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Plastics, microplastics and other polymer materials – A threat to the environment

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Abstract: Plastics are synthesized polymer compounds mostly made from petrochemical raw materials and characterised by high molecular mass and plasticity. They have many applications and find widespread use due to their cheapness and versatility. In this study, global plastics production and the accumulation of plastic waste was documented. This waste has huge adverse impacts on oceans and other ecosystems which has led to increasing scientific and public concern. It is also worthy to mention that plastic and polymer waste are not useless as they can be recycled into new products. This article with a systematic review of the literature aims to present the threats and the weight of evidence for plastics, microplastics pollution causing environmental harm, along with a review of the life cycle assessment (LCA) studies which have been carried out on bioplastics and petroleum-based plastics to help compare/contrast and shed more light on the phases contributing the most environmental burdens. The LCA studies found the bioplastics to pose more environmental burdens in the production phase due to the use of chemicals, the weight of the bioplastics, and also the electricity usage for cleaning, but are more sustainable in the long-term. To curb the adverse and detrimental effects and to make plastics more environmental friendly, producers must adopt the green chemistry techniques to find alternatives to additives responsible for health hazards. Also, a comprehensive plan should be adopted for zero tolerance against plastics/polymer waste and people's participation is a must to achieve the full success.

Keywords: Plastics, microplastics, Hazardous substance, Environment and Life cycle assessment.

1. Introduction

It is not only our feet that leave footprints wherever we go – our excessive reliance on plastic materials is creating an invisible yet damaging "plastic footprint" in the environment. This increasing usage is generating considerable amounts of plastic waste, ultimately endangering our environment and life within it. Considered a major threat to both wildlife and human wellbeing, plastic pollution is now widespread in the oceans [1], causing an unprecedented environmental crisis with an estimated 10 million tonnes of litter leaking into the marine environment every year [2]. Its worldwide distribution is so vast that many scientists use it as a key geological indicator of the anthropocene [3]. Plastic materials can be used as stratigraphic markers in the archaeological field by considering them as recent and precise indicators of earth deposits. Some authors identify the period from 1945 onwards as a moment of a significant increase in plastics deposition, to the point that they have used this stratigraphic marker as an excellent indicator [4].

Plastics, microplastics and other polymer materials offer many benefits to society but unfortunately also have many drawbacks. The word 'plastic' refers to the capability of being shaped or moulded, and the noun 'plastic' is a colloquial term that denotes a group of synthetic, organic, polymeric, high-molecular-weight materials. According to the International Organization for Standardization (ISO), plastic is a material that contains a high-molecular weight polymer as an essential ingredient, which at some stage in its processing into finished products can be shaped by flow [5]. The International Union of Pure and Applied Chemistry (IUPAC) defines plastics as a generic term used in the case of "polymeric materials that may contain other substances to improve performance and/or reduce costs" [6].

1.1 Sources of plastic material

Fossil- or petrochemical-based plastics utilize fossil feedstock like petroleum and natural gas. About 7% of all petroleum is converted into plastics. Examples of some of the most commonly used fossil-based plastics are polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET) and polystyrene (PS). Bio-Based Plastics/Bioplastics are another type of plastics; these are defined as "plastics" in which 100% of the carbon is derived from agriculture, such as corn starch, rice straw, soybean protein and cellulose, and forestry resources which makes them renewable. The main origin of plastic wastes are industrial, commercial and municipal.

1.2 Industrial waste

A major proportion of this waste comes in the form of wrapping of polyethylene film that has been used as a protection covering for goods delivered to the factories and industries. Waste plastics also come from electronics, construction and demolition companies as they provide waste tiles, PVC pipes and fittings, etc. Considerable amount of this waste remains uncollected or dumped at municipal dumps.

1.3 Commercial waste

It contains a considerable amount of packaging material made of PE which is obtained from hotels and restaurants, supermarkets, workshops, craftsmen, shops, and wholesalers.

1.4 Municipal waste

Due to the littering habits of people, a large proportion of plastic waste is found within Municipal Solid Waste. However, this waste plastic could have been collected from residential areas, streets, parks and waste dumps before they enter the municipal solid waste. Contamination with other hazardous waste makes it difficult for this plastic waste to be separated and cleaned easily. Many a times waste starts degrading under the sunlight before it is being collected. But it does not mean that the plastic waste becomes unable to be reprocessed. The above-mentioned problem can be controlled to some extent by increasing the awareness among people about the correct disposal techniques of this plastic waste.

