressure, and impacts. Manufacturers should take into account the true cost of materials and design products while keeping in mind asset recovery.Resourceful products are generated from waste materials in a circular economy. It reduces the waste content and there can be a 70% reduction in greenhouse gas emissions in a circular economy [22]. Generally, two types of models are followed in a circular economy. One is that repair, remanufacture, and upgrade materials and extend their service life. The second method is one in which oldgoods are converted into new materials using recycling. A circular economy behaves as a lake as there is a generation of jobs, the saving of energy, and a decline in resource consumption. On the other hand, a linear economy behaves like a river in which all the natural resources are wasted. One example is Michelin a tyre manufacturing giant that has adopted a circular economy model, as it is providing customers the option of regrooving tires instead of throwing them away through its various workshops.

The circular economy contributes to 3-dimensional development i.e. economic, environmental, and social [23]. The conventional perception of the system is open-ended. Capital goods as the temporary embodiment of resources (R), and circular economy production (P) produces consumer goods (C) and capital goods (K). Consumption finally creates utility (U). Fig. 1 represents a conventional circular economy. Fig. 2 represents a close-ended circular economy where W is waste and r is recycling. It works onthe first law of thermodynamics which states that total energy and matter remain constant in the closed system.When box r is added to the open end system it converts it into a circular economy [24]. Fig. 3 represents graphical representation of documents published yearly in recycling area (based upon Web of Science data of past 20 years).

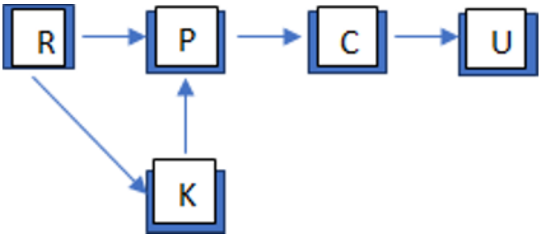

Fig.1. Conventional circular economy open ended [24]

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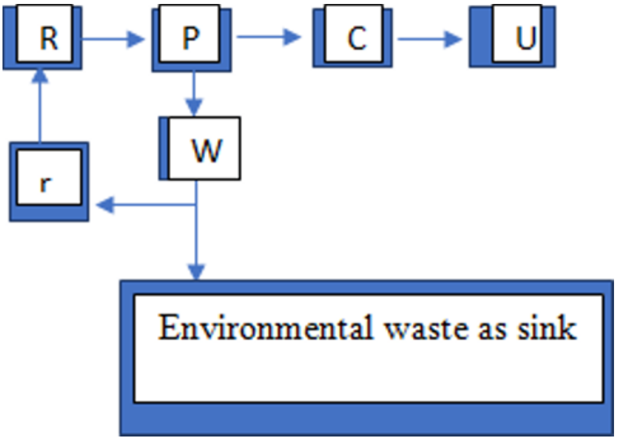

Fig.2. Circular economy close ended [24]

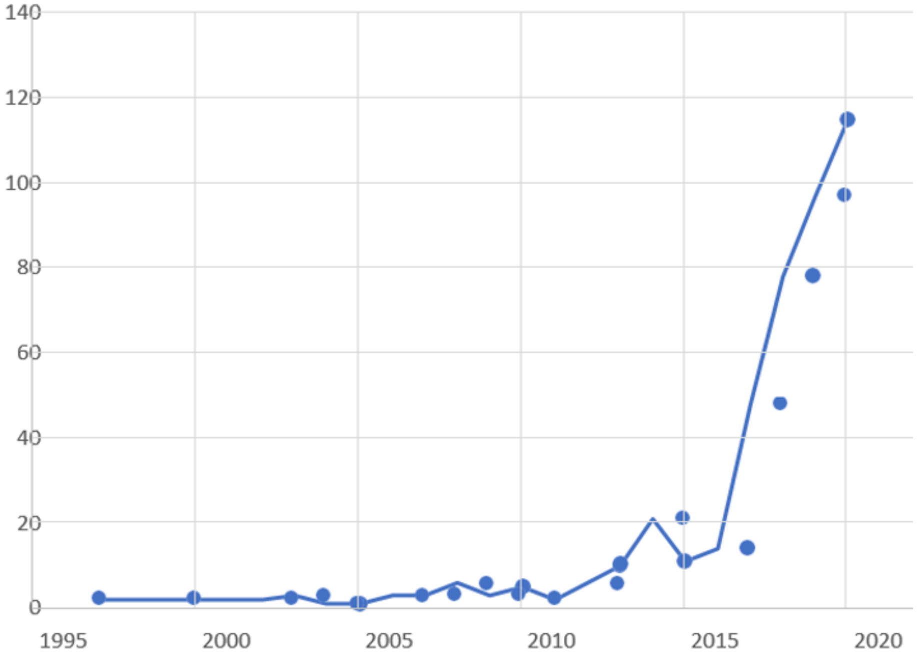

Fig. 3. Graphical representation of documents published yearly

2 Types of polymer waste

2.1 Electronic (E) wastes (with polymer matrix)

E-waste recycling has become a biggerenvironmental problem. In the recent past, researchers have studied different types of E-waste and potential environmental contaminants associated with E-waste. It hasbeen outlined that environmental contaminants like Pb, Sb, Hg, Cd, and Ni can be traced in drinking water and consumable food items, especially in underdeveloped countries. Contaminants have also been found in agricultural and manufactured products. Researchers have suggested different remedial options to make a safe distance from E-waste contamination [25]. Some researchers havestudied the mechanical recycling of E-waste specifically printed circuit boards (PCB). In this study, different separation methods such as mechanical, chemical and electrical have been examined. A most effective method for the segregation of different components from PCB scrap has been developed for the separation of Al and Cu. Results were supported by X-rayand EDS micrographs [26]. Calculation of E-waste depends upon the contribution of an item to an annual E-waste production. It can becalculated as E=MN/L where M is the mass of item in kg, N is the number of units in service Lis life span. Life cycle assessment (LCA) has been applied to different home appliances like washing machines, refrigerators, television (TV) sets highlighting the final phase of theproduct, and calculating the threshold time beyond which it is harmful to handle this type of equipment.It is in accordance with EU directives issued for waste electrical and electronic equipment and should be treated inan eco-friendly way. With cognizant of EU directives producers should finance collectionfacilities, treatment, and recovery of electronic waste [27]. Some researchers have reviewed different recycling processes for electric and electronic equipment waste (WEEE). Some of the processes used are eddy current separation, corona electrostatic separation, and jigging. For mechanical recycling, there has been shredding of electrical and electronic waste and particle size of 5-10 mm is gained. It is accepted to havea mechanical recycling process for upgrading oflow metal content plastic scrap [28]. There has been an exponential increase in E-waste production. Countries like Nigeria heavily rely on 2nd hand equipment from developed countries primarily from Europe and NorthAmerica for rapid advancement in information and communication technology. Emphasis is onremanufacturing and recycling to check present low-end manufacturing practices. In 1952 when EU directives were introduced waste management was majorly prioritized. In acomparison study between Italy and Romania, it has been outlined that in Romania all types of WEEE have been collected but in Italy, the main emphasis is on household appliances. It has been proposed in EU directives that post-consumer responsibility for a product life cycle up to its final disposal has to be fixed.

Heavy metals like Pb, Hg, Cd and flame retardants like polybrominated biphenyls must be replaced by safer alternatives. High impactequipment should be a priority recycled in countries with transient economies rather than recycling all usable ones [29]. There will be aphenomenal increase with new technologies andaffordable electronics. A more verifiable inquiry is required for generating stockpiling, capturing for reuse and recycling. Standardized methods and techniques are required to estimateWEEE generated in different countries. Cost-effective methods are required to reduce the financial burden on developing countries. A very swift and accurate method should be globally incorporated for the effectivemanagement of electronic products [30]. Waste electrical and electronics consists of valuableresources like metals, and plastics. It is necessary to reduce environmental problems and human health risks work should be done to eliminate toxic substances entering downstream of the material. Entering of heavy metal substances in E-waste should be avoided [31]. Fig. 4 represents the general E waste recycling procedure.

