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Focus on potential environmental issues on plastic world towards a sustainable plastic recycling in developing countries

Onwughara Innocent Nkwachukwu[1,3*], Chukwu Henry Chima[2], Alaekwe Obiora Ikenna[3] and Lackson Albert[3,4]

Abstract

Due to the tremendous growth of plastics in the world, it has brought about environmental concerns for over the past two or three decades. Most of these plastics, due to poor management, are currently disposed of in unauthorized dumping sites or burned uncontrollably in the fields. The paper outlines environmental concerns of so many applications of plastics. The most important mechanisms of degradation of plastics, environmental impacts and recommendations for sustainable development are fully discoursed, with recycling option being overviewed as the route under most intense development at this time because of its broad public appeal and obvious environmental advantages.

Keyword: Plastic waste; Plastics' end-of-life; Degradation; Environmental impacts; Health effects; Recycling and recommendation

Review

Introduction

Plastics are organic polymeric materials consisting of giant organic molecules. Plastic materials can be formed into shapes by one of a variety of processes, such as extrusion, moulding, casting or spinning. Modern plastics (or polymers) possess a number of extremely desirable characteristics: high strength-to-weight ratio, excellent thermal properties, electrical insulation, and resistance to acids, alkalis and solvents, to name but a few. Some have unique electrical insulating properties, such as their strength, stress resistance, flexibility and durability, which make them important materials for use in electronics. These polymers are made of a series of repeating units known as monomers. The structure and degree of polymerisation of a given polymer determine its characteristics. Linear polymers (a single linear chain of monomers) and branched polymers (linear with side chains) are thermoplastic; they soften when heated. Cross-linked polymers (polymers with bond formed between polymer chains, either between different chains or between different parts of the same chain.) are thermosetting, that is, they harden when heated.

Development of synthetic polymers, used to make plastics such as polyethylene, polypropylenes, polyesters and polyamides (including nylon), has revolutionized the types of containers for products, the types of materials for packaging and the materials used for carry bags. However, most of these polymers are not biodegradable and, once used and discarded, become major waste management challenges [1]. However, plastic waste can also impose negative externalities such as greenhouse gas emissions or ecological damage. It is usually non-biodegradable and therefore can remain as waste in the environment for a very long time; it may pose risks to human health and the environment. In some cases, it can be difficult to reuse and/or recycle. There is a mounting body of evidence which indicates that substantial quantities of plastic waste are now polluting marine and other habitats [2]. The widespread presence of these materials has resulted in numerous accounts of wildlife becoming entangled in plastic, leading to injury or impaired movement and, in some cases, resulting in death. Concerns have been raised regarding the effects of plastic ingestion as there is some evidence to indicate that toxic chemicals from plastics can

* Correspondence: onwugharankwachukwu@yahoo.com
[1]Reliable Research Laboratory Service, D30 Orji Kalu Housing Estate, Umuahia, Abia State, Nigeria
[3]Department of Pure and Industrial Chemistry, Nnamdi Azikiwe University Awka, P.M.B. 5052, Awka, Anambra State, Nigeria
Full list of author information is available at the end of the article

accumulate in living organisms and throughout nutrient chains. There are also some public health concerns arising from the use of plastics treated with chemicals [2].

As with most materials, global plastic production is estimated to decrease from 245 million tonnes (Mt) in 2008 to around 230 million tonnes in 2009 as a result of the economic crisis. Over the past 50 years, however, there has been a very steep rise in plastic production, especially in Asia (Figure 1). The European Union (EU) accounts for around 25% of world production. The total consumption of plastics in Western Europe was approximately 39.7 million tonnes in 2003, which means about 98 kg/person, and the amount has been increasing [3]. China produces more plastic than any other country, at 15% of global production. Germany produces the greatest amount of any EU country, accounting for about 8% of global production as shown in Figure 2 [4]. Societies are increasingly reliant on plastics, which are already a ubiquitous part of everyday life. As the development of new materials is ongoing, limiting their detrimental effects poses new challenges for policy makers. Regulatory instruments designed to mitigate the effects of plastics on human health and the environment must evolve in line with trends in production, use and disposal [2].

Polyethylene has the highest share of production of any polymer type, while four sectors: polyethylene terephthalate (PET), which accounts for 20% of thermoplastic resin capacity, followed by polypropylene (PP), which accounts for 18%, polyvinyl chloride (PVC) and polystyrene/expanded polystyrene (PS/EPS), represent 72% of plastic demand: packaging, construction, automotive and electrical and electronic equipment as shown in Figure 3. The rest includes sectors such as household, furniture, agriculture and medical devices [4]. Plastic packaging accounts for the largest share of plastic production in the world level. About 50% of plastic is used for single-use disposable applications, such as packaging, agricultural films and disposable consumer items [6]. Plastics were the second largest component in waste from electrical and electronic equipment (WEEE), and approximately 30% of the mass electronic scrap consists of plastics [7-9]. Plastics consume approximately 8% of world oil production: 4% as raw material for plastics and 3% to 4% as energy for manufacture [1,6].

The plastic industry is in constant development, with technology evolving in response to the ever-changing demand. Some trends that emerge clearly are continued innovation and improvements such as weight reduction of individual items, increasing use of plastics (and bioplastics) in vehicle manufacturing, a shift in primary plastic production to transition and emerging economies and continued growth in the market share of bioplastics (despite some sorting and price barriers).

Bioplastics make up only 0.1% to 0.2% of total EU plastics [11]. It is estimated that plastics save 600 to 1,300 million