2. Categories of Plastics

2.1 Thermoplastics

These are polymers that do not change their chemical composition when heated and can, therefore, undergo moulding multiple times. These include the common plastics polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC) and polytetrafluoroethylene (PTFE) with molecular weights in the range of 20,000 to 500,000 AMU (atomic mass unit).

2.2 Thermoset Plastics

These are polymers that remain solid and cannot be melted nor modified. The chemical change here is irreversible, and hence these plastics are not recyclable because they have a highly cross-linked structure, whereas thermoplastics are linear. Examples include phenol-formaldehyde, polyurethanes, etc.

2.3 Fibre plastics and non-fibre plastics

At this junction, it is worthy to state that fibre plastics are a category of composite plastics that specifically use fibre materials which are usually glass, carbon, aramid or basalt to mechanically enhance the strength and elasticity of plastics, e.g., polyamide, polyethylene terephthalate, polyester, polyvinyl chloride (PVC) vinyon, polyolefins, polyurethane fiber, etc. The original plastic material without fibre reinforcement is known as the matrix or binding agent or non-fibre plastics, e.g., epoxy, vinyl ester, polyester thermosetting plastic, phenol formaldehyde resins, etc.

3. Microplastics

The term "microplastic" refers to plastic particles that are less than 5 mm in size. The term ‘microplastic’ was further refined by Cole and colleagues [7], who described ‘primary microplastics’ and ‘secondary microplastics’, dividing the particles according to origin, i.e., particles that were manufactured in a microscopic size range (including pellets or beads) versus the degradation products of large debris (produced via physical, biological or chemical fragmentation) [7]. Microplastics can contain two types of chemicals: (i) additives and polymeric raw materials (e.g., monomers or oligomers) originating from the plastics, and (ii) chemicals absorbed from the surrounding ambience. Additives are chemicals intentionally added during plastic production to give plastic qualities like colour and transparency and to enhance the performance of plastic products to improve both the resistance to degradation by ozone, temperature, light radiation, mould, bacteria and humidity, and mechanical, thermal and electrical resistance [8]. They include inert or reinforcing fillers, plasticizers, antioxidants, UV stabilizers, lubricants, dyes and flame-retardants [8].

3.1 Primary microplastics

Primary microplastics are the by-products of particulate emissions released from industrial production, the release of plastics dust from plastics products. They are widely used in cosmetics formulations [7, 9] such as makeup, sunscreen, nail polish, hair colouring, eye shadow, shower gels, and personal care products containing scrubs and abrasives (such as toothpastes, facial cleansers and air-blasting) [10-13], also including fibres released from synthetic textile and clothing manufacture [14]. Primary microplastics are hardly visible to the naked eye and likely to flow straight from the bathroom drain into drainage systems and can easily escape capture by wastewater treatment plants (preliminary sewage treatment screens [15].

3.2 Secondary microplastics

Secondary microplastics are larger plastic particulate materials mostly derived from fragmentation and degradation of large plastic debris into tiny fragments when suffering high solar UV-radiation and mechanical abrasion by a comprehensive consequence of physical (mechanical), chemical (photolytic) and biological processes, which can be directly transported into the marine environments from shorelines, rivers, and sewage pipes. These microplastics eventually end up in water bodies travelling all the way from rivers to seas or oceans.