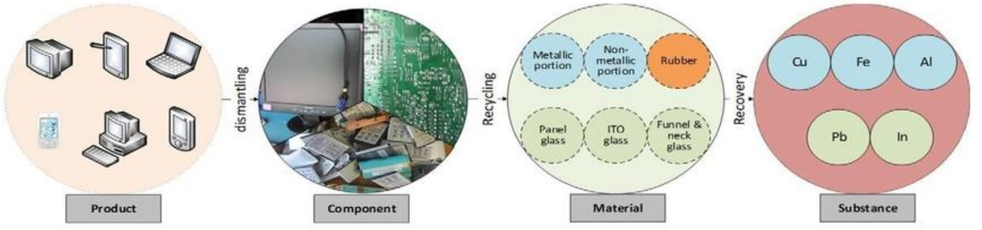

Fig. 4. E-waste recycling process in terms of four levels for product, component, material, and substance [31]

2.2 Polymer waste in other engineeringapplications

Some researchers have studied the recycling of polypropylene (PP) by injection molding. Changes in chemical structure and melt viscosity, crystallization behavior, tensile and fracture properties have beenstudied. There is a decrease in molecular weight and eventually the melt viscosity of the polymer. Also there isan increase in the crystallization rate and equilibrium melting temperature. There is also an increase in elastic modulus and yield stress, however a sharp decline inelongation at break and fracture toughness was noticed. Melt flow index increases due to chain scission mechanism. As the molecular weight decreases due to recycling, there was an increase in mobility and the foldability of molecular chains [32].

Another study outlined reprocessing of low and high viscosity grade ABS for the injection molding process. The design of the experiment (DOE) has been applied to plan experiments and later analysis. As the number of processing cycles was increased low viscosity grade had shown a reduction in melt viscosity while high viscosity grade had shown an increase in melt viscosity. A successful mathematical model has been developed to forecast the rheological behavior of the merged materials [33]. The study suggested a detailed description of Dutch post-consumer plastic packaging. It consists of a polymeric composition of recycled milled goods and household products. About 173 different post-consumer plastic packaging samples from different locations have been collected. Material flow analysis, data reconciliation, and process technological parameters wereused to describe the complete network. Net yield obtained from post-consumer plastic is 30% of the total amount. A successful experimental model has been developed for the composition of milled goods and recovered masses [34]. In another study researchers outlined the impact of bio-based plastics on the current recyclingcycle of the plastics. How a small quantity of PLA affects the recycling cycle of PET and polyhydroxyalkanoate (PEF).The study was focused on three areas:

- Different types of incompatibilities, the amount at which these incompatibilities become noticeable.
- Effectiveness of current recycling processes.
- Amount of progress by doing dedicatedcollection and recycling.

Researchers have developed a support policy to evenguide the recycling development process by carefully managing new contaminants [35]. Fig. 5 represents stepby step procedure to recycle plastic bottle waste.

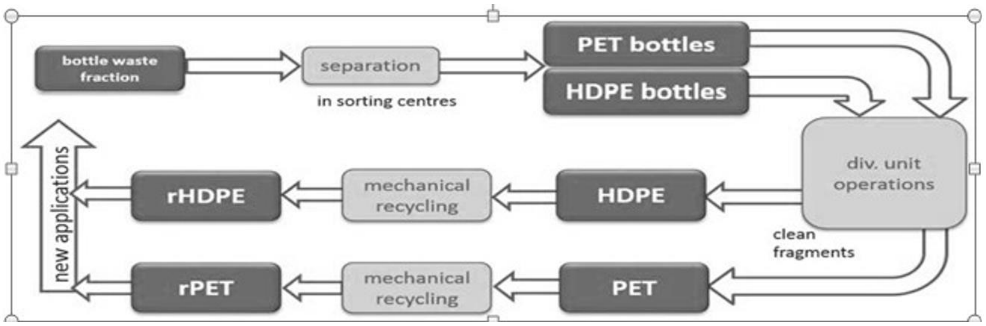

Fig. 5. High-level overview of the unit operations from bottle collection to recycle PET and HDPE [35]

In past one decade numerous studies have been reported on use of 3D printing for recycling of thermoplastics. Researchers have optimized inbuilt parameters of 3D printing. A balance between raft size and supportstructure material followed by reduced raft size helps in the reduction of scrap material in 3D printed parts. To improve the mechanical properties increase in the numberof infill and number of shells has been done. Controlled parameter interactions have resulted in better part production. An experimental approach for each design is necessary for proper process optimization [36]. Some researchers have studied the effect of recycling on the mechanical, thermal, rheological and processing properties of the recycled materials. It has been observed in the study that if PET waste is added with PLA in the presence of compatibilizer there has been a remarkable improvement of thermal stability of the composite. Similarly, when ABS is added to poly-caprolactum (PC) waste with the presence of compatibilizer there has been a remarkable improvement in mechanical properties of the formed composite [37]. In another study, researchers have outlined continuous or repeated extrusion cycles of low-density polyethylene (LDPE). Its rheological, molecular and thermal properties have been investigated.There has been molecular re-arrangement due to thermo-mechanical and thermo-oxidative degradation while doing mechanical recycling. Chain scission and cross-linking are observed in rheological measurements. There has been a decrease in melt flow index (MFI) with an increase in number of extrusion cycles. The differential scanning calorimetry (DSC) measurements have shown a decrease in crystallinity after the 50^{th} extrusion cycle.These results support a cross-linking mechanism over chain scission during extensive mechanical recycling [38]. Table 1 represents work done related to polymer recycling for various engineering applications.

Table 1. Work done related to polymer recycling

Sr. No	**Authors and year**	**Materials Recycled**	**Iethodology used**	**Investigations**	**Remarks/Conclusions**
1.	Boronot *et al.*[33](1990)[1]	Low and high viscositygrade ABS	Injection moulding.	Rheological properties	There is improvement in rheological properties ofrecycled polymer.
2.	Brouwer et al.,[34](2017)[2]	Plastic packaging material.	Mechanicalrecovery	Compositional observations	The model revealed the origin of contaminants in therecycled plastics
3.	Alaerts *et al.,*[35]((2018)[3]	polyethyleneterepthalate(PET) and polyhydroxyalkanoate (PEF).	Mechanicalrecycling	Incompatibilities	a support policy to even guide the recycling development process by carefully managing new contaminants.
4.	Hamad *et al.*[37](2013)[4]	polyethyleneterepthalate(PET) and polylactic acid (PLA).	Mechanicalrecycling	Mechanical,ther mal, rheological properties	There has been a remarkable improvement in the thermal stability and mechanical properties of the composite.
5.	[5]Jin *et al.,*[38](2012)	Low-Density Polyethylene (LDPE)	Mechanicalrecycling	Mechanical, thermal, rheological properties.	There has been an improvement in the mechanical properties of the developed composite.

6.	Pillin *et al.*[39](2008)[6]	Polylactic acid (PLA)	Injection molding.	Mechanical, thermal, rheological properties.	There has been an improvement in mechanical and rheological properties if the developed composite.
7.	Jia et *al.*[40](2017)[7]	Polyetylene grafted maelic anhydride (POE-g-MAH) in PA6	Fused deposition modeling(FDM)	Mechanical properties	There has been a significant improvement in tensile strength with reduction inwraping problem.
8.	Colmenero*etal.*[41](2020)[8]	Glass Fibre reinforcedPA6	FDM	Mechanical properties	Low volume industrial components are successfullydeveloped.
9.	Iizuka*etal.* [42] (2020)[9]	Carbon Fibre reinforced thermoplastics (CFRT's)	FDM	Structurel properties.	Reverse Piezo-resistivity has been obserbed in CFRT composites.
10.	Peng *etal.*[43](2020)[10]	Carbon Fibre reinforcedin PA6	FDM	Mechanical properties	Significant improvement in rebound behaviour and absorption capacity has been obserbed.
11.	Fraternali*etal.*[44](2019)[11]	ABS&PA6	FDM	Mechanical and tribological properties	Higher yield strength, weasr resistant with greater Young's modulus prototypes has been obserbed.
12.	Maiti*etal.*[45](2015)[12]	Tertiary butylene styrene grafted MaelicAnhydride (SEBS-g- MA)	Injection molding	Mechanical, wear properties.	High Yield strength,wear resistance and Young's modulus has been obserbed.
13.	Lei *etal.*[46](2019)[13]	PA6 & Carbon fibrereinforced PA6	FDM	Experimental ,theoretical and numerical analysis of water absorption capability of prototypes	Under the same ageing conditions carbon fibre reinforced PA6 absorbs morewater as compared to PA6
14.	Singh *et al.*[47](2020)[14]	PLA-PA6-TiO_2	FDM	Flexural,wear ,morphological properties.	Developed prototypes are biomedically compatiable.