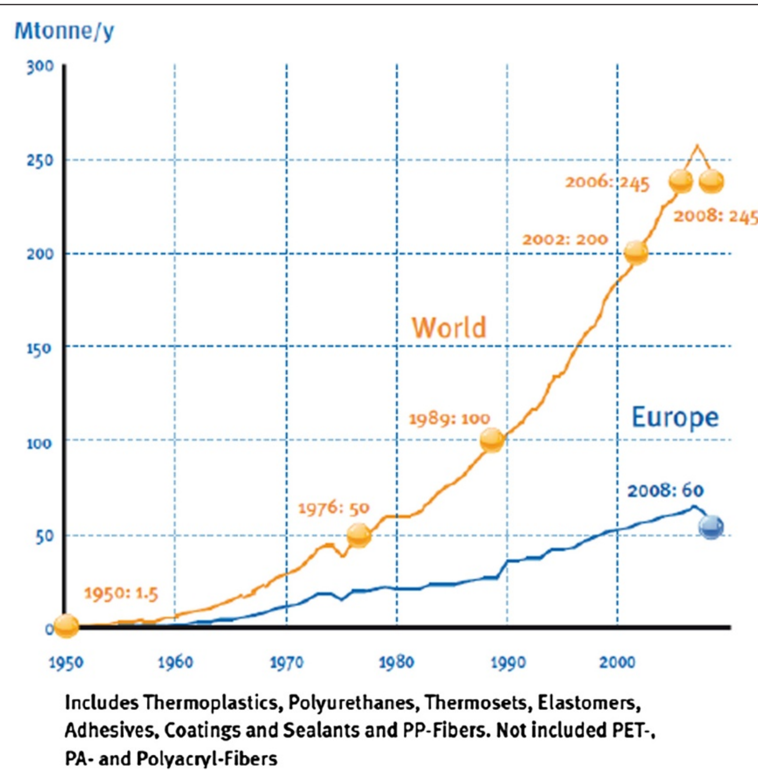

Figure 1 **World plastic production, 1950 to 2008 (Mt) (adapted from [5]).**

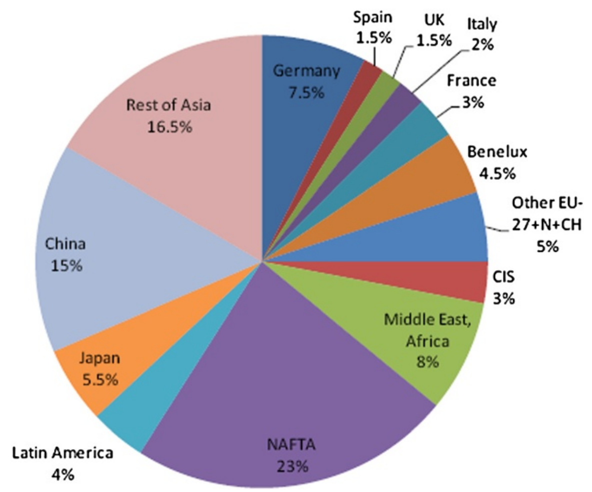

Figure 2 Distribution of world plastic production (adapted from [4]).

tonnes of CO_2 through the replacement of less efficient materials, fuel savings in transport, contribution to insulation, prevention of food losses and use in wind power rotors and solar panels [12]. In 2000, the consumption of polymers for plastic applications in Western Europe was 36,769,000 tonnes, an increase of 3.4% from 1999 [13]. Of the generated municipal solid waste (MSW) in Thailand, 14% were plastics [14]. According to Onwughara [15], the percentage components of plastics and nylon of different categories of solid generated in Umuahia, capital of Abia State, Nigeria were 1.5% and 10.2%, respectively. Of the generated wastes in Kathmandu Valley in Nepal, 22.65% were plastics [16].

The chemicals produced known as dioxins and furan from plastic, especially incinerating plastics, have been implicated in birth defects and several kinds of cancer. The slag and fly ash were found to be environmentally beneficial in cement production and for off-gases for power production [17]. Thermoplastics make up 80% of the plastics produced today [17]. Examples of thermoplastics include high-density polyethylene (HDPE) used in piping, automotive fuel tanks, bottles and toys; low-density polyethylene (LDPE) used in plastic bags, cling film and flexible containers; PET used in bottles, carpets and food packaging; PP used in food containers, battery cases, bottle crates, automotive parts and fibres; PS used in dairy product containers, tape cassettes, cups and plates; and PVC used in window frames, flooring, bottles, packaging film, cable insulation, credit cards and medical products.

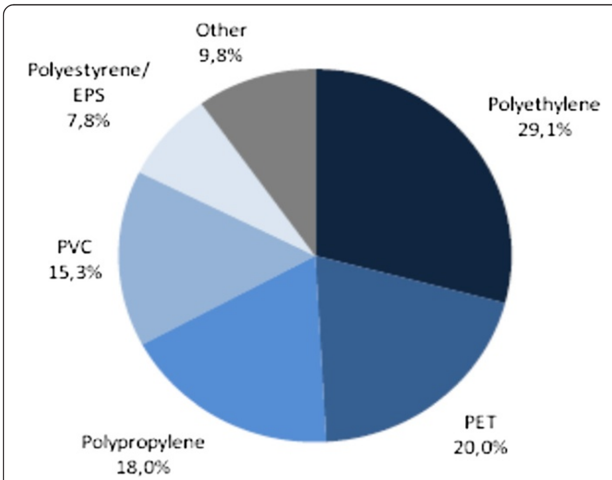

Figure 3 World thermoplastic resin capacity, 2008 (adapted from [10]).

There are hundreds of types of thermoplastic polymer, and new variations are regularly being developed. In developing countries, the number of plastics in common use, however, tends to be much lower. Thermosets make up the remaining 20% of plastics produced. They are hardened by curing and cannot be re-melted or re-moulded and are therefore difficult to recycle. They are sometimes ground and used as a filler material. They include polyurethane (PU) - coatings, finishes, gears, diaphragms, cushions, mattresses and car seats; epoxy - adhesives, sports equipment and electrical and automotive equipment; and phenolics - ovens, handles for cutlery, automotive parts and circuit boards. The global demand for plastic composites has grown significantly over the past few years (Figure 4).

Nowadays, the raw materials for plastics come mainly from petrochemicals, although originally plastics were derived from cellulose, the basic material of all plant life. The materials used in electronics have several important characteristics. In PC monitors and televisions (TVs), acrylonitrile butadiene styrene (ABS) and high-impact polystyrene (HIPS) are used for cathode ray tube protection. Also, polyphenylene oxide (PPO) has good properties such as high temperature resistance, rigidity, impact strength and creep resistance.

Table 1 shows the summary of typical resins used in different electrical and electronics equipment [7], and Table 2 shows the weight percentage of manufactured plastic from organic compounds [7,15]. Polymer types used in various construction applications are described in Table 3.

A more recent projection (Figure 5) shows slightly slower growth to just over 1.4 Mt in 2013, but the trend is still strongly positive. The SRI study projects total consumption of biodegradable polymers worldwide at an average annual growth rate of 13% from 2009 to 2014 [19].