IUPAC also defines polymers as substances composed of monomers forming macromolecules, very large molecules with molecular weights ranging from a few thousand to as high as hundreds of gram/mole. They are synthetic, made mostly of petrochemicals and exhibit high molecular mass, plasticity and some additive chemicals are added to increase the performance and efficiency of the products. Being easily manufactured, low cost, resistant to water, chemicals, temperature to a certain level and light resistance, plastics are used in a wide range of products. Production of plastics has increased exponentially; because of their widespread usage, plastics constitute a large material group with global annual production that has doubled in 15 years, reaching 350 million tonnes in 2017 [16]. For many applications, plastics can even offer lower carbon footprint alternatives compared to other materials [2]. The global production of plastics reached the 360 million tonnes mark in 2018 [17]. Consequently, this widespread use of plastics, as well as the resistance to degradation by many plastics and all polymer materials, ultimately leads to their accumulation in oceans, deeps seas, landfills and other terrestrial niches therefore adversely affecting wildlife and also human health. In the oceans, plastic product debris and sediments are ingested by and/or trapped inside marine organisms and fragmented into smaller pieces and microplastics [18]. Although the presence of plastics pollution was mentioned for the first time in 1972, there was less attention on the harmful effects of it on the environment. The plastic polymer is considered to be biochemically inert due to its large molecular size and is therefore not regarded as hazardous for human health or the environment [19]. However, polymerisation reactions are rarely complete and, therefore, also unreacted residual monomers can be found in polymeric materials, several of which are hazardous for human health and the environment and/or affect polymer properties [20]. These residual monomers contents may vary a lot depending on the type of polymer, polymerisation technique and techniques for reducing residual monomer content [19]. A search for research articles that uses the terms "Plastic / microplastic / polymer and effect" showed that the number of published studies now number in thousands, and new studies are published daily. Early publications focused on methods for finding and identifying plastics and microplastics in different matrices, but more recently, the number of effect studies that measure the consequences of exposure have increased. As the research field has grown, the need for a common vocabulary has also grown. The objective of this study is to identify and compile the environmental threats, damages and health effects of the plastics, microplastics and polymers.

With the aim of detecting the potential threats plastics pose to humans and to the environment, plastics and polymers that are in circulation in the economy were identified; some of these polymer materials have global production exceeding 10,000 tonnes/year and the environmental and health hazards of chemicals used in these plastic polymer are as shown in Table 1. The hazard classifications were almost exclusively taken from the Annex VI

Table 1. Ranking of global annual production versus hazard rank.

Polymer type	Global production (million tonnes/year)	Hazard rank for polymer
Polypropylene (PP)	45	37 (a) [21]
Polyvinyl chloride (PVC)	37	5, 6, 11 (a) [21-23]
Polyethylene terephthalate (PET)	33	36*, 36* (a) [22-23]
High-density polyethylene (HDPE)	32	36 (a) [21]
Low-density (LDPE) and linear-low-density (LLDPE) polyethylene	39	36, 36, 36, 36**, 36** (a) [21-25]
Polystyrene (PS) (general purpose)	13	35 (a) [23]

* Contains≥10 wt.% non-classified substance.

** Contains≥10 wt.% non-classified substance, for which ranking may be underestimated.

[a] The sum hazard scores derived based on harmonized CLP classifications

Source: [21]

in the EU classification, labelling and packaging (CLP) regulation which is based on the UN Globally Harmonized System (GHS) (European Parliament and Council, 2008). Classifications including the 1st Adaptation to Technical Progress have been used (European Commission, 2009). These classifications reflect the intrinsic hazardous properties of a substance or mixture (with some exceptions, e.g., organic peroxides), and do not take exposure into account. The sum hazard scores derived based on harmonized CLP classifications for environmental or human health hazards were used to sort the lists of chemicals.

According to Lithner [21], the procedure for calculating the hazard score (sum) for the polymer is based on the classifications of the monomer(s) that the polymer is made of. Since a substance often has multiple classifications, e.g., is classified both as mutagenic category 2 and acute toxic category 3, the hazard grades (1-10,000) for each classification were summarised to create a hazard score for the substance. In this way, a substance that is both mutagenic and acutely toxic gets a higher hazard score (i.e., 1000+100=1100), than a substance that is only mutagenic (i.e., 1000). If more than one monomer is needed to produce the polymer, figures on each monomer's average weight fraction in the polymer are multiplied with the hazard score for each monomer. The weight fraction of a monomer is the mass of one monomer used, divided by the total mass of all monomers used to produce the polymer. Finally, the sum of the hazard scores for all monomers included in the polymer type are calculated, and a hazard ranking of the different plastic polymers is made. The ranking means that the polymer is made from hazardous substances (the greatest part being transformed during polymerisation). Release of these hazardous substances or degradation products may occur during production, use and end of life phase, and thereby there is a hazard associated with the ranked polymer type.

