Review Paper

Novel trends in plastic waste management

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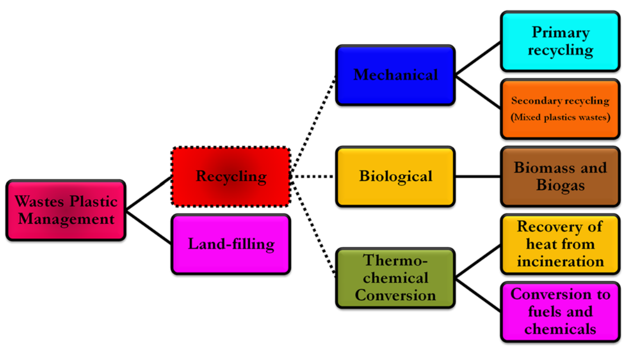
Abstract

Nowadays, there exists a global challenge confronting efficient management of municipal solid wastes. Varying degrees of environmental challenges including regular release of greenhouse gases and scarcity of available space for waste disposal have been caused by escalating accumulation of these wastes' materials resulting in inappropriate waste management. These challenges have aroused alarming public concerns, resulting in political legislation aimed at minimizing the amount of wastes getting into the environment. These activities attempt to offer solution which will enhance sustainable waste management, while promoting MSW recycling, and efficient conversion of waste materials to energy, and other valuable chemicals. These conversion procedures can be achieved through use of either biological processes such as anaerobic digestion or thermochemical procedures such as pyrolysis. Thus, the current review elucidates novel routes effectively utilized in converting MSW to energy and other valuable chemicals.

Graphic abstract



Keywords Thermolysis · Plastics recycling · Liquid fuel · Environmental friendliness · Waste management

List of abbreviations

General

ASTM	American society for testing and materials
PSW	Plastic solid waste
UNEP	United Nations Environmental Programme
MSW	Municipal solid waste
LCA	Life cycle assessment
IWM	Integrated waste management
CO_2	Carbon dioxide
NOx	Nitrogen oxides
SO_2	Sulphur dioxide
XRF	X-ray fluorescent
MPW	Municipal plastic wastes
FRs	Flame retardants

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PP	Polypropylene
PE	Polyethylene
PS	Polystyrene
PVC	Polyvinyl chloride
PET	Polyethylene terepthallate
WEEE	Waste electrical and electronic equipment
EPA	Environmental protection agency
USEPA	United States Environmental Protection Agency
LDPE	Low density polyethylene
HDPE	High density polyethylene
RDF	Refuse-derived fuel

1 Introduction

The inherent non-biodegradable nature of petroleum-based plastics has posed a hazardous threat to the environment due to their abundance in the waste stream. Waste plastics have continually littered the environment and have constituted critical challenges such as clogging of drains and escalated cause of health-related issues. Their abundant presence in the waste stream poses critical challenges especially without effective waste management. Many countries accumulate waste plastic pyramids requiring proper disposal; however, due to the cost of waste disposal, many rely on indiscriminate plastics dumping.

According to ASTM, a plastic is defined as a material composed mainly of an organic substrate of high molecular weight maintaining solidity in its final state, and, in certain stage in the manufacturing processing prior to being turned into finished product, can undergo shaping by flow [1]. However, this definition did not mention numerous additives, coatings, or treatments included in plastic blends and composites encountered during plastics recovery prior to re-utilization. Plastics play a vital function in our everyday living due to its lightweight, versatility, low cost of production, safety and hygiene, durability, chemicals resistance, electrical and thermal insulation in comparison with its competing materials. These properties have positioned plastics to become relatively indispensible in every aspect of life [2].

Plastics are applied in engineering, automotive, construction, medical, aerospace, electrical, robotics, and so on. The rapid growth in global economy and development has also improved the quest and reliance on these materials, resulting in its accumulation in landfills which poses danger to human and animal health, environmental pollution issues such as contamination of groundwater and sanitation challenges. Hence, an effective and sustainable route of treating these waste materials is critical to eliminating these challenges.

Plastics are composed of a wide range of complex chemical compounds formed into varying products, and various plastic resins are not easily differentiated. According to UNEP, about eight million tonnes of plastic is globally dumped into the oceans annually, killing marine life while also penetrating the human food chain. These pose challenges during collection, separation, and recycling of PSW. The durability of plastics causes their accumulation and persistency in the environment with estimated rate of over 25 MT per year [3].

Moreover, the conversion of plastics to their constituent chemicals is often technologically difficult and not profitable. The management of plastics recovered from MSW is a most sensitive industry due to the continual increase in the quantity of plastics recovered from MSW, biodegradability difficulty, and its hazardous effect on the society. The escalating quest for plastics has resulted in accumulation of pyramids of waste plastics in landfills which has occupied vast spaces, thereby contributing to environmental challenges. Due to the versatile application of plastics in numerous areas, there has been global increment in plastics production globally. This escalating quest for plastics has resulted in petroleum depletion as component of non-renewable fossil fuel because plastics are derived from petroleum.

MSW techniques can be approached through an LCA method capable of enabling identification of environmental influences associated with the alternatives in a fundamental manner facilitating identification of most sustainable alternatives [4]. It is imperative to note that about 90% of plastics presently utilized undergo synthesis via non-renewable fossil sources. Hence, it becomes imperative to inculcate IWM systems into plastic production and modification schemes of PSW. LCA programmes aid in the selection, appropriate techniques application, technologies, and management insight to attain specialized waste management aims.

The objective of IWM includes ability of controlling generated waste in order to attain standard requirements for ecobenign disposing through waste inhibition, re-utilization, and recycling [5]. The IWM scheme is separated into classes, namely: (i) waste generation (ii) waste transport, origin sorting and processing, (iii) gathering (iv) separating and processing (v) transfer base and waste transport management, and (vi) discarding. These functional groupings are imperative because of developmental activation and framework definition for evaluating impact of prospective variation in solid waste functions. Alternative routes established for the management of wastes plastic include recycling and energy recovery technologies. However, the recycling technique exhibited some limitations relative to the high cost of labor needed during the separation procedure which also resulted in contamination of water which in turn minimized the sustainability of the process. Hence, as result of these deficiencies, interests of researchers diverted toward other techniques of energy recovery in order to compensate for the high demand of energy. Thus, through wide and intensive research and development of technology, waste plastics conversion to energy evolved. Conversely, since petroleum is the major source of manufacturing plastics, plastics recovery to liquid oil via thermolysis process offered great prospects as the produced oil exhibited high calorific value in comparison with the commercial fuel. Fundamentally, the challenges of solid wastes continue to supersede its disposal issues.

However, despite the technical and environmental challenges of waste accumulation, there exists varying degrees of political, administrative, economical, and societal issues to contend with. Waste management refers to scientific techniques engaged in solving all these challenges and entails detailed plan, proper designing, and operational tools for the collection, transportation, processing, recovering, and finally waste disposal [6]. As a result of increasing depletion of sources of fossil fuel such as crude oil, natural gas, and coal, the current economic growth rate is not sustainable. Thus, numerous sources of renewable energy have been studied [7, 8]. However, prospects of developing other sources of fuel such as wastes plastics are yet to assume large-scale economic essence. Recently, emerging advancement in technology has resulted in large increases in production of varying types of plastic commodities, which result in either direct or indirect generation of waste as result of their versatile range of applications, in addition to their various forms and relative inexpensiveness. Due to the similarity of plastics calorific value to that of hydrocarbon fuel, the attainment of fuel from wastes plastics would offer an excellent avenue to use waste as a better option to dump sites. Varying techniques of plastics conversion of waste to fuel such as thermal and catalytic pyrolysis, microwave-enabled pyrolysis, and fluid catalytic cracking have been utilized. Also, co-pyrolysis of plastics waste inconjunction with biomass has also been used [9].

Generally, plastic wastes are referred to as industrial or municipal plastic wastes relative to their origins. Figure 1 reveals overall waste composition in United States of America (USA), China, United Kingdom (UK), and European Union (EU).