According to Kurudufu [21], it is estimated that 100 million tonnes of plastics are produced each year. The average European throws away 36 kg of plastics each year. Four percent of oil consumption in Europe is used for the manufacture of plastic products. Some plastic waste sacks are made from 64% recycled plastic. Plastic packaging totals 42% of the total consumption, and very

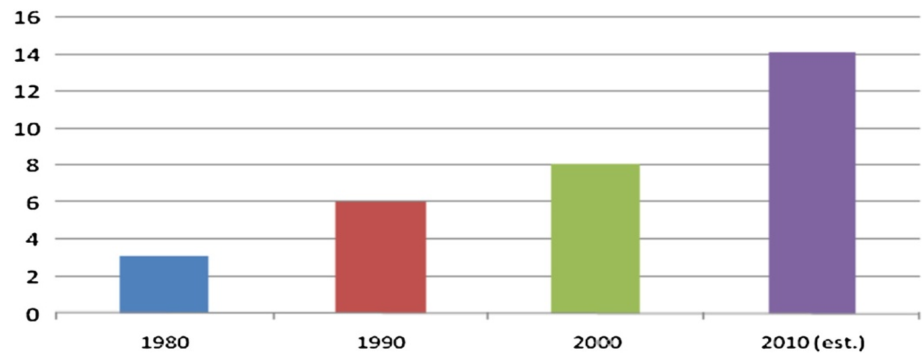

Figure 4 Global demand in the composite industry (Mt) (adapted from [18]).

little of this is recycled. In 2008, total generation of post-consumer plastic waste in EU-27, Norway and Switzerland was 24.9 Mt. Packaging is by far the largest contributor to plastic waste at 63%. Average EU-27 per capita generation of plastic packaging waste was 30.6 kg in 2007 [4]. There are lots of different plastics, and they will give off lots of different vapours when they decompose. Figure 6 shows various areas where plastics are used [22].

It could be just a simple hydrocarbon or it could contain cyanides, polychlorinated biphenyls (PCBs) or lots of other substances. Without knowing what the plastic was (including what additives might have been incorporated), it would be difficult to know what likely volatiles it would create; volatiles given off from plastics in house fires are a major cause of death. Halogenated plastics, those that are made from chlorine or fluorine, are problematic. This work will review environmental issue ascertained from the development of plastics.

Sources of waste plastics

Industrial waste (or primary waste) can often be obtained from the large plastic processing, manufacturing and packaging industries. Rejected or waste material usually has good characteristics for recycling and thus will be clean. Although the quantity of material available is sometimes small, the quantities tend to be growing as consumption, and therefore production, increases. Commercial waste is often available from workshops, craftsmen, shops, supermarkets and wholesalers. A lot of the plastics available from these sources will be PE, often contaminated. Agricultural waste can be obtained from farms and nursery gardens outside the urban areas. This is usually in the form of packaging (plastic containers or sheets) or construction materials (irrigation or hosepipes). Municipal waste can be collected from residential areas (domestic or household waste), streets, parks, collection depots and waste dumps. In Asian cities, this type of waste is common and can either be collected from the streets or from households by arrangement with the householders [21].

Table 1 Resins used in electronic products

EEE	Resins
Computers	ABS, HIPS, PPO, PPE, PVC, PC/ABS
TVs	HIPS, PC, ABS, PPE, PVC
Miscellaneous	HIPS, PVC, ABS, PC/ABS, PPE, PC

ABS acrylonitrile butadiene styrene, *HIPS* high-impact polystyrene, *PPO* polyphenylene oxide, *PPE* polyphenylene ether, *PVC* polyvinylchloride, *PC* polycarbonate. Miscellaneous: fax, telephone, refrigerator etc.

Plastics' end-of-life

Several end-of-life options exist to deal with plastic waste, including recycling, disposal and incineration with or without energy recovery. The plastic recycling rate was 21.3% in 2008, helping to drive total recovery (energy recovery and recycling) to 51.3%. The highest rate of recycling is seen in Germany at 34% [4]. As plastic packaging has the longest established system for the recovery and recycling of plastic waste, it is natural that its recycling rates are higher than those of other streams. It is followed by agricultural waste plastic, which, although not under direct legislative obligation to increase recovery, is subject to economic incentives linked to the availability of homogenous materials. Although WEEE and construction plastic waste sources have relatively low rates of recycling overall, the rate of energy recovery is relatively high. Overall, total recovery is the highest for plastic packaging at 59.8% and the lowest for ELV plastics at 19.2% [4].

Table 2 Manufactured plastic from organic compounds

Manufactured plastic	Weight percentage (wt.%)
HIPS	59
ABS	20
PPO	16
PP or PE	2
Others	3

HIPS high-impact polystyrene, *ABS* acrylonitrile butadiene styrene, *PPO* polyphenylene oxide, *PP* polypropylene, *PE* polyethylene.

Table 3 Main polymers used for applications

Application	Most common polymers used
Pipes and ducts	PVC, PP, HDPE, LDPE, ABS
Insulation	PU, EPS, XPS
Window profiles	PVC
Other profiles	
Floor and wall coverings	
Lining	PE, PVC
Fitted furniture	PS, PMMA, PC, POM, PA, UP, amino

PVC polyvinylchloride, *PP* polypropylene, *HDPE* high-density polyethylene, *LDPE* low-density polyethylene, *ABS* acrylonitrile butadiene styrene, *PU* polyurethane, *EPS* expanded polystyrene, *XPS* extruded polystyrene.

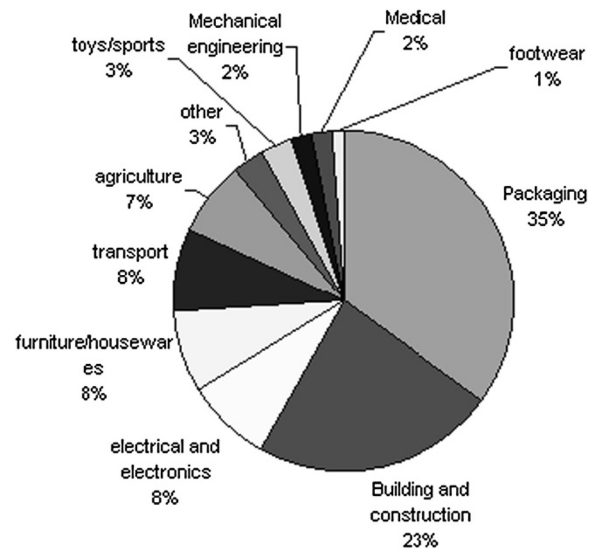

Figure 6 Utilization of plastic in various fields.