15.	Terekhiana *et al.*[48](2020)[15]	PA6	FDM	Mechanical properties.	Significant improvement in tensile strength has been obserbed with XZ build orientation.
16.	Kusmono *etal.*[49](2008)[16]	SEBS-g-MA	Injection molding	Ductility,impactstrength and thermal properties.	There is a significant improvement in thermal stability and mechanicalproperties of the prototypes.
17.	Singh *etal.*[50](2018)[17]	PA6-TiO_2	FDM	mechanical properties	Biocompatibility and biodegradability of the composites has been improved.
18.	Parandoush*etal.*[51](2019)[18]	Carbon fibre reinforced thermoplastics (CFRTs)	FDM	Mechanical properties	Development of high performance light structure isthere.
19.	Stansbury *etal.*[52](2016)[19]	ABS,PA6	FDM	Mechanical properties	3D printing in dentistry and medicines has been explored.
20.	Sedlecek *etal*. (2018) [20]	ABS+SCF(short carbonfibre)	FDM	Mechanical properties	There has been a significant improvement in tensile strength of the protypes.

3 Different recycling Processes

3.1 Primary recycling

Fig, 6 represents different recycling processes. Sorting is one of the important techniques used in primary recycling. The identification of primary plastic through waste is done through sorting [54]. Hydroclones are generally used for density separation of waste plastic.

Hydroclones work with the effect of the centrifugal force.Hydroclones have a cylindrical structure on the top and conical structures on the base. A high-speed plastic waste mixed with liquid enters at the top of the cylinder in the tangential direction. Low-density fluid separates but the high-density fluid settles in the base and is separatedwhich consists of coarse particles and is discharged through an orifice from the cone tip [55].

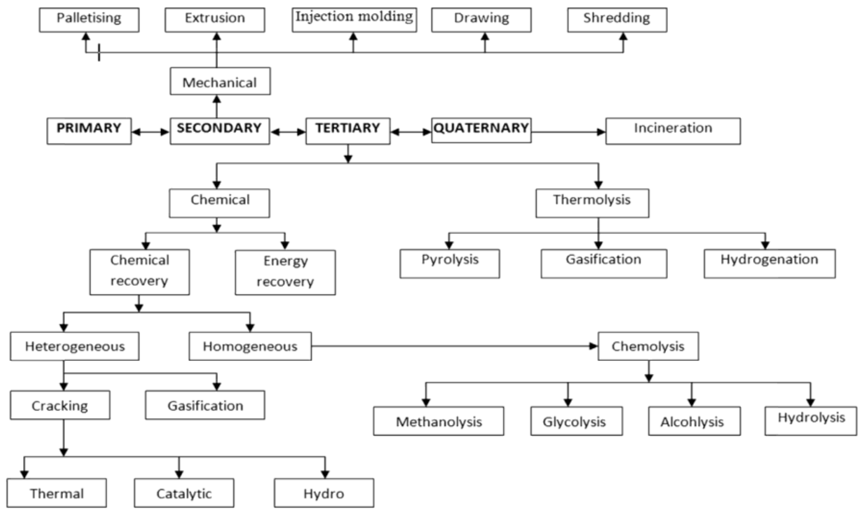

Fig.6. Classification of recycling processes [9]

3.2 Secondary recycling

Mechanical recycling started started in 1970 generally single polymer plastics like PP, polyethylene (PE), polystyrene (PS) are mechanically recycled [21]. Some methods of mechanical recycling are:

3.2.1 Grinding/ two roll milling

It is one of the effective method which is used methods which is used in polymer recycling[22]. Mechanical regrinding consists of a roll mill also the apparatus consist of powder- separation equipment. A particle size of about 125 µm can be obtained. The process is quite economical some chemicals like isocyanate can be added with changed levels to maintain foam density. Fig. 7 represents schematic of two roll milling process[23].

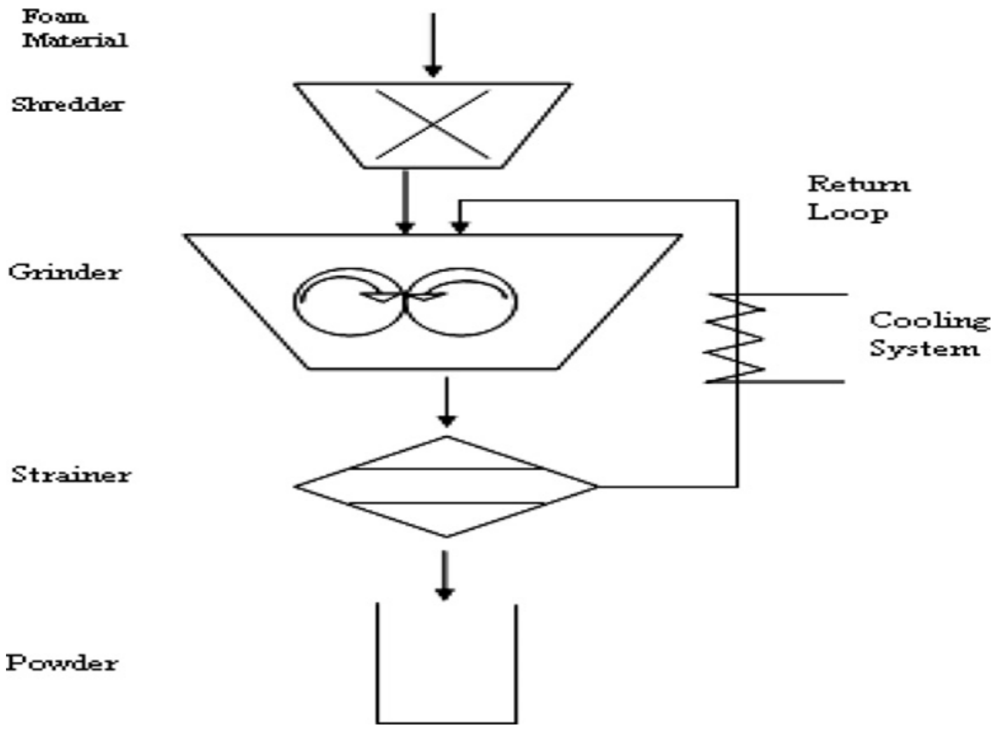

Fig.7: Schematic of two-roll milling process [56]

3.2.2 Adhesive pressing

Adhesive pressing is the process in which there is a surface coating of grounded plastic particles using anadhesive binder. These particles are pressed in a heated hydraulic press about 100-200˚C with pressure about 3-20MPa.[24]. Adhesive recycling is used for the production of mats, under lays, sports hall floor parts, and sound insulation. Western Europe and North America have market potential of about 10000-20000 tonn/yr [25].

3.2.3 Compression molding

Compression molding is used in the case of free-flowing plastic in granular form or viscous form. In compression molding particles are pressed at high temperature and pressure approximately (180˚C, 350 bar) enough to generate the shear force needed to flow the particles together [26]. Curing time is of approximately 3 minutes. Generally two types of compression molding processes exist:

1. Sheet molding compound (SMC)
2. Bulk molding compound (BMC).

For SMC 5mm thick sheet is used and for BMC 20mm- 50mm thick sheet is used as feedstock.