However, these groups have varying attributes and properties and are aligned to varying management systems [10]. A major portion of municipal waste is occupied by plastic wastes. Furthermore, large quantities of plastic waste emanate as by-products or damaged products emitted as industrial or agricultural waste [11]. However, thermoplastics account for about 78 wt% of the overall plastic waste, while the remainders are thermosetting plastics. Thermoplastics can easily undergo recycling and consists mainly of polyolefins such as PP, PE, PVC, and PS [12]. On the other hand, thermosetting plastics mainly include plastics which are difficult to recycle such as urea formaldehyde, melamin formaldehyde, and polyurethanes [13]. Hence, the recycling of PSW has attracted attention of numerous researchers in previous decades.

These researches are also engineered by variations in environmental and regulatory challenges [14, 15]. The utilization of plastics has been noted in several applications

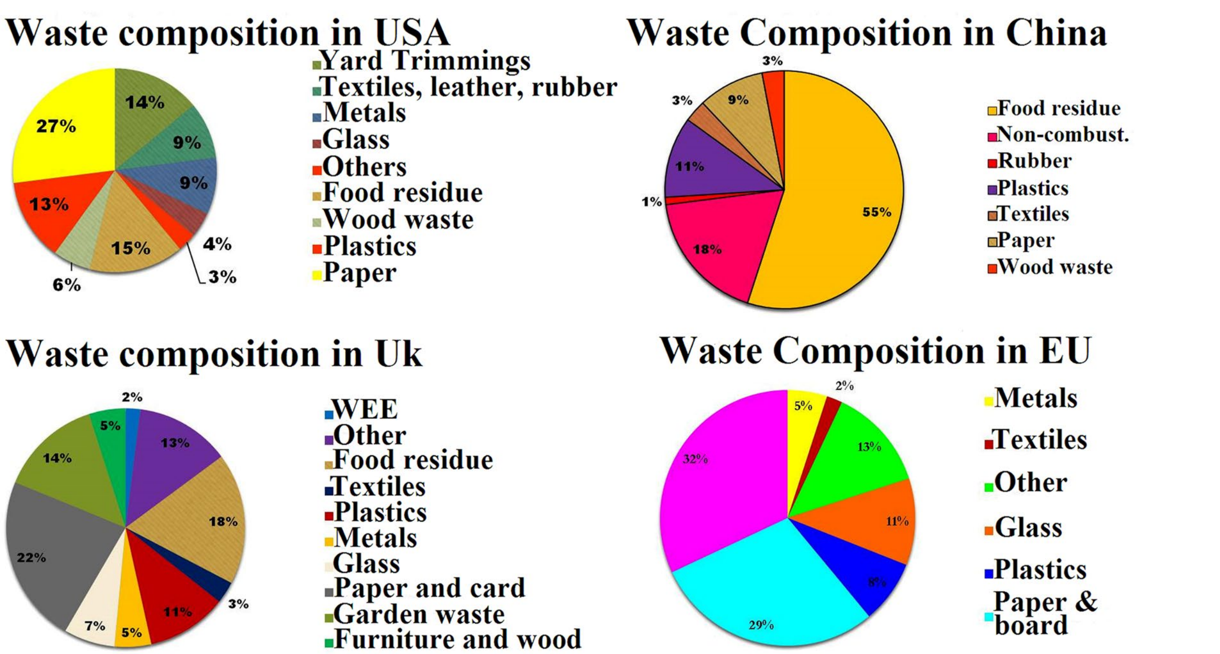


Fig. 1 Waste composition in the USA, China, UK, and EU

in our daily lives including bags, mulches, covers, wiring and coating, greenhouses, packaging-films, covers, and containers [16]. This invariably results in the evolvement of huge accumulation of PSW in end flow of municipal solid waste (MSW). There is significant presence of plastics in all MSW classifications because of their utilization in packaging such as bags, sacks, wraps, containers for milk, soft-drinks, and water which represent the highest tonnage [17, 18]. Plastics are also presently utilized in furniture, appliances, lead-acid battery casings, and other products. Plastic plays a key role in our daily lives. However, due to its accruable properties, such as versatility, lightweight, low cost of production, and economic development, the quest and dependency for these materials have escalated, resulting in its accumulation in landfills, thereby constituting a high risk on human and animal health, and created other environmental pollution problems, such as groundwater contamination, sanitary issues, and so on. Hence, a sustainable and effective plastic waste treatment is vital in alleviating these challenges. Pyrolysis is a thermochemical wastes plastic treatment method which can offer a panacea to these pollution challenges, in addition to recovering valuable energy, and products such as oil and gas [19]. The pyrolysis of PSW has attained prominence, because of its numerous advantages channeled toward alleviating environmental pollution, and reducing plastic products carbon footprint through the minimization of carbon monoxide and carbon dioxide emission, in comparison to combustion and gasification [20].

Decreasing cost and reducing landfill spaces are arousing interests for alternative routes of disposing PSW [21]. With evolving years of research, the plastic sector has successfully attained feasible techniques for recovering, treatment, and recycling of waste from used products which are economical and ecobenign. PSW emanating from commercially established grade resins have successfully gone through recycling to various end-products such as greenhouses, appliances, automobile-parts, textiles, mulches, and films. However, treatment of PSW and recycling procedures could be divided into four main classification including primary or re-extrusion, secondary or mechanical based, tertiary or chemically oriented, and quaternary or energy recovery. Notably, each technique offers peculiar benefits placing it at advantage for specific requirements, needs or applications [22]. Nevertheless, mechanical recycling technique, also referred to as secondary or material recycling, entails physical modification, in comparison with chemical recycling, which entails tertiary treatment, composed of feedstock recycling, which manufactures feedstocks for chemically based industries.

The process of recycling plastics has been elucidated as involving scrap or plastics waste recovery and subsequent material reprocessing into viable products which entirely vary from their original status [23]. The end product derived from varying techniques of plastic recycling has enabled classification between various plastic recycling techniques [24]. This classification can be fundamentally elucidated in Fig. 2.

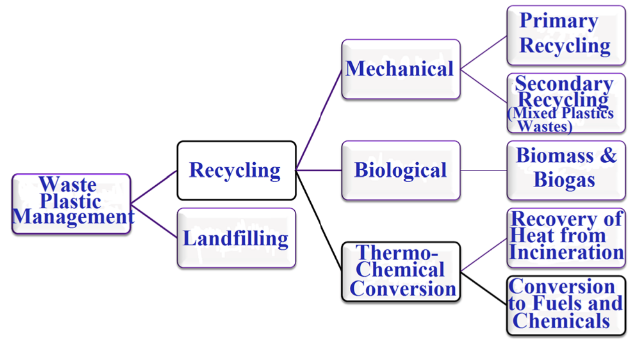


Fig. 2 Fundamental plastics recycling techniques

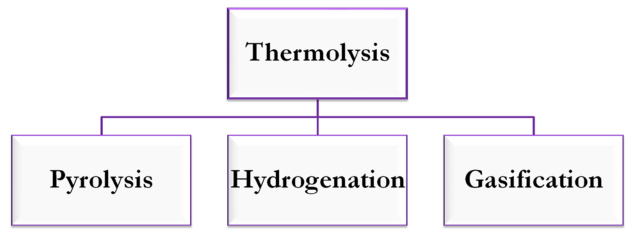


Fig. 3 Thermolysis of wastes plastics

Primary recycling where the recovered plastic is utilized in manufacturing products possessing the performance attributes equivalent to those fabricated utilizing the pristine plastics. Here, the recycling process involves material recovery, and plowing back to attain varying applications. In secondary recycling, the plastic derived is used in products requiring less pressing attributes, in comparison with original material usage. In tertiary recycling, the waste plastic is utilized as feedstock in the process generating the chemicals and fuels. In comparison with glass and metals, plastic may need higher processing duration. The combination of two different plastics results in low mixing entropy; hence, resins must be of almost similar composition to effectively mix together. When melting two differing plastic types together, phase separation tends to occur. The interfaces at the phase boundaries are weak, causing structural weaknesses in the emanating compounds. Hence, combined and untreated polymer blends have limited application [25]. Initially, plastic recycling industry focused on basic recycling of single plastics types which generate the highest financial reward. The process of wastes plastics thermolysis is schematically classified as elucidated in Fig. 3.