The final stage in the life cycle of plastics is disposal. In India, there are three common ways of getting rid of plastics: by dumping them in landfills, by burning them in incinerators or by littering them. In the case of littering, plastic wastes fail to reach landfills or incinerators. It is the improper way of disposing plastics and is identified as the cause of manifold ecological problems. Incineration is a process in which plastic and other wastes are burnt, and the energy produced, as a result, is tapped. In combination with halogens in the plastic fraction, they can form volatile metal halides, but they also have a catalytic effect on the formation of dioxins and furans [9]. WEEE should not be combined with unsorted municipal waste destined for landfills or open burning of garbage because electronic waste can contain more than 100 different substances (toxic chemicals), many of which are toxic such as lead, mercury, hexavalent chromium, selenium, cadmium and arsenic [23]. Additional harmful substances in WEEE can include arsenic, PCBs, chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) and nickel. Some of these toxic chemicals, even when

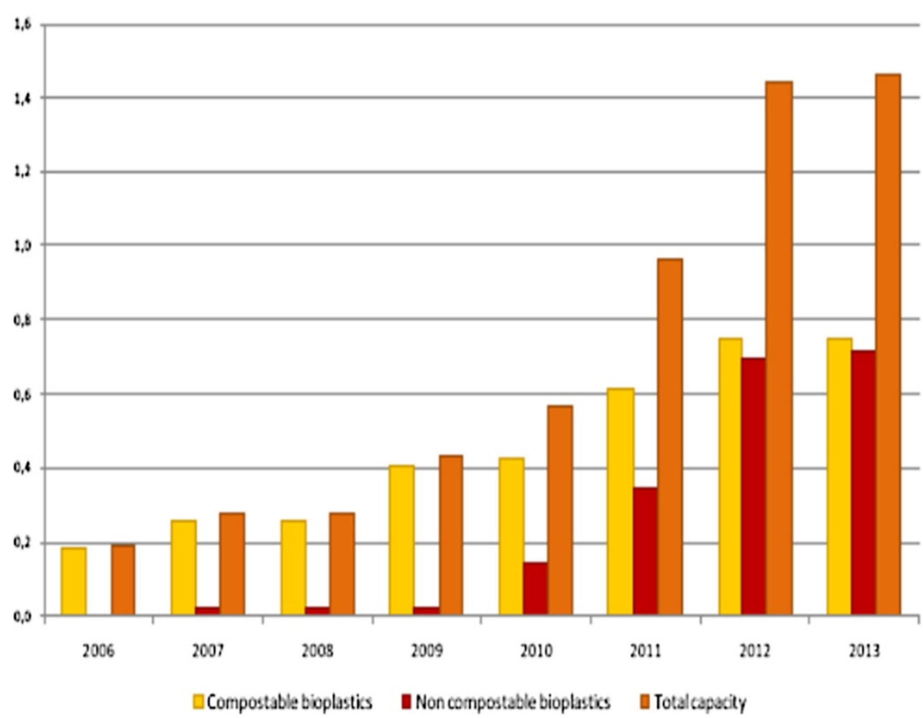

Figure 5 Global production capacity of bioplastics (Mt) (adapted from [20]).

present in small amounts, can be potent pollutants and contribute to toxic landfill leachate and vapours, such as vaporization of metallic and dimethylene mercury [15].

During burning of WEEE, toxic chemicals such as dioxins and furans may be release to the environment; furthermore, runoff water carries leachate from acidic ash into the sea affecting the aquatic life. Also, the ash leached into the soil which causes groundwater contamination. The municipal solid wastes in Nigeria contain all sources of unsorted wastes, such as commercial refuse, construction and demolition debris, garbage, electronic wastes etc., which are dumped indiscriminately on roadsides and any available open pits irrespective of the health implication on people [15]. Most plastics (thermosets) are from electronic wastes [15]. With the rapid improvements in the electronic industry, electronic waste (e.waste), including all obsolete electronic products, has become the fastest growing component in the solid waste stream. This phenomenon has been a source of hazardous wastes such as PCs and TVs, which contain heavy metals and organic compounds that pose risk to the environment if not properly managed. Balakrishnan shows that 19% of plastic are found in WEEE [8].

More than 20,000 plastic bottles are needed to obtain 1 tonne of plastic [24]. The durability of the most widely used polyethylene plastic films used for protected cultivation varies from a minimum of one cultivating season to a maximum of 2 to 3 years, and at the end of their useful life, they are classified as waste. Most of this waste is currently disposed of in unauthorized dumping sites or burned uncontrollably in the fields. Management of the huge quantities of waste produced in this way represents a problem with great environmental implications. In order to minimize the environmental impact of this plastic waste stream, it is desirable that the films used in protected cultivation have an increased life, thus producing less waste per annum. However, sustainability requires that a degradable material breaks down completely by natural processes so that the basic building blocks can be used again by nature to make a new life form. Plastics made from petrochemicals are not a product of nature and cannot be broken down by natural processes. It is assumed that the breakdown products will eventually biodegrade. In the meanwhile, these degraded, hydrophobic, high surface area plastic residues migrate into the water table and other compartments of the ecosystem causing irreparable harm to the environment [25].

Mechanisms of degradation

Degradation is a complicated non-linear time-dependent process which affects directly or indirectly several properties of the material related to its functional characteristics. In its final stage of degradation, a material does not meet its functional requirements and is easily prone to mechanical failure. As a practical rule, the useful life of a material is considered to be reached when its initial mechanical strength is reduced by 50%. There are several factors to monitor and criteria to define the degree of degradation. Not all properties are affected by degradation in the same way though. Thus, the elongation at break (expressed as a percentage) appears to be a more sensitive 'index' of degradation than the tensile strength, the stress at yield or the modulus of elasticity. In fact, the material becomes more brittle with degradation, so it cannot retain its initial elongation at break [7].

Degradation of polymers is induced by different external factors and mechanisms. Briefly, the various degradation types for polymers are the following:

1. Thermal degradation occurs due to use or processing of polymers at high temperatures.
2. Photo-induced degradation occurs when, on exposure to the energetic part of the sunlight, i.e. the ultraviolet (UV) radiation, or other high-energy radiation, the polymer or impurities within the polymer absorb the radiation and induce chemical reactions.
3. Mechanical degradation occurs due to the influence of mechanical stress–strain.
4. Ultrasonic degradation is the application of sound at certain frequencies which may induce vibration and eventually breaking of the chains.
5. Hydrolytic degradation occurs in polymers containing functional groups which are sensitive to the effects of water.
6. Chemical degradation occurs when corrosive chemicals, such as ozone or the sulphur in agrochemicals, attack the polymer chain causing bond breaking or oxidation.
7. Biological degradation is specific to polymer with functional groups that can be attacked by microorganisms.