3.2.4 Screw Extrusion process

Screw extrusion (both single and twin) is widely used in the polymer recycling process. The stages involved in screw extrusion are melting of polymer then generation pressure after that thermochemical and chemical homogenization and finally is product formation[27].Twin-screw extruder machine consists of a housing, barrel, two shafts having identical or opposite screw threads engraved on them. Shafts with identical screw threads run in the same direction, while the shafts with nonidentical screws run in the opposite direction. Raw plastic material is gravity fed from the top of the hopper. The temperature of the barrel varies from 200˚C to 275˚C from front to the end with two or more individual temperature-controlled heater zones. As the screws start rotating molten material is automatically pushed along the barrel. Finally, the developed wire is passed through a water tank and collected[28].Fig. 8 represents single screw extruder machine.

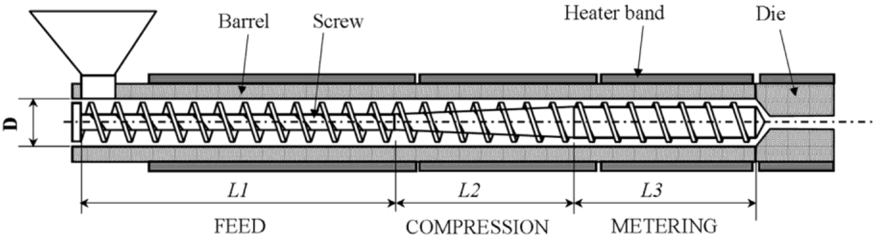

Fig.8: Schematic of single screw extruder [9]

3.3 Tertiary recycling

3.3.1 Chemical dissolution process

Polymer Dissolution

In the chemical dissolution process as the name suggests polymer waste is treated with chemicals or suitable solvents for its effective dissolution[29]. Some of the solvents used for dissolution are benzene, toluene,xylene, chloroform 2-butenol, linalool, and geraniol. Some solvents do not induce any degradation in the polymer chains and develop green process polymers like limestone, p-cymene, terpinene, phellandrene. These can be easily recycled by distillation. At optimum temperature a slight increase in dissolution has been observed but up to a particular temperature after whichthe polymer starts degrading. Polymer when chemically recycled is degraded into monomer by the process ofsolvolysis or pyrolysis. Monomers are purified and finally, polymers are formed from them [30]. Some researchers have discussed polymer multilayer packaging. Different separation techniques have been discussed like by-delamination or selective dissolution- reprecipitation technique. Other method of recycling used is compatibilizing of non-miscible polymer types. The delaminization process proves to be more energy- efficient as compared to the dissolution-reprecipitationprocess. In the delamination process, all qualities of polymers are regained but the only selective quality of polymer is regained in the dissolution-reprecipitation process. Eventually, it can be said that separation by delamination is the most economical and environmentallyfriendly procedure. Separation of multilayer polymer stream is a major challenge in the delamination process. Eventually, it can be said that if separation of delaminated polymer and sorting of multilayer packaging items is possible then delamination is the most economical and environmentally friendly procedure[31]. In polymer dissolution, important points are solvent diffusion and chain disentanglement.

Techniques to study polymer dissolution are:

Differential refractometry In this technique as the concentration of polymer during the dissolution process is ascertained based upon refractive index of the concentrate. Some drawbacks of this process are that no information of the surface layer ofthe pallet can be obtained from the refractive index of the polymer. This process is also not suitable when the quantity of polymer used is much small[32].

Interferometry Interferometry is widely used to monitor polymerdissolution. A beam of monochromatic light is passed through polymeric material which is held between two mirror slides. The quantitative data about the thickness ofthe transition layer between dissolved polymer and solvent is obtained. The size of the substrate is approximately 0.5µm-1.5µm. An unpolarized beam oflight is projected from 2mW He-Ne laser. Usually 10° is taken as the angle of the incidence. Silicon photocells collect the reflected beam. Constructive and destructive interference pattern are produced. Absolute filmthickness is related to the periodicity of the pattern. Someof the drawbacks of this process are the non-uniformsurface of the film. Transparency is required while film monitoring. Nonuniform surfaces cause scattering of the light which is very difficult to interpret. Michelson laser interferometer acts as an effective tool for studying polymer-solvent intermixing[33].

Pyrolysis To convert plastic waste into an energy pyrolysis process is applied in which polymer is heated up to 300-900°C in the absence of oxygen. Pyrolysis has become one of the most suitable ways to treat plastic waste. Pyrolyse zeolite-based acid catalyst has been used for the pyrolysisof polyolefins. A continuous pyrolysis unit consists of a reactor which is also a main component of the unit. It is cylindrical from the top and is of conical shape from the bottom side. The reactor is divided into two sections in cylindrical and in conical with a total length of 340mm length of conical section H_c is 205mm (Fig. 9 and 10).The angle of the conical portion Ÿ, the internal diameter of cylindrical section $D_{i,}$ the diameter of the cylindrical section D_o are 28°,20 mm, and 10mm respectively. The reactor has been designed with a understanding of hydrodynamic studies. There is an arrangement of a continuous feed system in a pyrolysis plant. It consists of ball valve where the polymer which has to be recycled is located. A polymer is rotated by steady nitrogen flowfrom the bottom. A cartridge which consist of ceramic resistance is placed at the bottom of the reactor. Released nitrogen gets heated by the resistance and reaches the reaction temperature. A thermocouple applied at the upper end of resistance is used to measure the temperature. Another resistance is placed which issurrounding the wall of the section it also consists of a thermocouple. Furthermore, energy losses are minimized by insulating the reactor. By-products of pyrolysis are char and gas. Factors like temperature, pressure, heating rate strongly affect the by-product proportions[34].

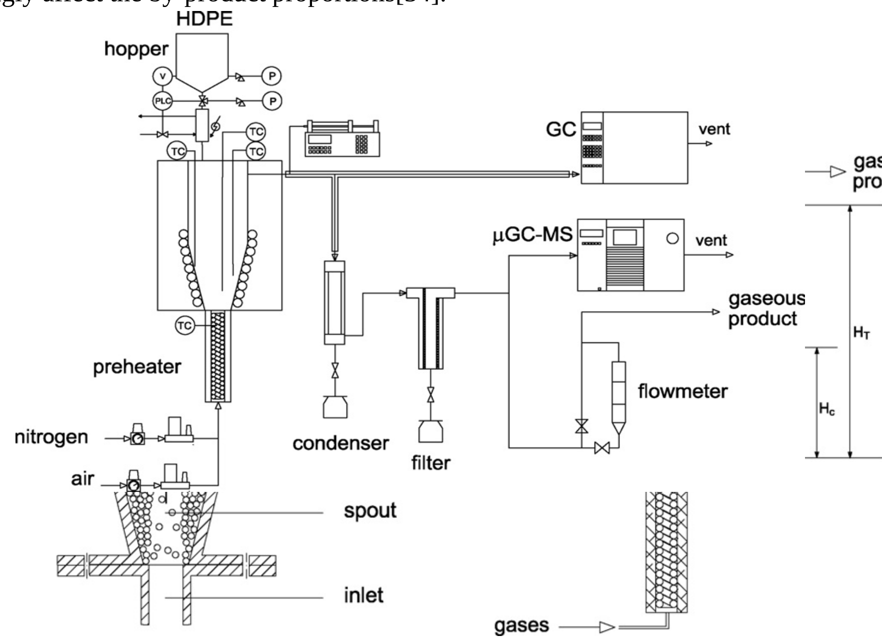

Fig.9. Schematic of continuous pyrolysis unit [34]
Fig.10. Schematic of the continuous pyrolysis unit exploded view [34]

Gasification In gasification waste plastic or biowaste is converted into CO, H_2 by heating waste material at a hightemperature>700 °C by allowing a controlled supply of oxygen and steam. A gasifier unit consists of three main sections:

1. Feeding system 2. Fluidized bed gasifier 3.Cleansing unit

The ballast feed is heated up to 150°C in the first electric heater. The temperature is being raised to the desired inlettemperature by the second heater. Air is injected into the system from the bottom bed and fuel is injected from over bed system. A cylindrical section of gasification is composed of 0.381m internal dia.Its height is 5.90m. Preheated blast gases and three external heaters are used to heat it to the reaction temperature. A syngas cleaning section is composed of a cyclone, scrubber, and flare. Three electric heaters along with the reactor increase temperature up to 700°C [35].