Pyrolysis is a thermochemical plastic waste treatment technique which can find solution to varying types of plastic wastes pollution challenges, in addition to other valuable energy products such as gas and oil. PSW pyrolysis has attained prominence as a result of accruable benefits toward environmental pollution and reduction of carbon footprint of plastic products through the minimization of carbon monoxide and carbon dioxide emissions in comparison with combustion and gasification [26]. Figure 4 shows a block elucidation of waste plastic pyrolysis route.

In comparison with combustion and gasification, pyrolysis of PSW has attained prominence due to its environmental friendliness, and amelioration of plastic products carbon footprint through the minimization of carbon monoxide and carbon dioxide emission. Generally, plastic plays a vital role in our daily lives due to its versatility, lightweight, and low cost of production. Plastics have become essential in many sectors of technological advancements, such as construction, medical, engineering applications, automotive, aerospace, and so on. Moreover, rapid economic growth and development have increased the quest and dependency on plastics resulting in its accumulation in landfills thereby posing a risk on human and animal health, causing environmental pollution challenges including contamination of groundwater, sanitary-based challenges, and so on. Therefore, a sustainable and effective plastic waste treatment is vital to eliminating these challenges. The main parameters elucidated in this paper include emerging trends in catalysts, varying reactors, temperatures effects, residence-time, pressure, fluidizing gas types, and so on. Additionally, several viewpoints to optimize the liquid oil production for each plastic are also discussed in this paper. Thus, the incumbent paper presents state of the act in plastic thermolysis to liquid fuel and emerging trends in plastics recycling processes.

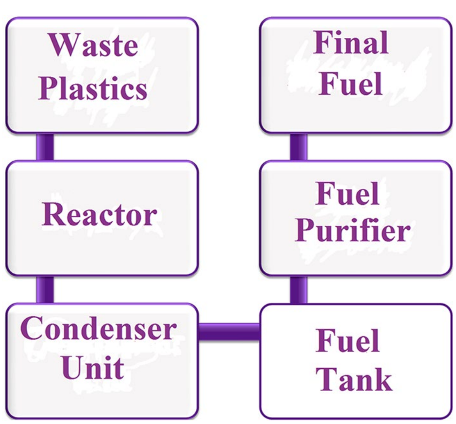


Fig. 4 Block elucidation of waste plastic pyrolysis

2 Re-utilization, sorting, and initial recycling

2.1 Advantages of re-utilizing and major sorting methods

Nowadays, multiple trip plastics have become a widely acceptable choice resulting in alleviation of PSW in the MSW end-stream. The re-utilization of plastic is more acceptable when compared with recycling because of the use of less energy and resources. Though, plastics are used in several applications daily, some plastic products end up in the waste stream after a cycle or after a brief period after purchasing. Plastics re-utilization has some benefits including (i) fossil fuels conservation. This is because plastics production uses about 4–8% of global oil production, composed of 4% feedstock during conversion; (ii) energy reduction and MSW, and (iii) release of CO_2, NOx, and SO_2 [27]. Several methods have undergone development for the separation and sorting of PSW [28]. In the UK, recyclable and returnable plastic crates used in transport and other purposes have quadrupled from 1992 (8.5 million tonnes) to 2002 (35.8 million tonnes) [29].

Sorting and identification must rapidly be conducted in a short period of time during recycling, so as to positively affect the recycler's financial base. For a successful recycling procedure, there must be rapid and correct identification of the main plastic contained in a specific product, followed by some form of manual or automated process. With regards to sorting of plastics, automated methods do occur though not always feasible because of variation in shape and sizes, or the presence of paint and coating which delays the route of analysis, and so on. In order to improve efficiency of density sorting, hydrocyclones are usually utilized [30]. Hydrocyclones improve the wettability of the materials while using centrifugal force. A feasible technique of sorting PSW is by tribo-electric separation, distinguished by rubbing two resins on each other. Tribo-electric separating device differentiates materials based on surface-charge transfer method [31]. When materials undergo rubbing against one another, one material becomes positively charged, while the other becomes negatively charged or maintains neutrality. In this cylindrical rotating drum, particles maintain as a mixture contacting one another while allowing charging. Here, materials exhibiting particle sizes in range of 2–4 mm demonstrated highest purity and recovery in the tribo-electric procedure [32].

Another technique used in separating PSW includes speed accelerating device developed by Result-Technology AG (Switzerland). This method utilizes a higher-speeding accelerating device in delaminating shredded waste, while the delaminated material undergoes separation via air separator, sieving tools, and electrostatic devices. Despite the effectiveness or efficiency of a recycling system, the most vital step in the recycling procedure is sorting or separation. A major challenge encountered by the recycling entrepreneur is paint elimination from plastics due to potential of compromising properties of recycled plastics because of the stress concentration resulting from the coating substrates [33]. MBA-Polymers-Inc. has established a technological mechanism capable of separating virgin resin containing FRs using XRF spectroscopic technique in identifying varying types of FRs. Various techniques are utilized in paint removal from plastics prior to recycling. These techniques include grinding, grinding–cryogenic, abrasion, and solvent stripping [34].

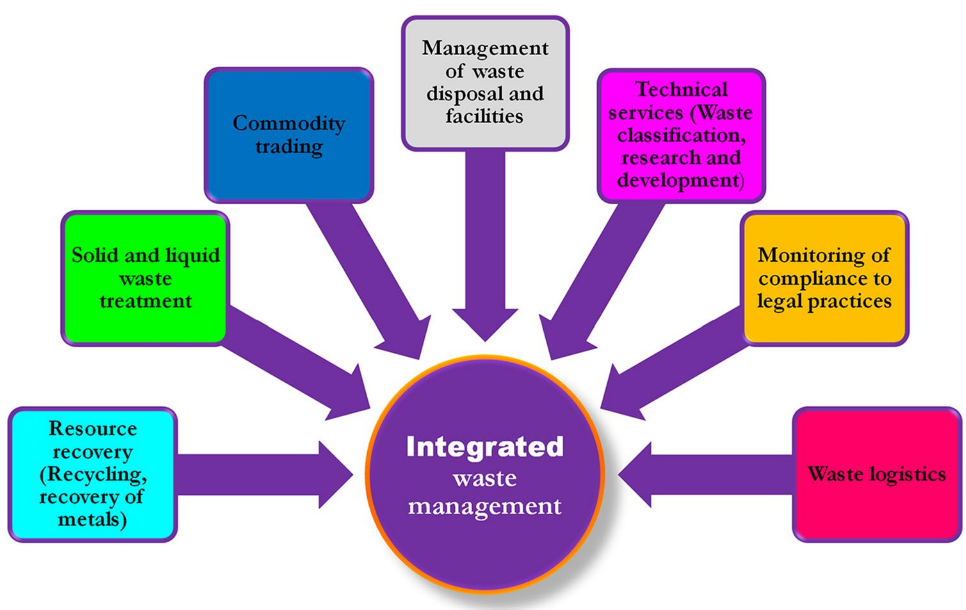
3 Integrated solid waste management

There exist stiff challenges in the treatment and disposal of PSW [35]. The total cost of waste management includes cost of solid waste collection and transportation to the treatment site or landfills. And since careful transportation of waste makes for better and secured health and hygiene, then no cost is spared to secure safe transport of the waste to the proper facilities. Unless scientifically managed, landfill sites have affinity to contaminate the soil and groundwater while waste incineration has demonstrated challenges to do with odor, and air pollution, and may not be feasible because of the intrinsic attributes of the waste material. Moreover, the aims of waste management policies include waste quantity and toxicity alleviation. Figure 5 is a summary of activities of integrated management.