Environmental management issues

Landfill option

Landfill not only takes up large areas of land but can also generate bio-aerosols, odours and visual disturbance and may lead to the release of hazardous chemicals through the escape of leachate from landfill sites. Organic breakdown following landfill disposal of biodegradable waste, including bioplastics, causes the release of greenhouse gases. Landfill of waste usually implies an irrecoverable loss of resources and land (since landfill sites can normally not be used post-closure for engineering and/or health risk reasons), and in the medium to long term, it is not considered a sustainable waste management solution [26].

Incineration option

The environmental impacts of incinerating plastic waste (as for most solid wastes or fuels) can include some airborne particulates and greenhouse gas emissions. Plants that are compliant with the Waste Incineration Directive are not thought to have any significant environmental impact. However, in some circumstances, energy recovery of plastic waste in MSW incinerators can result in a net increase in CO_2 emissions due to substituted electricity and heat production [27]. Therefore, all incineration activities should be associated with suitable filter system trap for released toxic substances, where the incinerators operate in a way not to pollute the atmosphere, soil and groundwater. There will also be an environmental burden due to the disposal of ashes and slag. For example, flue gas cleaning residues often have to be disposed of as hazardous waste due to the toxicity of the compounds they absorb. The net societal cost or benefit would of course depend on the alternatives, e.g. the existing power generation mix and the risk of open-air burning or landfill fires.

Recycling option

In western countries, plastic consumption has grown at a tremendous rate over the past two or three decades. In the consumer societies of Europe and America, scarce petroleum resources are used for producing an enormous variety of plastics for an even wider variety of products. Many of the applications are for products with a life cycle of less than 1 year and then the vast majority of these plastics are then discarded. In most instances, reclamation of this plastic waste is simply not economically viable. In the industry (the automotive industry for example), there is a growing move towards reuse and reprocessing of plastics for economic as well as environmental reasons with many praiseworthy examples of companies developing technologies and strategies for recycling of plastics. Plastic recycling needs to be carried out in a sustainable manner. However, it is attractive due to the potential environmental and economic benefits it can provide. There is a wide variety of recycled plastic applications, and the market is growing.

However, the demand depends on the price of virgin material as well as the quality of the recycled resin itself. The use of recycled plastics is marginal compared to virgin plastics across all plastic types due to a range of technological and market factors. Recycled plastics are not commonly used in food packaging (one of the biggest single markets for plastics) because of concerns about food safety and hygiene standards, though this is beginning to change. Another constraint on the use of recycled plastics is that plastic processors require large quantities of recycled plastics, manufactured to strictly controlled specifications at a competitive price in comparison to virgin plastic. Such constraints are challenging, in particular, because of the diversity sources and types of plastic waste and the high potential for contamination. Not only is plastic made from a non-renewable resource but it is also generally non-biodegradable (or the biodegradation process is very slow). This means that plastic litter is often the most objectionable kind of litter and will be visible for weeks or months, and waste will sit in landfill sites for years without degrading.

Although there is also a rapid growth in plastic consumption in the developing world, plastic consumption per capita in developing countries is much lower than in industrialised countries. These plastics are, however, often produced from expensive imported raw materials. Not all plastics are recyclable. There are four types of plastics which are commonly recycled:

1. Polyethylene - both high density and low-density polyethylene
2. Polypropylene
3. Polystyrene
4. Polyvinyl chloride

A common problem with recycling plastics is that plastics are made up from parts of more than one kind of polymer or there may be some sort of fibre added to the plastic (a composite) to give added strength. This can make recovery difficult. When thinking about setting up a small-scale recycling enterprise, it is advisable to first carry out a survey to ascertain the types of plastics available for collection, the type of plastics used by manufacturers (who will be willing to buy the reclaimed material) and the economic viability of collection. The method of collection can vary. The following gives some ideas:

- House-to-house collection of plastics and other materials (e.g. paper)
- House-to-house collection of plastics only (but all types of polymer)
- House-to-house collection of certain objects only
- Collection at a central point, e.g. market or church
- Collection from street boys in return for payment
- Regular collection from shops, hotels, factories etc.
- Purchase from scavengers on the municipal dump
- Scavenging or collecting oneself

The method will depend upon the scale of the operation, the capital available for the set-up, transport availability etc. It should be noted that the ideas above assume an expansion in recycling capacity, which will require associated expansion in collection activities, use of secondary plastic materials and, associated with the latter, better methods for separating the different types of plastic to reduce contamination levels. These will allow the delivery of higher quality plastic waste streams to facilitate higher levels of recycling and to ensure quality markets for the secondary raw materials that result. Figure 7 is an example of the life cycle of recycled waste.

Recycled PET Post-consumer PET is often an attractive material for recycling. Unlike other polymers, nowadays, recycled PET can be produced and then directly suitable for contact with food if it is submitted to further decontamination steps such as super clean processes, which are able to decontaminate post-consumer contaminants to concentration levels of virgin PET materials [28]. PET can also be used in applications such as carpet fibres, geotextiles, packaging and fibre fill. PET can be converted into polybutylene terephthalate (PBT) resin, which can be a valuable material for injection and blow-moulding applications. PBT is created through chemical polymerisation which converts the PET molecular chain into 'small repeating units', and through additional catalyst-assisted processes, PBT is produced. The polymerised PBT contains approximately 60% of the original mass of PET and can reduce solid waste by up to 900 kg for each tonne of PBT produced. Making PBT from recycled PET is often less energy consuming than producing the resin directly from oil stock (at 50 to 20 GJ/tonne, respectively) [29].

The main trends of interest in terms of economic impacts are anticipated to be the relative expansion of the recycling sector and questions regarding the economic impact of potentially lower economic growth on plastic waste treatment and secondary raw material use. The main social impacts are anticipated to be associated with health, and in particular, the epidemiological impacts are associated with the treatment of waste in third countries and the social perceptions around the continued use and increasing levels of plastic consumption and waste production.

Re-use option

Products could be designed for re-use by facilitating the dismantling of products and replacement of parts. This could involve standardising parts across manufacturers. For example, LED lamp designs could benefit from standardisation of parts (many of which are plastic) to facilitate disassembly and remanufacturing [30].