Incineration In the incineration process waste plastic is heated at a temperature more than 850°C. A limited amount of air is supplied during combustion to ensure complete burningof plastic waste material. The heat produced by combustion can be used to produce steam than to run turbine blades by the steam produced and run turbineblades by the steam produced and finally for electricity generation. Thereafter exhaust gases are cleanedfollowing stringent environmental standards. Lime powder and atomize fine slurry is used to neutralize pollutant acidic gases. Carbon is also injected to remove the heavy metals or pollutants from the exhaust gas. Thenthe additional filter is applied to remove dust from fine particulates[36]. It is a sort of waste reduction process. This process also has some drawbacks. In this process waste streams, consisting of hazardous metals, and chlorinated organic chemicals are converted into moretoxic compounds like dioxins. Dioxins are hazardous chemical compounds these can cause life-threatening diseases like cancer. These can sustain in the air about more than 100 years[37].

Micronization Nowadays there has been the use of multi-material polymer matrix for the further enhancement of the product design. The Micronization technique has beenused to ensure the recyclability of multi-material polymers without separating it into components. Therehas been no degradation of polymer by the use of micro ionization process results are supported by SEM and dynamic mechanical and thermal analysis(DTMA). Therehas been a loss in ductility and tenacity but at the same time, tensile strength has been increased by 18.43%. A decrease in storage modulus has been noted at atemperature above 30ºC [38].

4 Impacts of recycling on economy

To understand the relationship between circular economy (CE) and distributed recycling different research paths at micro,meso and macro-level has been proposed. Different stages for distributed recycling by additive manufacturing are recovery, preparation (compounding, feedstock, printing, quality). A large amount of work has been reported for compounding, feedstock printing, quality but very less amount of work has been reported for recovery and preparation.Waste management policies can be enhanced by the development of different aspects like economic, social, and technical for improving closed and open-loop recycling[39].Implementation of the CE concept in micro,meso, and macro form has beendone.There are many similarities in the recycling laws of China, Japan, and Germany.The main focus through theselaws is for a reduction in waste disposal land increase manufacturer's responsibilities and to improve energy andwaste efficiency stages of the CE concept that are: Design, Production, Consumption and Waste management. In cognizance with this study, countries candevelop proper implementation methods for various sectors like social economic and general[40].Recycling moves plays important role in transforming the economy from a linear to a circular one. The study focused on two recycling scenarios one which is currently in practice up to 2020, and the second one is 45% in the case of plastic and 85% in the case of paper respectively.These are in accordance with current recycling trend and policies[41].Different strategies, targets are structured for smarter product use and manufacturing and it consists of refuse, rethink and reduce. For extension of the lifespan of products and parts, it consists of reuse, repair, refurbish, remanufacture, repurpose. For the useful application of materials it consist of recycle and recovery.The transition towards circular economy can be adopted in several ways like by following waste reduction, barring production loops, efficient use of resources, materials and products retention[42].Currently, plastic production ways and disposal have deficiencies. These are also not much environment friendly. A big question is that how performance lag can be eliminated and countries can become more efficient towards recycling in circular way. For 26 European countries multidirectional efficiency analysis tool has been applied.Some countries have good plastic recycling rates like Czeh Republic, Denmark, Germany, Luxembourg, Malta and these countries areconsidered efficient.On the other hand, some countrieshas very low recycling rates such as Austria, France, Norway, and England.In the year 2016 Czech Republic showed the highest recycling rate with more than59%.Larger economic growth entirely depends on more recovery and recycling activities.Mechanical recycling or pyrolysis in Europe and US is considered more efficient than landfill or incineration.Further plastic manufacturers should take responsibility and make proper arrangements for collection and sorting and bring back plastic waste in the value chain. [84].Today majority of developednations like Europe, USA is setting stringent targets to regulate recycling of polymer waste for material recovery with the help of comprehensive programs. In the present study, researchers have scientifically reviewed different results from pilot projects, literature case studies focusing on how to recycle household waste. Researchers have reviewed new operational practices to restrain processefficiencies. There has been a study for the up-gradation of the recycling plants by applying new technologies for separation. Eventually taking into cognizance from several factors like materials complexity, fast-growingurbanization, and central sorting these will play an important role shortly [85]. Some researchers have discussed polymer recycling, feedstock recycling, tertiaryrecycling, and catalytic recycling. High cost associated with the collection, sorting, and transportation of lowchlorine-containing polymer waste to recycling sites is a major concerning problem. Improving the economics of the process by using a zero-cost catalyst will make the process more viable.If large quantity waste streams are targeted to reduce the collection cost and if careful characterization is there, then the supply of quality- controlled polymer waste is possible[86].Plastic waste has become a global environmental issue demand for renewable plastic is rising (fully biodegradable to CO_2 without harmful products).Solar-based driven processes with the help microalgae,cyanobacteria can help to produce a wide quality of bioplastic.It can act as a long- term carbon sink.With innovation and new technologies regulation cost and the cost of externalities like recycling of plastic,environmental degradation and health related cost can be decreased to large extent.Also the new improved regulations can increase the speed oftransportation and can lead to a better circular economy[87].Current Brazilian system works on public policy where low income workers collect the dry sorted urban residue and sell them to earn money.There hasbeen a increase in environmental threat as municipal department is directly delivering post-sorted residues to landfills.In the present study researchers have discussed about the packaging of industrialized organic food which is cultivated in small organic farms.

A novel method of recycling and a simplified binary equation has been developed to easily estimate the recyclability rate of the polymer packaging at the projection level.This tool can act as a guideline for material and process selection.It could assist in the preliminary comparative stage of packaging [88].There are number of benefits from direct recycling additive manufacturing (DRAM) as compared to centralized waste recycling. In one of the reported study scrap from windshield blades was step by step recycled by distributed recycling methods.Methods used in distributed recycling were fused granular fabrication, heated syringe printing, 3D printed molds coupled to injection moulding, development of filament to fused filament fabrication. Finally high value, bespoke biomedical products and fingertip grips for hand prosthetics were demonstrated.DRAM models serve to provide variety of solutions for circular economy[89].Stronger policy implementation and better coordination iskey for successful CE development in China. CE enhances cyclic and responsible use of resources for sustainable development.CE strategies can be catagorizedby how they preserve product components ,materials, embodied energy. Also the impact of CE on environmental social or economic dimensions. For CE monitoring framework there has been classification ofmicroscopic and macroscopic indicators .Number of indicators work on the preservation of materials.CE is accessed by set of indicators inspite of single one.One indicator may not be sufficient as CE consists of many dimensions.Similarly set of indicators are promoted on macro scale. Direct CE with specific strategies covers mainly type of materials and produced waste. AnAncially aspect of CE framework is measured by indirect indicators [91]. To bring transparency in the CE concept 114 CE definitions are analysed systematically these are coded against 17 dimensions of the framework. It hasbeen observed from the study that CE is combination of reduce,reuse and recycle activities of 3R framework.Coherence in the CE concept has been introduced through study.To move towards sustainabledevelopment it operates on a micro level, macrolevel, andmesolevel.Earlier researchers focused on environmental aims in CE while now most authors are focusing on economical aims.Also study concluded that social aspectsand business models are being neglected earlier and are being cover thoroughly in this study[43]. Plastic debrisin marine life is creating ecological concern(1)Mismanaged plastic waste (MMPW) which consist of both microplastic <5mm and macroplastic>5mm is majorly contributed by top 10 rivers.These rivers contribute upto (88-95)% of total plastic waste in the sea bed[44]. It can be concluded from the study that reducing plastic load by 50% in the top raked rivers can reduce total load to the seabed by 45%. In another study mechanical recycling of PET and PE bottles has been carried out. Different phases like collection, compaction, sorting, reprocessing has been analyzed. A different concern scenario of waste and management policies has been verified by a suitable and defined tool. This research project has been carried out with Italian consortium for packaging (CONAI) with the engagement of Italian companies[45]. To gain sustainability challenges circular economy is gaining pace. In the last few decades, circular economy's circle shape has changed with the continuous change in aspects of economy circles like responsibility, politics, limits, space, and sustainability.Based on two policies reports strong and weak economic paradigms have been categorized.In a weak interpretation of the economy, power is shifted from the state to individuals and entrepreneurs.Unequal power relations are reinforced by weak economy interpretation.