Generally, waste is ascribed minimal or nil value. However, waste can be attributed as a material lacking its main economic value while exhibiting intrinsic secondary value. The reduction in waste and its efficient treatment is very challenging in the area of sustainable environment. Various types of wastes emanate from different sectors, due to continual technological advancements in the processing industries. Therefore, it is anticipated that wastes attributes are also variable [36]. It is imperative to note that conventional waste issues can be ameliorated through reduction in wastes accumulation, in addition to product substitution, waste recovery, and recycling. Waste accumulation exerts a notable influence on waste management. Thus, waste materials influence potential precautionary parameters, and measures to avert, in addition to important administrative procedures as regards its transportation, exportation, processing, sale, and re-utilization [37]. The waste hierarchy elucidates some steps taken in the reduction and management of waste as schematically illustrated in Fig. 6.

Here, prevention of waste is accorded the best alternative in waste management and expressed as combinations of source minimizations in addition to materials re-utilization. Thus, the percentage of product to be thrown away after use is reduced while the motivation to reuse a specific product in varying applications is increased. Hence, product efficient designing, manufacturing, and packaging with decreased content of volume and toxicity can result in effective attainment of source minimization thereby enabling improvement in prolonging shelf life of the particular product. Thus,

Fig. 5 Activities of integrated management



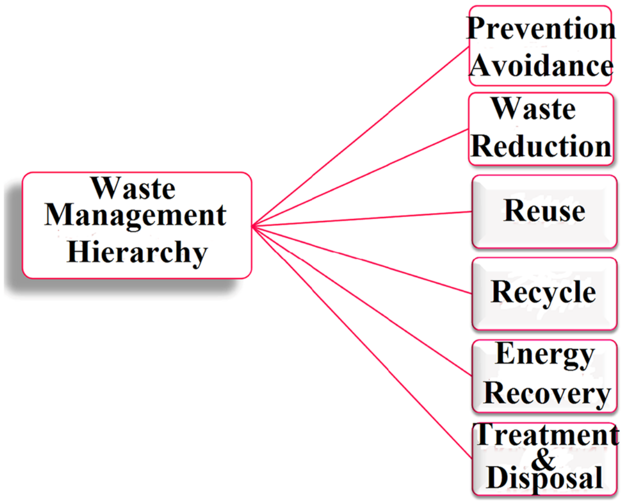


Fig. 6 Schematic representation of waste management hierarchy

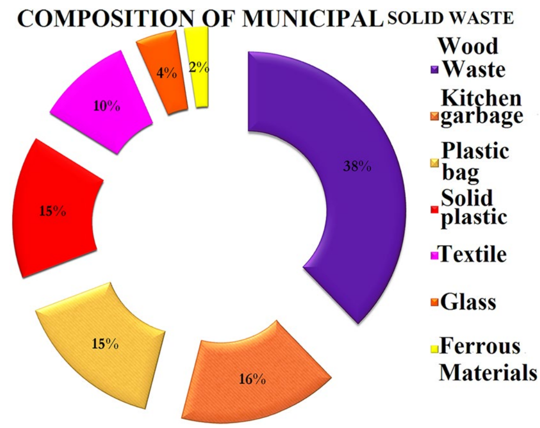


Fig. 7 Typical composition of MSW

product reuse follows source minimization in the hierarchy of waste management and elucidated as a waste minimization strategy that encourages consistent re-utilization of a particular product for varying purposes devoid of the occurrences of any physical variation.

Product re-utilization, when feasible, is a preferred alternative to recycling because the product does not undergo any form of reprocessing prior to its utilization. Post-waste prevention, materials recovery for recycling and composting is attributed high importance. Re-utilization varies from recycling or remanufacturing because it elucidates the utilization of accrued waste materials with potentials of being used as raw material for a novel compound. Hence, it presents opportunity of reclaiming resources that are valuable and capable of minimizing the amount of waste transferred to landfills [38]. Thus, relative to the polymer characteristics, it may or not undergo recycling. However, the process of recycling plastics poses some technological challenges relative to high contamination propensity which requires special attention. Thus, insight into important processes of minimization, re-utilization or reuse, and recycling is extremely relevant to the sustainable development idea. As a result of potentials of contradicting the precepts of environmentally friendly waste prevention, the parameters including incineration, resource recovery, and land filling are less preferred alternatives in the hierarchy of waste management [39].

4 Municipal solid waste management

Solid wastes apart from toxic and radioactive materials are considered as MSW and are mainly composed of all solid and semi-solid materials thrown away by society. Notably, waste is a necessary societal product. Figure 7 illustrates typical composition of MSW while Fig. 8 summarizes activities of MSW management.

In general, MPW are usually categorized as part of MSW because of their mode of discarding and subsequent collection as household wastes. Numerous plastic sources of MSW includes domestic wastes such as (food packaging containers and foams, disposable cups, plates, and cutleries, CD and cassette cases, fridge liners, vending cups, electronic equipment cases, drainage pipes, carbonated drinks bottles, plumbing pipes and guttering, flooring [40]. Others include cushioning-foams, thermal insulation foams, surface coatings, and so on. Agricultural waste includes mulch films, feed bags, fertilizer bags, coverings for hay, silage, and so on, wire and cable, automobile wreckages,

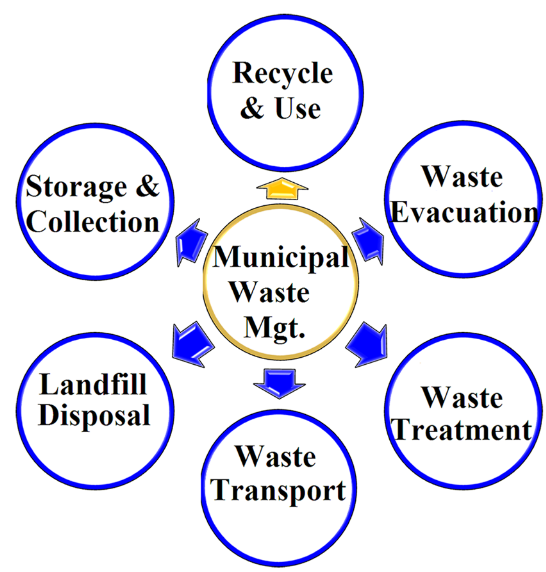


Fig. 8 MSW management activities

and so on. Hence, plastic wastes collected under the auspices of MSW are major components of PP, PE, PS, PVC, PET, and so on [41]. Though all accruable solid wastes emanating from sources such as commercial, residential, industrial, and institutional sources may be regarded as MSW, they do not include waste production from construction sites, automobile wreckages, municipal sludges, combustion ashes, and industrial-based waste not considering these wastes are also disposable to municipal landfills.

As a significant component of WEEE, waste emanating from computer is attracting great attention because of its great generation and susceptibility to environmental challenges [42]. The complicated and varying material composition in the computer places them ideally for recycling. On the other hand, abundance of hazardous constituents including fire retardants and heavy-metals creates hurdles during recycling process [43]. A large quantity of computer wastes undergoes either landfilling or incineration resulting in chemicals leaching and the release of hazardous gases, respectively. Research opines that methodological separation and recycling of computer waste parts is more economic in comparison to landfilling and incineration. Hence, conventional petroleum resources can undergo conservation by recycling waste materials resulting in sustainable formation of new products [44].

Nowadays, as a result of consensus improvement in environmental conservation, the techniques used for waste management have become highly sophisticated. Continual variations in wastes classes instigate environmental conservation interests while also stimulating the necessity for recovery of resources [45]. In recent times, scientific landfills have taken over open dumps, while incinerating techniques have remarkedly improved with improved energy efficient and pollution controlling devices. Also, waste recycling has also become economically more viable. Severally processes are connected in a bid to estimate MSW quantities capable of being generated in a community [46]. Such processes include input evaluation, secondary data evaluation, and output analysis. Here, output analysis which directly measures the quantity of MSW by weighting waste products discarded at a dump sites which is more preferable because of potentials of direct quantification [47].