Environmental impacts

Pollutants released from burning plastic waste in a burn barrel are transported through the air either short or long distances and are then deposited onto land or into bodies of water. A few of these pollutants such as mercury, PCBs, dioxins and furans persist for long periods of time in the environment and have a tendency to bioaccumulate, which means they build up in predators at the top of the food web. Bioaccumulation of pollutants usually occurs indirectly through contaminated water and food rather than breathing the contaminated air directly. In wildlife, the range of effects associated with these pollutants includes cancer, deformed offspring, reproductive failure, immune diseases and subtle neurobehavioral effects. Humans can be exposed indirectly just like wildlife, especially through consumption of contaminated fish, meat and dairy products.

Environmental pollution can also be harmful to the structural integrity of the polyethylene due to chemical attack of the polymer bonds. Atmospheric pollutants such as nitrogen oxides, sulphur oxides, hydrocarbons

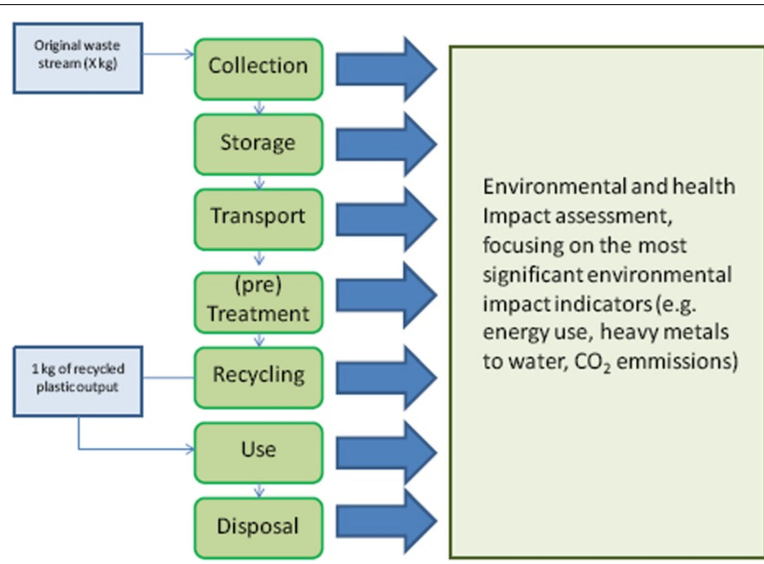

Figure 7 Life cycle approach for analysing the environmental impacts of plastic recycling.

and particulate can enhance the degradation of the polymers especially when combined with applied stress and must also be taken into account [31]. For instance, infrared studies have revealed that polyethylene reacts with NO_2 at elevated temperatures and that chemical attack is observed even at 25°C, probably due to the presence of olefinic bond impurities which react readily with NO_2. Similarly, SO_2 is rather reactive, especially in the presence of UV irradiation, which it readily absorbs and forms triplet excited sulphur dioxide ($^3SO_2{}^*$). This species is capable of abstracting hydrogen from the polymer chains leading to the formation of macroradicals in the polymer structure, which in turn can undergo further depolymerisation.

Overall, the level of environmental impact associated with plastic waste is anticipated to increase over the period until 2015 due to continued growth in plastic waste production (associated with continued rises in plastic waste consumption). More specifically, greenhouse gas emissions associated with the plastic life cycle are anticipated to increase, albeit on a lower trajectory than in the past. Negative consequences in terms of littering and plastic pollution in marine waters would also be anticipated to increase in the absence of any additional curbs [4]. Due to many factors, not the least of which is their ready availability, 96% of all plastic grocery bags as an example are thrown into landfills [32]. However, plastic bags decompose very slowly, if at all. In fact, a bag can last many years, inhibiting the breakdown of biodegradable materials around or in it [32].

Lightweight plastic grocery bags are additionally harmful due to their propensity to be carried away on a breeze and become attached to tree branches, fill roadside ditches or end up in public waterways, rivers or oceans. In one instance, Cape Town, South Africa had more than 3,000 plastic grocery bags that covered each kilometre of the road [32]. In this century, an estimated 46,000 pieces of plastic are floating in every square kilometre of the ocean worldwide [32].

What is most distressing is that over a billion seabirds and mammals die annually from ingestion of plastics [32]. According to UNEP, plastic waste in the ocean causes the deaths of up to one million seabirds, 100,000 marine mammals and countless fish every year [33]. Big animals (e.g. turtles, whales, seals, and sea lions) can be trapped by nets and films and eat the small particles of plastics which may block their digestive systems. Entanglement and ingestion of plastic fragments can even lead to death by drowning, suffocation, strangulation or starvation through reduced feeding efficiency. At least 267 different species are known to have suffered from entanglement or ingestion of marine debris, including seabirds, turtles, seals, sea lions, whales and fish [34]. According to Brown, in Newfoundland, 100,000 marine mammals are killed each year by ingesting plastic [35]. However, the impact of plastic bags does not end with the death of one animal; when a bird or mammal dies in such a manner and subsequently decomposes, the plastic bag will again be released into the environment to be ingested by another animal.

Another environmental issue involves blowing agents used to make foamed plastics. All blowing agents eventually escape to the atmosphere, and among them, there is a particular concern with the CFC stratospheric ozone layer. An international treaty was signed in 1990 on CFCs which was completely implemented in 2000. In some more restricted geographical area, the smoke-forming potential of hydrocarbon blowing agents is also considered an issue.

Because CFCs have been widely employed in foamed plastics, including polystyrene, rigid and flexible polyurethanes and polyolefins, for example, there has been intense activity to develop satisfactory substitutes. Among the most promising of these are the HCFCs, which have only 2% to 10% of the ozone depletion potential of CFCs, and hydrofluorocarbons, which have zero ozone depletion potential. The current consensus is that the HCFCs represent a transitional solution to the problem. There has been promising development work with CO_2 as a blowing agent for polystyrene foam sheet. In this application, CO_2 is considered environmentally benign.

Dioxins

Dioxins are unintentionally but unavoidably produced during the manufacture of materials containing chlorine, including PVC and other chlorinated plastic feedstocks. Burning these plastics can release dioxins. Polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzofurans, hexachlorobenzene and PCBs are unintentional persistent organic pollutants (U-POPs), formed and released from thermal processes involving organic matter and chlorine as a result of incomplete combustion or chemical reactions. These U-POPs are commonly known as dioxins because of their similar structure and health effects [36].