5 Effect of recycling on environment

From year1950 to year 2015, 4900 million tons from 8300 million tonne plastic produced has been discarded,with the current speed of recycling rate of 0.7%. The 44% will be the global recycling rate by 2020.The incineration rate will reach 50% global discard rate will be decreased from 58% to 60% respectively.Lifecycle impacts were less for proposed because of lighter weight and innovatiove recycling [46].The study was focused on three factors: the way we dispose plastic,second way is to understand the harms of land filling and third way is to understand the reuse behavior finally the synthesis and summarization of the main elements is there by the impact of plastic on environment. Individual traceability and garbage archeology are some of the proposed methods to reduce impact on environment .Recycling causes an enormous amount of benefits inspite of reducing greenhouse gas content there is also a decline in air and water pollution. New chemical andbiological extraction methods are employed for recycling and are termed hybrid recycling .

6 LCA assessment of polymer recycling

Two types of studies with total number of 12 polymers has been studied. The LCA assessment has been applied to access polymer production within ISO standards. Assessment of each polymer is done through development of matrices generated through green design principle. A positive correlation between reduced environmental impacts and green design principle can be seen. Inspite of ranking high in green design biopolymers cause high environmental impacts. There is need to redefine the environmental principles to reduce harmful impacts of fertilizers and pesticides on environment. LCA tool helps to determine the recyclability of the components in the component design phase. Carbon fibre reinforced polymers (CFRP'S) are more valuable becauseof their lesser weight and high strength. To find befetting design and optimization valuable information is provided by LCA. LCA is holistic approach consist of not only the material selection involving CFRP but also variety ofaspects such as increased capital cost, complexity in the parts and vailable molding capabilities of manufacturing. Recycling technologies play a major role for providing high performance materials emission reductrions and financial savings[106]. LCA tool has been applied onmunicipal solid waste (MSW).Decision making and structuring of information has been done through LCA process[47].

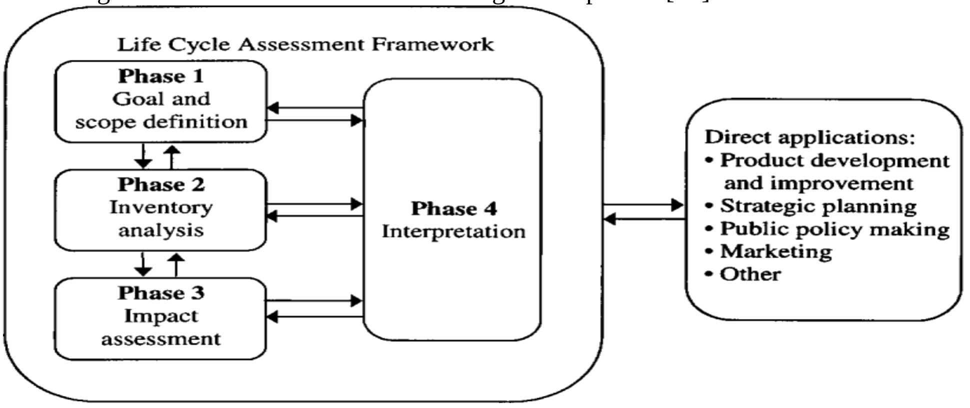

Fig.11. Lifecycle assessment framework[48]

Fig. 11 represents step by step life cycle assessment framework.Commercial biomass alternatives are befitting substitutes of petroleum based products developed by the polymer industry. A LCA model had been constructed to evaluate assessment of programmed photodegradation of polymeric materials. Recycling process enhances photo trigger process and reduces environmental impact by 11%-23%.Methodology consist of 5 steps namely goal definition, scope definition, inventory analysis and interpretation. Polymer synthesis consist of following stages that are conversion of biomass to fructose, synthesis of 5-hydroxylmethyl from fructose then synthesis of biopolymer followed by recycling. More research is required through future LCA studies on programmed photodegradation and decomposition alternatives. In recent decades development advances in protein engineering, synthetic biology and chemicals. Development of commodity chemicals by the fermentation of the sugar has been done. Need of green & sustainable technologies is emerging with the current climate change mitigation. Recycling and disposal system performances are measured through LCA tool. Itis considered as one of the best environment managementtool. Each and every step from the extraction of the raw materials to the final dumping of the waste material is considered in the study. Quantification of mechanical recycling of the plastic containers with that of conventional recycling has been done in this study. Study suggests that mechanical recycling is one of the economical

Current recyclic methods[49]. Production,consumption and disposal of mass electronic waste has become a major problem in Korea. Whole life cycle of electronic waste recycling consist of pre-manufacturing, production, transportation use & disposal. Pre-manufacturing and disposalsdelivers maximum environmental impacts about 90%.Target audience in this study is product designers, recovery managers and environmental policy makers. LCA has been conducted with 46% and 100% recycling rate. Someenvironmental impacts of PC waste recycling are abiotic depletion, global warming and eco toxicity acidification and ozone layer depletion. have drawbacks as they are unable to reduce ozone layer depletion also unable to reduce toxic environmental pollutants. LCA has been conducted and meaningful findings are obtained on recycling and on environment. Electricity consumption should be minimized while design engineers design the machine. Further enhancements in infrastructure and recycling technologies is proposed in this study. In number of developed products end of life treatment has increased the overall life of the product. There is requirement of generation of new methods for the development of new products. There are limitations in the current LCA procedure also the current guidelines and methods arestill insufficient to access environmental impacts on multilife cycle assessment (MLCA) so it becomes basic needto transform from current concept of LCA to MLCA. From this study knowledge gaps from LCA & MLCA studies are identified and how LCA can be converted to MLCA. LCA assessment of PLA'S different recycling methods like chemical, mechanical & composting has been covered here. It has been observed from the study mechanical recycling has least environmental impact[50]. In the present study LCA of polysaccharide products is compared with conventional counterparts. It has been observed from the study that in terms of non-renewable energy use(NREU) and greenhouse gas emission(GHG) polysaccharide-based productsshowed better results. When we see in use phase natural fibre polymers help to reduce weight in vehicles that's why helps in improving their fuel economy . There is no significant difference seen in case of packaging . Overall it can be seen that cradle to grave polysaccharide products are better than their conventional counterparts expectation is cotton as it require more chemical andenergy while production[114]. A comparative study of 6 different models has been done which are developed in EU & America. Variations in the results and conclusions has been observed in the study. Awareness about thecomparison of validation of LCA results among life cycleassessment community and recipients of the studies has been done. Scope and goal of study are the main factors on the basis of which a model is chosen's provide information to the politicians & public simple models are sufficient but for more detailed study more complex models are required. The case study from city of Dresden has been done.3 of 6 models has been studied that areIWM 2 & UMBERTO.It is inappropriate to apply static and linear modelling approach to reflect actual conditions.