A significant increase in plastics percentage in MSW has been noted [48]. Plastics wastes amounted about 20% of the total volume and 8% of overall weight of MSW in USA during 2000 with significant increment to about 11.7% by 2006 (EPA) 2006 reports and about 15–25% in Europe (2004) [49]. In 2015, USEPA revealed modes of municipal plastic wastes management from 1960 to 2015 as illustrated in Fig. 9.

Plastics have rapidly grown more than man-made materials and have posed environmental challenges. However,

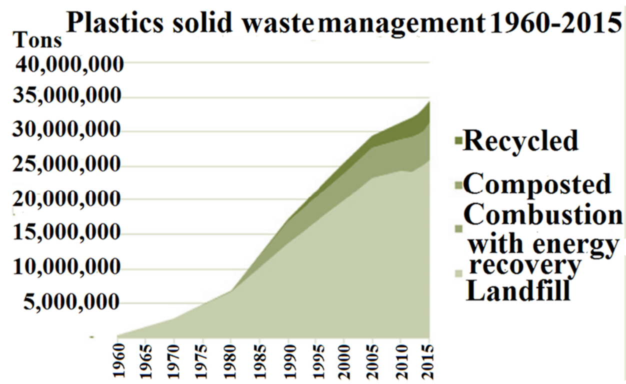


Fig. 9 US plastics waste management 1960–2015

escalating global awareness, especially with regards their shelf life is not noted. Nevertheless, through identification and synthesizing distributed data on production, application, and end-of-life management of polymer resins, synthetic fibers, and additives, the first global analysis of overall mass manufactured plastics have been presented. Estimatedly, about 8300 million metric tons (Mt) as of pristine plastics have been produced presently. Also, approximately 6300 Mt of plastic waste had undergone generation, and about 9% of these had undergone recycling, 12% has been incinerated, and 79% has undergone accumulation in landfills or in the environment. If the present manufacturing rate and waste management trends continue, it is estimated that 12,000 Mt of wastes plastics will be released in the landfills or in the natural environment by 2050 [50].

Prior to 1980, plastic recycling and incineration were insignificant. Nowadays, mostly non-fiber plastics had undergone significant recycling. Thus, globally for non-fiber plastics, the rates of recycling and incineration have gradually increased and accounted for 18 and 24%, respectively, of non-fiber plastic wastes generated by 2014. Based on limited data available, the highest rates of recycling in 2014 persisted in Europe (30%) and China (25%), while in the USA, plastic recycling has remained consistent at 9% since 2012 [50]. In Europe and China, the rates of incineration rates escalated with time to attain 40 and 30%, respectively, in 2014 [50]. However, in the USA, non-fiber-plastics incineration peaked at 21% in 1995 before reducing to 16% in 2014 as rates of recycling increased, with rate of discarding remaining consistent at 75% during the period [50]. It is estimated that if the rate of production continued on this trend, man will have produced 26,000 Mt of resins, 6000 Mt of PP and A-fibers, and 2000 Mt of additives toward ending of 2050. With assumption of constant use patterns and projecting present global waste management trends to 2050, 9000 Mt of plastic waste will have undergone recycling, 12,000 Mt incinerated, and 12,000 Mt undergoing discarding in landfills or in the environment [50].

In a bid to facilitate recycling of municipal wastes plastic, plastics segregation from other household wastes is essential. For mixed plastics, mechanical separation equipment is presently utilized. For instant, through the utilization of wet separation procedure, mixed plastics can undergo separation into two groups: those possessing density higher than water such as PS and PVC, and possessing density less than water such as PE, PP, and expanded PS. Thus, the latter group is larger than the initial group. Thus, municipal plastic wastes recycling deal with plastic mixtures of PE, PP, and PS, as long as the aforementioned separation procedures are used [51].

5 Application of IWM for MSW management

The concept of IWM inherently incorporates feasible waste management schemes inconjunction with waste stream, collecting, treating, and disposing techniques. The main aim is to attain environmental advantages, economic optimization, and societal acceptance. IWM efficiently minimizes solid waste quantity through recycling, incineration, composting, or discarding of waste-residue via scientific route [52]. Waste management cannot be dealt successfully in an environmentally sustainable route with economic efficiency by a single technique. It involves a combination of numerous closely interrelated and integrated processes.

Ab initio, solid waste management techniques were developed to eliminate dangerous health effects inflicted by increasing levels of waste generated within a given society. Previously, the management of solid waste generally involves collecting, land disposing, and incinerating of household waste. Industrial waste discarding did not arouse much interest. However, consuming less exhibits numerous advantages such as saving the wastes which would have terminated in the municipal waste stream, while also minimizing the energy, materials, and waste linked with providing these items [53]. Hence, the objective of sustainable solid waste management should include recovering more viable products from waste stream while using less energy and simultaneously creating more conducive environmental influence relative to human health and safety. The IWM concept utilized at communal levels mainly consists of the following five steps: waste characterization and identification of source; effective and scientific waste collection; waste volume and toxicity reduction; selection of suitable technologies with regard to varying waste characteristics [54].

5.1 Utilization of IWM fundaments and source reduction in plastic waste management

Waste regression, waste alleviation, or source reduction are regularly positioned at the apex of conventional waste treatment process pyramid [55]. Source minimization is a form of waste management concept attained through the design and manufacture of products and packaging with reduced quantity and toxicity in order to enable prolongment of the product shelf life. With regards to the consumer or consuming household, source reduction implies minimized consumption and reduced throwing away [54]. Source alleviation implies technological variation, raw material, process design, packaging, and materials or products utilization in routes aimed at minimizing wastages or toxicity prior to final disposal. Source reduction initiates efficiency at improved waste management and involves material reuse, which presents a superior management process due to reduction in cost of waste management.

6 Plastics waste recycling

Recycling involves the combination of varying technologies on plastics waste in order to facilitate production of secondary raw materials. Almost, all waste materials present in MSW can undergo the process of recycling with varying degrees of proficiency. However, important parameters include environmentally friendliness, technical feasibility, and economic profitability. High priority is accorded recovery of secondary raw materials via recycling and composting after source reduction and reuse in the hierarchy of solid waste management [55].

As already mentioned, plastics are categorized into two major categories, namely thermoplastics and thermosetting plastics. Approximately, 80% of plastics wastes are thermoplastics which undergo repeated formation to novel products via heat application. These recyclable thermoplastics include polyolefins such as polyethylene terepthalate (PET), LDPE, HDPE, or PP. Polyolefin plastics are globally utilized in applications such as carbonated drink bottles, clear-films used in packaging such as PET containers, LDPE pipes, milk and water bottles, housewares, industrial wrappings and HDPE films, automotive parts, battery casing, drinking straws, and electrical components. Addition polymers such as PE are not easily recycled using simple chemical techniques unlike condensation polymers [56]. A general schematic elucidation of varying polyolefin recycling routes is shown in Fig. 10.

Hence, thermochemical recycling techniques (pyrolysis) are utilized in production of varying refined petrochemical products similar to gasoline. A schematic illustration

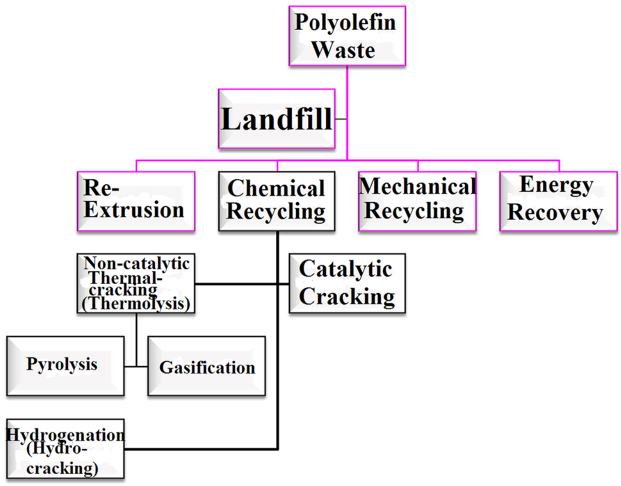


Fig. 10 Varying routes of recycling wastes polyolefins

of thermochemical recycling techniques is elucidated in Fig. 11.