Dioxin is a known human carcinogen and the most synthetic carcinogen ever tested in laboratory animals. A characterization by the National Institute of Standards and Technology of cancer-causing potential evaluated dioxin as over 10,000 times more potent than the next highest chemical (diethanol amine), half a million times more than arsenic and a million or more times greater than all others. Also, open burning of plastic or incineration involves air emissions of sulphur dioxide, nitrogen dioxide, chlorine, dioxin and fine particulates and emissions of greenhouse gases of CO_2 and nitrous oxide (N_2O); ash which remains after incineration needs to be disposed of and can be toxic.

The pyrolysis or combustion of even a simple synthetic polymer produces mix grill of gases. Most of these gases are self-toxic, i.e. interfering with the normal biochemical processes of the body or exclude O_2 from the victim. It must be understood that the type and the concentration of these gases in any fire situation vary from material to material as well as the environment. A few of them together with their physiological effects are shown in Table 4.

Table 4 Physiological effects of some gases involved in combustion

Gas concentration	Effect in all fire conditions
Oxygen (O_2 (%))	
21	Normal concentration in air
2 to 15	Shortness of breath, headache, dizziness, quickened pulse, fatigue on exertion, loss of muscular coordination for skilled movement
10 to 12	Nausea and vomiting, exertion impossible, paralysis of motion
6 to 8	Collapse and unconsciousness, but rapid treatment can prevent death
6	Death in 6 to 8 min
2 to 3	Death in 45 s
Carbon monoxide (CO (ppm))	
400	Nausea after 1 or 2 h, collapse after 2 h and death after 3 to 4 h
1,000	Difficulty in ambulation, death after 2 h
2,000	Death after 45 min
3,000	Death after 30 min
5,000	Rapid collapse, unconsciousness and death within a few minutes
Carbon dioxide (CO_2 (ppm))	
250 to 350	Normal concentration in air
25,000	Ventilation increased by 100%
50,000	Symptoms of poisoning after 30 min, headache, dizziness and sweating
120,000	Immediate unconsciousness, death in a few minutes
Hydrogen cyanide (HCN (ppm))	
45 to 54	Tolerable for 1/2 to 1 h[a]
110 to 135	Fatal after 1/2 to 1 h[a]
181	Fatal after 10 min[a]
280	Immediately fatal[a]
Hydrogen chloride (HCl (ppm))	
5 to 10	Mild irritation of mucus membranes[b]
50 to 100	Barely tolerable[b]
1,000	Danger of lung oedema after a short exposure[b]
1,000 to 2,000	Immediately hazardous to life[b]
Acrolein (CH_2CHCHO (ppm)) (PVC)	
1	Immediately detectable irritation[c]
5.5	Intense irritation[c]
<10	Lethal in short time[c]
24	Unbearable[c]

[a]Effect from nitrogen-containing polymeric materials, e.g. acrylics, wool, urethane foam etc.; [b]effect from chloride-containing polymers e.g. PVC; [c]effect from many polymeric materials, e.g. wool and polypropylene.

Health effects

Because of the persistent and bio-accumulative nature of dioxins and furans, these chemicals exist throughout the environment. Human exposure is mainly through consumption of fatty foods, such as milk. IPEP [36] notes that 90% to 95% of human exposure to dioxins is from food, particularly meat and dairy products. Their health effects depend on a variety of factors, including the level of exposure, duration of exposure and stage of life during exposure. Some of the probable health effects of dioxins and furans include the development of cancer, immune system suppression, reproductive and developmental complications and endocrine disruption [36]. The International Agency for Research on Cancer has identified 2,3,7,8-tetrachlorodibenzodioxin as the most toxic of all dioxin compounds.

High exposure to PDBEs, which accumulate in the human body, has been linked to thyroid hormone disruption, permanent learning and memory impairment, behavioural changes, hearing deficits, delayed puberty onset, impaired infant neurodevelopment, decreased sperm count, fetal malformations and possibly cancer. These activities lead to severe pollution of soils by POPs and heavy metals in the countries concerned, which may also affect the surrounding environment such as rice fields and rivers via atmospheric movement and deposition [37-39].

Toxic emissions produced during the extraction of materials for the production of plastic grocery bags, their manufacturing and their transportation contribute to acid rain, smog and numerous other harmful effects associated with the use of petroleum, coal and natural gas, such as health conditions of coal miners and environmental impacts associated with natural gas and petroleum retrieval [40]. Heavy metals may be released into the environment from metal smelting and refining industries, scrap metal, plastic and rubber industries, various consumer products and from burning of waste containing these elements. On release to the air, the elements travel for large distances and are deposited onto the soil, vegetation and water depending on their density. Once deposited, these metals are not degraded and persist in the environment for many years poisoning humans through inhalation, ingestion and skin absorption. Acute exposure leads to nausea, anorexia, vomiting, gastrointestinal abnormalities and dermatitis.

Impacts on human health are perhaps the most serious of the effects associated with plastic grocery bags, ranging from health problems associated with emissions to death. In the year 2005, the city of Mumbai, India experienced massive monsoon flooding, resulting in at least 1,000 deaths, with additional people suffering injuries [32]. City officials blamed the destructive floods on plastic bags which clogged gutters and drains, preventing the rainwater from leaving the city through underground systems. Similar flooding happened in 1988 and 1998 in Bangladesh, which led to the banning of plastic bags in 2002 [40]. By clogging sewer pipes, plastic grocery bags also create stagnant water; stagnant water produces the ideal habitat for mosquitoes and other parasites which have the potential to spread a large number of diseases, such as encephalitis and dengue fever, but most notably malaria.

Conclusion

Overall, the level of environmental impact associated with plastic waste is anticipated to increase over the period until 2015 due to continued growth in plastic waste production (associated with continued rises in plastic waste consumption). Over this period, the rise in environmental impacts is anticipated to be comparatively slower than in the past as much of this increase in production is dealt with by recycling and energy recovery expansion. However, disposal levels are only anticipated to remain static or drop in a limited way, maintaining the overall picture of the environmental footprint.

In terms of environmental impacts, the following trends are considered to be of most significance:

Rising use of plastics. The primary plastic feedstock will remain fossil fuels, despite the anticipated rapid rise in the production of bioplastics. This implies continued reliance on carbon-intensive production methods, with relatively high levels of embodied carbon and energy in the products. While traditional refineries might be driven to be more efficient over the projection period due to changes in rules surrounding for example the Fuel Quality Directive (which requires life cycle reductions in transport fuels), such efficiencies are likely to be offset by the increasing the level of production and demand.