7 Effect of recycling onremanufacturing

Remanufacturing and development of the composite made up of PLA base and high reinforcement continuous fibre is being done. There has been a significantimprovement in tensile strength also the bending strength showed the improvement by 25% of the reinforced composite.100% material recycling rate for CCRF'S and 73% recycling rate for PLA matrix has been achieved. The impregnated carbon fibre filament can be easily rolled and can be easily used in 3D printing process.There has been need of systematic and comprehensive methods for the reuse of generic products.Remanufacturing is a sort of reuse in which product is taken to its original performance level. A new method has been introduced to understand the benefits of remanufacturing energy related products in cognizance with environmental prospective. A possible balancebetween environmental balance and energy efficiency canbe analysed. It can be applied at earlier design stages when some specification has to be defined yet. Policy and standard development is possible by this method. It has been observed from the above study that environmental benefits increased as the reused components increased the only condition is that reproduction/remanufacturing should not increase more than 7% of the original one. Based on the case study new methods to promote reuse measures has been applied[51]. The demand is increasing to put the volume of waste in the production stream again.A survey has been done to know whetherthe firms can balance between production and consumption patterns . Also to know whether theefficiency of the process can be increased by adding waste stream in the production process. Proceeding with industrial symbiosis create a change within whole global economic activity worldwide. Demand of Recycle remanufacture waste treatment RRWT products can be increased if the products are competitively positioned by their looks. Third party standards can be increased in the supply chin such as SPEQ (Specific pallets engineered quality) can be added in supply chain management to built trust between suppliers. To effectively improveenergy and material utilization also used to control environmental emissions at low cost. To make review of remanufacturing trend summarization of remanufacturing technologies & to give conclusion of remanufacturing in energy a comprehensive literature review has been done.Firstly some remanufacturing methods based on LCA has been analysed .2ndly framework for accessing energy and environment has been built. Then in the description of integrated study of energy environment and economic assessment has been done[52]. Also some limitations of LCA has been described later. Material level recycling and component levelremanufacturing are two categories of WEEE.Some features of industry 4.0 are like smart devices with easy connectivity high inoperability and data transparency. Main highlights in the study include contribution to the digital twins how manufacturing and remanufacturing is supported by the digital twin simulation. Maintaining linkage between industry 4.0 and digital twins as it plays prime role in WEEE recycling. On the basis of international standards design to manufacturing based product information model has been developed. There arecertain limitations of the current system.The will and the support of the stakeholders is crucially essential. Social awareness through education is also one of the important factors. A proper supportive privacy policy should beengaged so that right person should access data at theright time. Enormous amount of environmental benefits from recycling and remanufacturing can be achieved. To determine quality of uncertainty in returned items a complex quality coefficient measurement method has been developed. Now with the help of validated experiments and real time data analysis comparative study of carbon emission between component recycling and remanufacturing has been done. Investigations of relationship between quality conditions and environmental benefits has been done. Environment regulations and other references are provided through the model developed so that the firms can complete theirenvironmental accomplishments.

Generally four types of remanufacturing technologies has been investigated that are machine remanufacturing, remanufacturing components from cannibalization, directly

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reuse components, component scrapping for materials. Assessment of cost and environmental benefits has been done in these four cases. It has been observed from the study that with increase in the complex quality coefficientthere is reduction in emissions also there rising rates decreases gradually.

Recycling through 3D printing

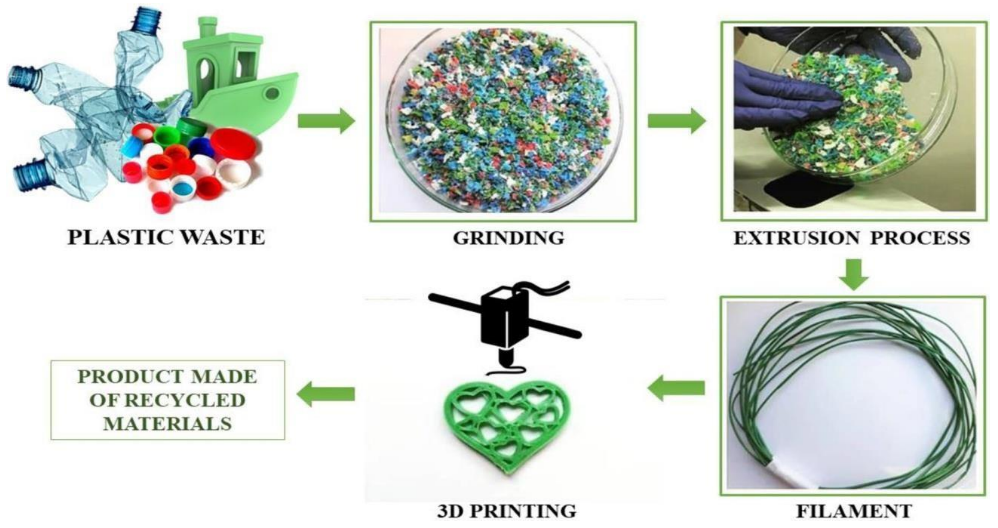


Fig.12 Flowchart of Plastic recycling through 3D printing[53]

Fig. 12 represents step by step methods of polymer recycling through 3D printing. Waste high density polyethylene (HDPE) and low density polyethylene(LDPE) has been recycled through screw extrusion and FDM printing. For the composition of (HDPE 90% +10%Fe) there has been improvement in the peak elongation, break strength and shore D hardness. For 100%LDPE shore D hardness and peak strength showed better results. Better break strength was obtained in case ofreinforced LDPE. Study suggested that properties of polymers can be significantly enhanced by addition of metal powders.

To eliminate plastic waste and control environmental pollution various type of reinforcements in thethermoplastics has been added. Classification of different polymers has been also done in the present study. Moreover advanced processes in polymer additive manufacturing combined with advanced composite fabrication can further enhance waste plastic material usability. Research on the applications of FDM has been summarized in the present work. A conductive filament has been developed in the present work. Further development of chemical sensors, force sensors is been done through developed conductive filament. Cell adhesion and growth are facilitated by biocompatible and biodegradable composites. A proper selection of process parameters can result in proper part production through FDM . Effect of recycling on the environment has been assessed. Parameters include fossil fuel consumption, green house gas emission and photochemical oxidant precursors. Enormous number of environmental benefits can be achieved through recycle and reuse strategies. Comparison between two packaging systems is there one consist of expanded polystyrene (EPS) which are encased in PE shrink wrap consist of molded expanded (EPS) fused with HIPS coating and placed in shrink wrap. Due to light in weight EPS-HIPS/PE shrink wrap packaging proved more environment friendly as compared to EPS/PE shrink wrap packaging. Moreover, oil consumption in case of EP- HIPS/PE packaging is also $1/3^{rd}$ less than the EPS/PE packaging. In the present study shredded waste fromused electronics items has been recycled using FDM printing and then usable daily need products have been developed like ice scrapper. High strength about 64.9 MPa has been obtained from the printed parts. It has been observed that high strength and high resistant productscan be developed from PC waste components at verylow cost. To overcome the problem of uneconomical and energy intensive centralized recycling an inhouse rapid prototyping has been developed. HDPE High density polyethylene has been used as raw materiala filament has been extruded with the rate of 90mm/min. Further study suggests that inhouse recycling dramatically reduces the development cost. A reduction ingreenhouse gas emission has also been observed due to conventional activities of recycling like transportation and collection of plastic waste. In house recyclingof PLA through 3D printing has been done here. There is increase in elastic modulus as the number of recycling cycles increased. More homogenization as decrease in internal defects is also observed in this process.3D printing can provide more viable alternative as compared to centralized recycling which is more expensive due to transportation and energy involvement. To improve cost effectiveness and to reduce plastic waste there has been a urgent need to generate feedstock filament from recycled plastic waste. Feedstock filament from recycled HDPE has been developed and the results are supported by DSC, TGA thermogravimetric analysis, Fourier transform and infrared spectroscopy. It is quite acceptable with good water repelling properties. Some of the limitations of the process were shrinkage, warping andsome adhesion problem was also there. To obtain effective waste utilization of polymer and to obtain consumable products. In this study alternative of plastics through developing of 3D printing filaments by plastic recycling has been explored. Through this study impact ofrecycling on their chemical and mechanical propertieshas also been analyzed. One of the examples of reusing recycle waste is the development of the face shields [130]. Development of High-density polyethylene (HDPE) basedfeedstock filament has been done with reinforcements of Sic and Al_2O_3.Four different compositions has been studied in the present work.1.100%HDPE 2. 90%HDPE+10%Sic/$Al_2O_3$3.80%HDPE+20%Sic/$Al_2O_3$4. 70%+30%Sic/Al_2O_3. Mechanical properties of the developed wire were significantly improved [131].Development of FGM functionally graded material wire with LDPE as base matrix and SiC and Al_2O_3 as reinforcement has been done. A better way to recycle plastic solid waste PSW has been developed[54].