Plastic recycling includes both chemical recycling (pyrolysis) and incineration. The varying routes proposed for waste plastics recycling include: primary and mechanical recycling. Primary recycling involves the in-plant waste recycling of scrap materials. Mechanical recycling involves separating plastics from its attendant contaminants and further processing via melting, shredding, or other similar procedures. Plastics mechanical recycling involves separating various plastic resins in accordance with their chemical orientation. As a result of varying melting points occurring at specific temperatures, a batch of plastic resins may change entirely while another batch may exhibit partial variation.

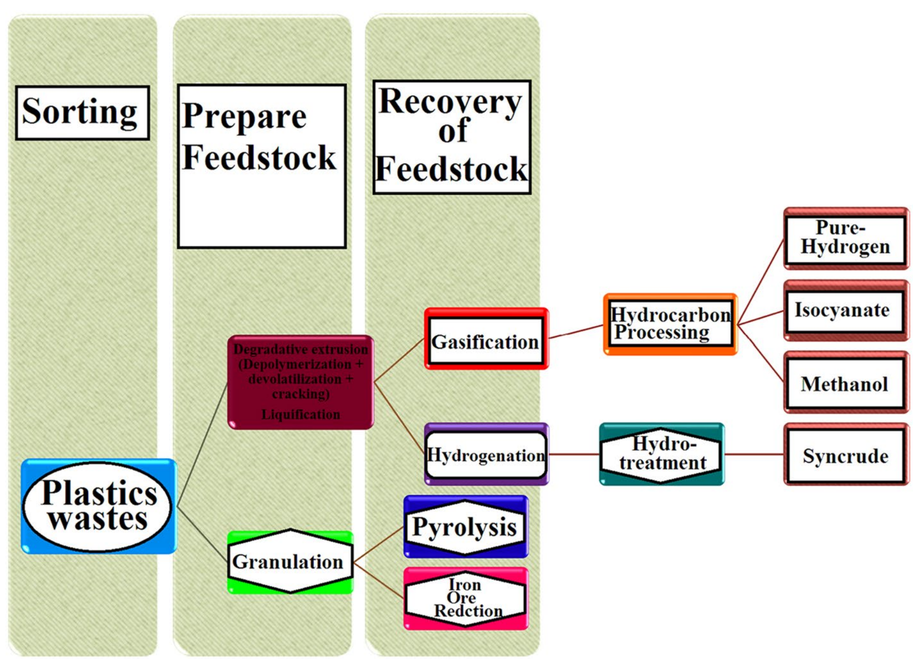
Hence, mechanical plastics wastes recycling is mainly conducted using a single-polymer waste stream so as to attain optimum efficiency and homogenous mechanical attributes for produced goods [57]. Mechanical recycling majorly occurs at about 200–300 °C resulting in emission of toxic gases. Another notable form of recycling plastic is chemical recycling or feedstock recycling, which ultimately results in complete or partial plastics depolymerization. Chemical or feedstock recycling also involves hydrogenation, pyrolysis and gasification as illustrated in Fig. 12.

Any of these techniques can be used for plastics recycling depending on the requirements of secondary materials and availability of technology, in addition to economic viability. Chemical recycling involves full depolymerization of associated monomers or partial deterioration in order to produce secondary commercial products.

Pyrolysis is a significant alternative chemical recycling procedure. As a result of thermal instability of organic compounds, pyrolysis occurring in a zero oxygen condition results in combination of thermal cracking and condensation reactions which finally result in generation of numerous liquids, gaseous and solids fractions.

Pyrolysis is regularly referred as destructive distillation, an endothermic route in contradiction to most combustion procedures which are exothermic in nature. The major compounds generated via pyrolysis are functions of the organic attributes of the compounds which mainly consist of a gas stream composed of carbon dioxide, hydrogen, carbon monoxide, and methane, in

Fig. 11 Thermochemical recycling techniques



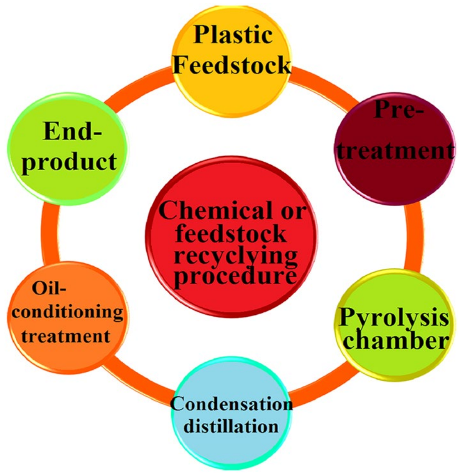


Fig. 12 Schematic of chemical or feedstock recycling procedure

addition to a liquid fraction consisting of tar–oil stream composed mainly of acetic-acid, acetone, and methanol and a char composed of almost purified carbon in conjunction with some inert materials. The effectual pyrolysis temperature for waste plastic-streams varies from 400 to 650 °C or even higher. However, the procedures are mainly fractioned into three categories including low, medium, and high temperature depending on the appropriate temperature for full or partial plastics deterioration.

The chemical recycling of plastics wastes depends mainly on feeding plastics, feed rate, effectual temperature, time of residence, and on reactor efficiency [58]. However, attainment of liquid compound occurs more at lower temperatures in comparison with gaseous compounds occurring at higher temperatures. However, a study reported the generation of catalysts, oil and gaseous fractions from the chemical recycling of HDPE, LDPE, and PP. The gaseous and oil fractions generated exhibit prospects of being reused as feedstock in the petrochemical industries.

Chemical recycling has been established as efficient route for production of fuel such as gasoline. The chemical recycling of PE and PP at low temperatures (400–500 °C), results in generation of high-calorific value gases, and waxes, in conjunction with admixture of hydrocarbons. The gaseous by-products produced exhibit high calorific value with potentials of been reutilized as feedstock and liquid fractions composed of linear olefinic and paraffinic mixtures. At elevated temperature beyond 700 °C, PP and PE release olefinic mixture exhibiting prospects of being reused in the production of corresponding polyolefins. However, HDPE and LDPE thermal cracking are relatively difficult due to their poor heat dissipation properties [59].

7 Incineration of plastic waste

An efficient route of reducing solid waste is though burning in an appropriately designed and operation condition via the incineration process [60]. Usually, during incineration, combusted residue chemically combines with molecular oxygen to facilitate generation of CO_2 and H_2O, while the residue generates metallic oxides and minerals.

The main benefits of municipal incinerator include the need for less land and effective utilization in energy amassing. Despite this awareness, waste incineration expresses accruable benefits such as volume minimization, rapid disposal devoid of slow biodegradation, minimized requirement for land, destruction of toxic wastes, and wastes value addition, and electricity generation [61].

7.1 MSW incineration: comparison of technologies

Numerous techniques are available for MSW incineration based on conversion-plant and potential inclusion of waste pretreatment units. Incinerating for energy recovery is typically conducted via two procedures [62]. Acquired MSW may directly be utilized for mass-combustion incineration or preprocessing for production of a more homogenous product known as RDF [63] This is composed of combustible MSW which is generally produced via shredding and sorting of relatively uniform portion of MSW. Going from the perspective of energy generation, MSW incineration via RDF-gasification exhibits optimal efficiency, though with several environmental disadvantages and side effects. In a bid to attain environmental sustainability, a specified incinerator haven air pollution control implements enables optimal results [64].

However, with regards to economic profitability, gasification accrues highest revenues from energy sales. The choice of an appropriate route for an MSW incinerating mechanism is function of the size of the facility under consideration. Several studies have utilized natural fiber wastes as reinforcement in fabrication of polymer nanocomposites [65–77]. The gasification process portrays suitable electrical conversion efficiency while exhibiting higher operation costs. A report has concluded that gasification is superior to the conventional process of combustion. A higher degree of electricity is generated by gasification resulting in lowered total costs in addition to minimized CO_2 emissions.