Rising levels of plastic waste generation. This implies the need for an expanded waste management system simply to remain capable of dealing with the anticipated increase waste production.

Increasing levels of recycling. Recycling rates are anticipated to increase over the outlook period, and end markets are developing. However, the proportion of disposal is expected to remain significant. This implies a significant expansion in the overall Mt amount of waste recycled, i.e. a similar proportion of a greater quantity of waste will be recycled. This in turn implies three key evolutions in the plastic waste recycling business. Firstly, an expansion in the collection of plastic waste, secondly an expansion in processing capacity and thirdly an expansion in the use of secondary plastic materials. Legislation has already been proposed or passed in the USA of the federal, state and local levels restricting or banning the use of some plastics in applications where there is perceived problem. This trend is sure to continue. The technical community has not lagged in developing responses to these challenges expect in the developing nations. The principal routes being followed are degradation, incineration and recycling. Another important approach which involves both consumers and manufacturers is source reduction. The activity in this area is focused largely on warning consumers from the throwaway habits that have developed over recent decades, particularly with packaging waste stream. These efforts are evolving so rapidly that it is difficult to predict how each one will impact the problem over the longer term.

European approaches. In Europe, the principal measures implemented to deal with plastics are the producer responsibility mechanisms - these do not target plastic bags specifically but aim to encourage the recycling and recovery of plastics. Different member states use different approaches, but in most countries, the packaging industry makes payments to designated bodies that are responsible for arranging the collection, separation, recycling and recovery of a predetermined amount of packaging. A notable feature is that these fees paid by the packaging industry are not necessarily passed on to consumers in a transparent manner. Therefore, the collection of taxes and public awareness can reduce indiscriminate use of plastic bags.

Recommendation

The redesign of plastic products, both at the scale of the individual polymer and in terms of the product's structure, could help alleviate some of the problems associated with plastic waste. With thoughtful development, redesign could have an impact at all levels of the hierarchy established by the European Waste Framework Directive: prevention, re-use, recycle, recovery and disposal [1]. Infrastructure for the safe disposal and recycling of hazardous materials and municipal solid waste should be developed. Approximately 50% of all waste is organic and can therefore be composted. Another large segment of the remainder can be recycled, leaving only a small portion to be disposed. The remaining portion can then be disposed through sanitary landfills, sewage treatment plants and other technologies.

In general, disposal via modern, sanitary landfills is not very effective with biodegradable plastic materials because the limited availability of oxygen and moisture retards most biodegradation processes. As yet, bioplastics cannot replace all types of plastic, particularly certain types of food packaging that require gas permeability. Biodegradable plastics are most effectively treated in compositing systems where aerobic processes predominate. Biodegradation may also influence the types and concentrations of soil microflora in disposal areas. Enrichment of soil with certain microflora could have unanticipated risks, such as an outbreak of a new microbial disease [41].

At present, there is a growing consensus that the concept of degradable plastics has been oversold as a solution to the waste disposal problem, primarily because a large portion of degradable plastics will end up in landfills where breakdown tends to be very slow. The most promising applications of degradable plastics probably are for more limited problems, such as litter, where sunlight, air, moisture and microorganism are generally available to accelerate polymer breakdown [42].

High-temperature incineration of waste plastics has at least two potential advantages. First, increasingly scarce landfill space is conserved because the volume reduction from feed to ash with a well-operated incinerator is in 90% range or higher; second, the high generation of stream, electricity or both. Incinerators have drawbacks, however. They can emit corrosives such as HCl and traces of highly toxic dioxins and furans if chlorine-containing materials such as PVC or bleached paper are in the feed stream. These emissions could pose hazards, especially to people living close to the incinerator; compounds of toxic heavy metals such as lead, chromium and cadmium are present in some plastic products as stabilizers and pigments, and these elements tend to end up concentrated in the ash. If the compounds of these metals in the ash are leachable, soil and groundwater contamination is possible. Advocates of incineration are convinced; however, that current technology will prevent stack discharge of most toxic and corrosive combustion products. They further claim that only a very small fraction of the heavy metals in the ash is leachable, and this should pose no problem if proper disposal procedures are followed. Moreover, heavy metal-based pigments and stabilizers gradually are being phased out of many applications in favour of organic substitutes. Current trends suggest increasing reliance on the incineration approach despite the claimed drawbacks.

Recycling has obvious environmental advantages and is not opposed by any strong voting blocs or economic interests. Recycling of plastics should be carried in a manner to minimize pollution during the process and enhance efficiency and conserve the energy. Much of the future success of plastic waste recycling will depend on the development of effective collection and separation systems, which, along with appropriate incentives, will ensure the broad and willing participation of industry and consumers. In this case, involving pre-consumer waste or scrap, where the material identifies and uniformity can be reasonably maintained, it is often possible to recycle the plastic back to the same product. In other instances, including those where carefully targeted post-consumer collection methods are possible. A secondary product can be made of a single recycled plastic, for example, PET beverage bottle scrap can be recycled to fabricate bottles for non-beverage applications [7].

Clearer certification and labelling schemes are needed to ensure that the public understands what is meant by biodegradable, compostable or eco-friendly. DG Environment's report on Plastic waste in the environment [11] proposed that any targets on bioplastics should be combined with a labelling system and initiatives to increase public awareness and education. Labelling of plastic parts with the type of polymer they contain could also help in sorting for recycling and re-use. Along with the plastic waste issue, significant new developments can be anticipated as the industry continues its aggressive search for solutions to these important environmental problems. The redesign of plastics and bioplastics has the potential to reduce the use of fossil fuels, decrease CO_2 emissions and decrease plastic waste. There is a need to increase public awareness through litter education as an important supporting element and other initiatives that may be undertaken to reduce plastic waste and their impacts.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
This work was finished through the collaboration of all authors. OIN conceived the study and drafted the manuscript together with AOI. CHC and LA carried out the computations in the manuscript. CHC, AOI and LA participated in the coordination and in revising the manuscript. All authors read and approved the final manuscript.

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Author details
[1]Reliable Research Laboratory Service, D30 Orji Kalu Housing Estate, Umuahia, Abia State, Nigeria. [2]Department of Chemistry, Abia State Polytechnic, Aba, Abia State, Nigeria. [3]Department of Pure and Industrial Chemistry, Nnamdi Azikiwe University Awka, P.M.B. 5052, Awka, Anambra State, Nigeria. [4]Yagai Academy, P.O. Box 1180, Jalingo, Taraba State, Nigeria.

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