8 Bibliographic analysis

To understand the research gaps, bibliographic/ scientometric study was performed on technological solutions for recycling of polymer waste based upon Webof Science data (for year 2000-2020). The data so observed was processed on open source VOS viewer software. Fig. 13 shows networking diagram based upon scientometric study for recycling of polymer waste. As observed from Fig. 13, some work has been reported for recycling in correlation with 3D printing and other additive manufacturing techniques, CE, polymer waste. But little has been reported on impact of various technological solutions for recycling of plastic solid waste.

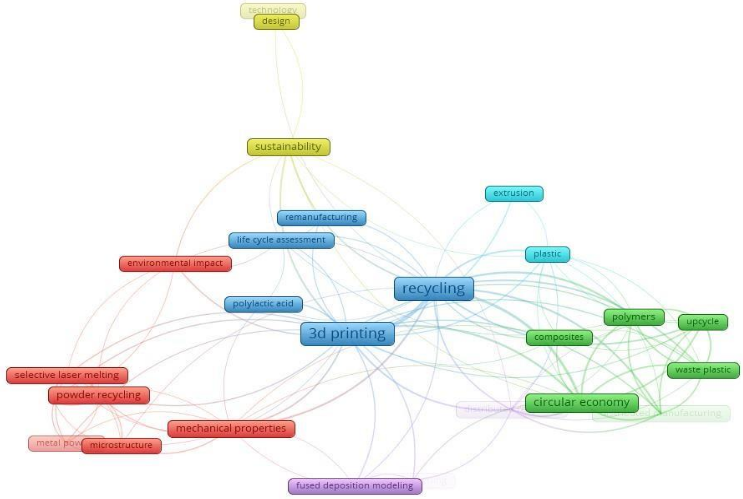
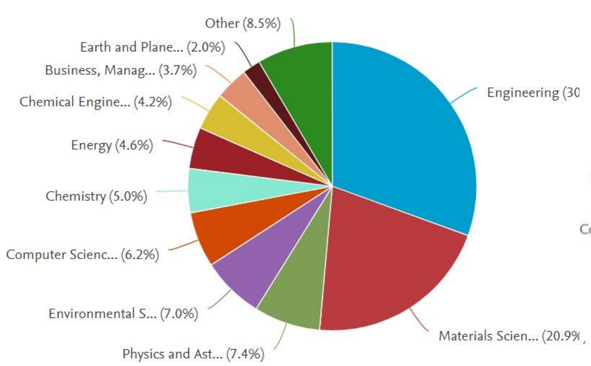


Fig. 13. Scientometric analysis for recycling of polymer waste

Fig. 14 and 15 shows percentage contribution among various disciplines for recycling of polymer waste (based upon Scientometric analysis). Further Fig. 16 and 17 respectively shows network of studies reported in reputed journals and network of different countries working for recycling of polymer waste (based upon Scientometric analysis).



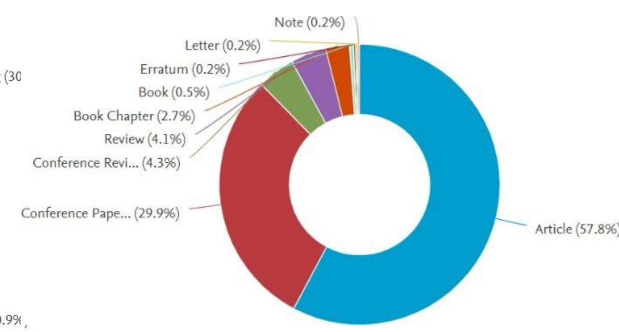


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Fig. 14-15. Percentage contribution among various disciplines for recycling of polymer waste (based upon Scientometric analysis)

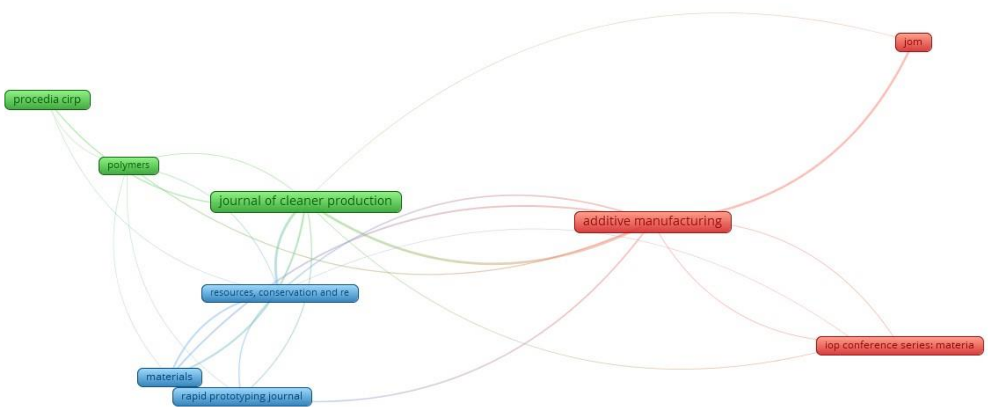

Fig. 16. Network of studies reported in reputed Journals for recycling of polymer waste based upon Scientometric analysis

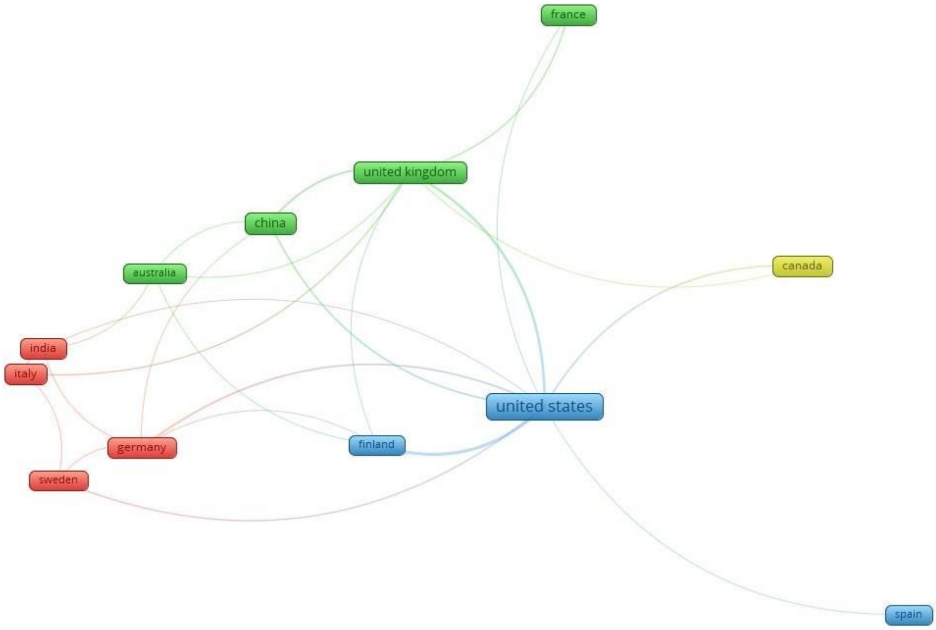

Fig. 17. Network of different countries working on recycling of polymer waste based upon Scientometric analysis

9 Conclusions

Plastic decomposition causes environmental pollution as natural degradation of plastic is not possible. Recycling of plastics through various modern technologies seems a befitting solution for plastic waste problem. In this review various types of plastic waste has been discussed and different types of recycling methods has also been explored. The primary, secondary and tertiary recycling processes were primarily discussed for commercial use. Further Impacts of recycling on economy, remanufacturing and environment has been discussed. The LCA of recycling processes has also been explored for cost benefit analysis. Recycling through 3D printingis also gaining popularity as it reduces cost which occurs due to transportation of heavy plastic waste. In general plastic recycling can serve as better solution to cope up with increased plastic pollution.

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