8 Conclusion

As regards existing statistics, there is continual increase in plastics consumption as a result of its wide scope of applications, resulting in increased plastics waste. However, the large quantity of plastic wastes released may undergo treatment with properly designed techniques to enable production of alternatives to fossil fuel. The technique should demonstrate superiority in all aspects especially ecologically and economically. The escalating amount of MSW poses a great challenge as regards monitoring and control, in order to alleviate their environmental effects. Conventional waste management techniques such as burning and landfilling exhibit a severe impact to the environment and humanity. Novel techniques capable of converting waste to valuable products and energy are consolidating as established routes of waste management. These techniques include both biological and thermochemical conversions, and researches have been carried out in previous decades resulting in enhanced energy and products yield in addition to reduced impact on the environment.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests

References

1. ASTM D883-17 (2017) Standard terminology relating to plastics, ASTM International, West Conshohocken, PA. www.astm.org
2. Abdelhafidia A, Babaghayoua IM, Chabiraa SF, Sebaaa M (2015) Impact of solar radiation effects on the physicochemical properties of polyethylene (PE) plastic film. Proced Soc Behav Sci 195:2210–2217
3. Adrados A, de Marco I, Caballero B, LÃpez A, Laresgoiti M, Torres A (2012) Pyrolysis of plastic packaging waste: a comparison of plastic residuals from material recovery facilities with simulated plastic waste. J Waste Manag 32(5):826–832
4. Alam O, Billah M, Yajie D (2018) Characteristics of plastic bags and their potential environmental hazards. Resour Conserv Recycl 132:121–129
5. Al-Salem M, Antelava A, Constantinou A, Manos G, Dutta A (2017) A review on thermal and catalytic pyrolysis of plastic solid waste (PSW). J Environ Manag 197:177–198
6. Agamuthu P (2018) Challenges in sustainable management of construction and demolition waste. Waste Manag Res 26:491–492
7. Al-Salem M, Lettieri P, Baeyens J (2010) The valorization of plastic solid waste (PSW) by primary to quaternary routes: from re-use to energy and chemicals. Prog Energy Combust Sci 36:103–129
8. Aluri S, Syed A, Flick D, Muzzy J, Sievers C, Agrawal P (2018) Pyrolysis and gasification studies of model refuse derived fuel (RDF) using thermogravimetric analysis. Fuel Process Technol 179:154–166
9. Andrady AL (2011) Microplastics in the marine environment. Mar Pollut Bull 62(8):1596–1605
10. Assis G, Skovroinski E, Leite V, Rodrigues M, Galembeck A, Alves M, Eastoe J, Oliveira R (2018) Conversion of "Waste Plastic" into photocatalytic nanofoams for environmental remediation. ACS Appl Mater Interfaces 10(9):8077–8085
11. Avio C, Gorbi S, Regoli F (2017) Plastics and microplastics in the oceans: from emerging pollutants to emerged threat. Mar Env Res 128:2–11
12. Banks S, Bridgwater A (2016) 14 - Catalytic fast pyrolysis for Â improved liquid quality. In: Luque R, Lin CSK, Wilson K, Clark J (eds) Handbook of biofuels production, 2nd edn. Woodhead Publishing, Cambridge, pp 391–429
13. Brar L, Elsayed K (2018) Analysis and optimization of cyclone separators with eccentric vortex finders using large eddy simulation and artificial neural network. Sep Purif Technol 207:269–283
14. Benedetti M, Cafiero L, De Angelis D et al (2017) Front pyrolysis of WEEE plastics using catalysts produced from fly ash of coal gasification. Environ Sci Eng 11:11
15. Danias P, Liodakis S (2018) Characterization of refuse derived fuel using thermogravimetric analysis and chemometric techniques. J Anal Chem 73:351
16. Das P, Tiwari P (2018) Valorization of packaging plastic waste by slow pyrolysis. Resour Conserv Recycl 128:69–77
17. Dayana S, Sharuddin A, Abnisa F, Daud W, Aroua M (2017) Energy recovery from pyrolysis of plastic waste: study on non-recycled plastics (NRP) data as the real measure of plastic waste. Energy Convers Manag 148:925–934
18. Devasahayam S, Strezov V (2018) Thermal decomposition of magnesium carbonate with biomass and plastic wastes for simultaneous production of hydrogen and carbon avoidance. J Clean Prod 174:1089–1095
19. Gu F, Guo J, Zhang W, Summers PA, Hall P (2017) From waste plastics to industrial raw materials: a lifecycle assessment of mechanical plastic recycling practice based on a real word case study. Sci Total Environ 601–602:1192–1207
20. Hartulistiyoso E, Sigiro F, Yulianto M (2015) Temperature distribution of the plastics pyrolysis process to produce fuel at 450°C. Proced Environ Sci 28:234–241
21. Hazrat M, Rasul M, Khan M, Azad A, Bhuiya M (2014) Utilization of polymer wastes as transport fuel resources- a recent development. Energy Proced 61:1681–1685
22. Heskett M et al (2012) Measurement of persistent organic pollutants (POPs) in plastic resin pellets from remote islands: toward establishment of background concentrations for international pellet watch. Mar Pollut Bull 64(2):445–448
23. Ivar do Sul JA, Costa MF (2014) The present and future of microplastic pollution in the marine environment. Environ Pollut 185:352–364
24. Kalogerakis N, Karkanorachaki K, Kalogerakis G, Triantafyllidi EI, Gotsis AD, Partsinevelos P, Fava FH (2017) Microplastics generation: onset of fragmentation of polyethylene films in marine environment mesocosms. Front Mar Sci 4:84
25. Kolská Z, Polanský R, Prosr P, Zemanová M, Ryšánek P, Slepička P, Švorčík V (2018) Properties of polyamide nanofibers treated by UV-A radiation. Mater Lett 214:264–267
26. Kunwar B, Cheng H, Chandrashekaran S, Sharma B (2016) Plastics to fuel: a review. Renew Sustain Energy Rev 54:421–428
27. Lee T, Oh J, Baek K, Tsang Y, Kim K, Kwon E (2018) Compositional modification of pyro-genic products using $CaCO_3$ and CO_2 from the thermolysis of polyvinyl chloride (PVC). Green Chem 20:1583–1593
28. Lebreton L, van der Zwet J, Damsteeg JW, Slat B, Andrady A, Reisser J (2017) River plastic emissions to the world's oceans. Nat Commun 8:15611
29. Lei J, Yuan G, Weerachanchai P, Lee S, Li K, Wang J, Yang Y (2018) Investigation on thermal dechlorination and catalytic pyrolysis in a continuous process for liquid fuel recovery from mixed plastic wastes. J Mater Cycles Waste Manag 20:137–146
30. Lehner B, Verdin K, Jarvis A (2008) New global hydrography derived from spaceborne elevation data. EOS Trans AGU 89(10):93–94

31. Lungu M (2004) Electrical separation of plastic materials using the triboelectric effect. Miner Eng 17:69–75
32. Mason SA, Garneau D, Sutton R, Chu Y, Ehmann K, Barnes J, Fink P, Papazissimos D, Rogers DL (2016) Microplastic pollution is widely detected in US municipal wastewater treatment plant effluent. Environ Pollut 218:1045–1054
33. Makarichi L, Jutidamrongphan W, Techato K (2018) The evolution of waste-to-energy incineration: a review. Renew Sustain Energy Rev 91:812–821
34. Murali D, Rajagopalan N, Sharma B (2018) Materials and energy recovery from E-waste plastics. ACS Sustain Chem Eng 6(4):4594–4602
35. Miller L, Soulliere K, Sawyer-Beaulieu S, Tseng S, Tam E (2014) Challenges and alternatives to plastics recycling in the automotive sector. Materials 7(8):5883–5902
36. Moya D, Aldás C, López G, Kaparaju P (2017) Municipal solid waste as a valuable renewable energy resource: a worldwide opportunity of energy recovery by using waste-to-energy technologies. Energy Proced 134:286–295
37. Miandad R, Barakat M, Aburiazaiza A, Rehan M, Ismail I, Nizami A (2017) Effect of plastic waste types on pyrolysis liquid oil. Int Biodeter Biodegr 119:239–252
38. Nakamura S, Kondo Y (2002) Input-output analysis of waste management. J Ind Ecol 6:39–63
39. Owusu P, Banadda N, Zziwa A, Seay J, Kiggundu N (2018) Reverse engineering of plastic waste into useful fuel products. J Anal Appl Pyrolysis 130:285–293
40. Özsin G, Pütün A (2018) Co-pyrolytic behaviors of biomass and polystyrene: kinetics, thermodynamics and evolved gas analysis. Korean J Chem Eng 35:428
41. Plastics Europe (2017) Plastics—The facts. Plastic Europe. https://www.plasticseurope.org/en/resources/publications/274-plastics-facts-2017. Accessed 20 Apr 2019
42. Park K, Oh S, Begum G, Kim J (2018) Production of clean oil with low levels of chlorine and olefins in a continuous two-stage pyrolysis of a mixture of waste low-density polyeth-ylene and polyvinyl chloride. Energy 157:402–411
43. Parthasarathy V, Dhanalakshmi V, Anbarasan R (2013) Thermal, melting and crystallinity behavior of esters grafted LDPE by thermolysis method. Int J Plast Technol 17(1):61–74
44. Palza H, Aravena C, Colet M (2017) Role of the catalyst in the pyrolysis of polyolefin mixtures and used tires. Energy Fuels 31(3):3111–3120
45. Qiu B, Deng N, Zhang Y, Wan H (2018) Application of industrial solid wastes in catalytic pyrolysis. Asia-Pac J Chem Eng 13:2150
46. Ragaert K, Delva L, Geem K (2017) Mechanical and chemical recycling of solid plastic waste. J Waste Manag 69:24–58
47. Rehan M, Miandad R, Barakat M, Ismail I, Almeelbi T, Gardy J, Hassanpour A, Khan M, Demirbas A, Nizami A (2017) Effect of zeolite catalysts on pyrolysis liquid oil. Int Biodeter Biodegr 119:162–175
48. Ruan J, Huang J, Qin B, Dong L (2018) Heat transfer in vacuum pyrolysis of decomposing hazardous plastic wastes. ACS Sustain Chem Eng 6(4):5424–5430
49. Santillo D, Miller K, Johnston P (2017) Microplastics as contaminants in commercially important seafood species. Integr Environ Assess Manag 13:516–521
50. Sági D, Solymosi P, Holló A, Varga Z, Hancsók J (2018) Waste polypropylene and waste cooking oil as feedstocks for an alternative component containing diesel fuel production. Energy Fuels 32(3):3519–3525
51. Schmidt C, Krauth T, Wagner S (2017) Export of plastic debris by rivers into the sea. Environ Sci Technol 51(21):12246–12253
52. Scarlat N, Dallemand J, Fahl F (2018) Biogas: developments and perspectives in Europe. Renew Energy 129(Part A):457–472
53. Shen Y, Chen X, Ge X, Chen M (2018) Chemical pyrolysis of E-waste plastics: char characterization. J Environ Manag 214:94–103
54. Suresh S, Bonda S, Mohanty S, Nayak S (2018) A review on computer waste with its special insight to toxic elements, segregation and recycling techniques. Process Saf Environ 116:477–493
55. Subramanian K, Yung W (2016) Review of life cycle assessment on consumer electronic products: developments and the way ahead. Crit Rev Environ Sci Technol 46(18):1441–1497
56. Sharuddin S, Abnisa F, Daud W, Aroua M (2016) A review on pyrolysis of plastic wastes. Energ Convers Manag 115:308–326
57. Singh R, Ruj B (2016) Time and temperature depended fuel gas generation from pyrolysis of real-world municipal plastic waste. Fuel 174:164–171
58. Tian J, Ni L, Song T, Olson J, Zhao J (2018) An overview of operating parameters and conditions in hydrocyclones for enhanced separations. Sep Purif Technol 206:268–285
59. Van Cauwenberghe L, Janssen CR (2014) Microplastics in bivalves cultured for human consumption. Environ Pollut 193:65–70
60. Veksha A, Giannis A, Oh W, Lisak G (2018) Catalytic processing of non-condensable pyrolysis gas from plastics: effects of calcium supports on nickel-catalyzed decomposition of hydrocarbons and HCl sorption. Chem Eng Sci 189:311–319
61. Van Emmerik T, Kieu-Le TC, Loozen M, van Oeveren K, Strady E, Bui XT, Egger M, Gaspéri J, Lebreton L, Nguyen PD, Schwarz A, Slat B, Tassin B (2018) A methodology to characterize riverine macroplastic emission into the ocean. Front Mar Sci 5:372
62. Vargas Santillán A, Farias Sanchez J, Pineda Pimentel M et al (2016) Olefins and ethanol from polyolefins: analysis of potential chemical recycling of poly (ethylene). Mexican case. Int J Chem React Eng 14(6):1289–1300
63. Wohlleben W, Neubauer N (2016) Quantitative rates of release from weathered nanocomposites are determined across 5 orders of magnitude by the matrix, modulated by the embedded nanomaterial. NanoImpact 1:39–45
64. Wong L, Ngadi N, Abdullah T, Inuwa M (2015) Current state and future prospects of plastic waste as source of fuel: a review. Renew Sust Emerg Rev 50:1167–1180
65. Idumah CI, Ogbu JE, Ndem JU, Obiana V (2019) Influence of chemical modification of kenaf fiber on xGNP-PP nano-biocomposites. SN Appl Sci 1:1261
66. Idumah C, Hassan A, Affam A (2015) A review of recent developments in flammability of polymer nanocomposites. Rev Chem Eng 31:149–177
67. Idumah C, Hassan A (2016) Characterization and preparation of conductive exfoliated graphene nanoplatelets kenaf fibre hybrid polypropylene composites. Syn Met 12:91–104
68. Idumah C, Hassan A (2016) Recently emerging trends in thermal conductivity of polymer nanocomposites. Rev Chem Eng 32:413–457
69. Idumah C, Hassan A (2015) Emerging trends in flame retardancy of biofibers, biopolymers, biocomposites, and bionanocomposites. Rev Chem Eng 32:115–148
70. Idumah C, Hassan A (2016) Emerging trends in graphene carbon based polymer nanocomposites and applications. Rev Chem Eng 32:223–264
71. Idumah C, Hassan A (2016) Effect of exfoliated graphite nanoplatelets on thermal and heat deflection properties of kenaf polypropylene hybrid nanocomposites. J Polym Eng 36:877–889
72. Idumah C, Hassan A (2016) Emerging trends in eco-compliant, synergistic, and hybrid assembling of multifunctional polymeric bionanocomposites. Rev Chem Eng 32:305–361
73. Idumah C, Hassan A (2017) Bourbigot S. Influence of exfoliated graphene nanoplatelets on flame retardancy of kenaf flour

polypropylene hybrid nanocomposites. J Anal Appl Pyrolysis 123:65–72
74. Idumah C, Hassan A (2017) Hibiscus cannabinus fiber/PP based nano-biocomposites reinforced with graphene nanoplatelets. J Nat Fibers 14:691–706
75. Idumah C, Hassan A, Ogbu J, Ndem J, Nwuzor I (2018) Recently emerging advancements in halloysite nanotubes polymer nanocomposites. Compos Interfaces. https://doi.org/10.1080/09276440.2018.1534475
76. Idumah C, Hassan A, Ogbu J, Ndem J, Oti W, Obiana V (2018) Electrical, thermal and flammability properties of conductive filler kenaf reinforced polymer nanocomposites. J Thermoplast Compos Mater. https://doi.org/10.1177/0892705718807957
77. Idumah C, Hassan A, Bourbigot S (2018) Synergistic effect of exfoliated graphene nanoplatelets and non-halogen flame retardants on flame retardancy and thermal properties of kenaf flour-PP nanocomposites. J Therm Anal Calorim. https://doi.org/10.1007/s10973-018-7833-3