This review aims to give a general and thorough description of the plastic pollution issue, with a focus on the quantities of plastic flowing into natural habitats, e.g., oceans, landfills, and the threats they pose to both inhabitants (living organisms) and the habitat itself (environment). Secondly, it will discuss current knowledge gaps and challenges underlying plastic, polymer waste management. Lastly, the conclusion will stress on the need to act now and, remedies to plastic waste pollution.

4. Methods

A systematic review was conducted of papers published up to the early of 2020, which were identified by the search engines, Google and Science hub. The search terms “plastics, microplastic” and “environment” were used and 150 peer-reviewed research articles identified. Additionally, streamlined searching was conducted to source for recent research work on the topic within the last two decades which helped to scale down the initial number of research articles identified. A further refinement of the search was done to include only those plastic and polymer materials which have a global production exceeding 10,000 tonnes/year. With such high production rate, these materials represent the great varieties of plastic and polymer types/families in circulation.

Further streamlined searching was conducted when cited literature yielded relevant peer-reviewed articles and applicablereports published by government agencies that were missed by the search engine. This review was also based on a literature review of the life cycle assessment (LCA) approach, and measurements of the harmfulness of plastics from cradle to grave, i.e., from manufacturing phase, use phase to disposal. With the aim of carrying out these methods, identifying, analysing, and quantifying plastics in the environment is imperative, and these are described in the following sections.

4.1 Methods of microplastic analysis

Majority of the monitoring studies employed solely visual identification methods (i.e., naked eye or dissecting microscopes), with a good number of those studies published in 2016 and 2017. Visual identification only permits identification down to 500 mm [26]. Although visual confirmation techniques are inexpensive in terms of time and cost, misidentification of natural particles such as coal ash or coal fly [27] and quartz or calcium carbonate [28] is possible. A multitude of authors have therefore concluded that the visual identification error rate for identifying natural particles as microplastics is unacceptably high, ranging from 33 to 70% [28-32]. Studies not using appropriate analytical confirmation techniques are likely overestimating environmental concentrations of relevant size fractions [33]. This is especially true for fibres, where visual analysis alone cannot differentiate between cotton or other natural fibrous materials and those of synthetic origin [31]. Advanced analytical confirmation methods (some form of Raman scattering or [m]-Fourier transform infrared spectroscopy [FTIR]), which allow particles to be characterized in terms of their chemical makeup and hence to distinguish from natural particles and identify polymer type, a substantial number of the studies were used. The use of various Raman and FTIR spectroscopy techniques can also lower the particle size detection limit to 1 and 10 mm, respectively [26, 34]; however, confidence in detection is decreased at <131 mm [35]. In 64% of the studies involving confirmation methods, confirmation was performed on <50% of particles sampled. A further 13% used a chemical identification technique to identify >50% of particles sampled, whereas 23% confirmed 100% of suspected microplastics. Confirmation of >50% of suspect microplastics was not limited to studies with low total particle counts (e.g., <500) despite the additional cost and effort for sample analysis. Similar to the studies using visual techniques, measured environmental concentration from any study where <50% of suspect microplastics have been confirmed, should be treated with caution. Problems can also be encountered in microplastic detection when using appropriate analytical confirmation methods because of difficulties pertaining to particle brittleness (breaking apart in the sample preparation stage), biofouling of particles (interfering with the signal), or the particle size being too small to be adequately analysed [36-37].

4.2 Accumulation of plastic waste in the natural environment

The dispersal and ill effects of large plastics have been the focus of research to date. The five heaviest plastic polluters geographically are; China, Indonesia, the Philippines, Vietnam and Sri Lanka, which between them contribute 56% of the global ocean plastic waste. This is mainly as a result of large populations living within 50 km of the coast, and relatively poor waste management facilities [38]. It has been estimated that more than 150 Mt of plastics have entered the world's oceans [39], which amounts to around 2.6% of the total plastics ever produced from primary plastics (5.8 billion tonnes) [40]. According to Geyer et al. [40], all the plastics produced from 1950 to 2015 were disposed by one of the following methods; Discarded (55%), Incinerated (25%) and Recycled (20%). Substantial quantities of plastic have accumulated in the natural environment and in landfills. Around 10 per cent by weight of the municipal waste stream is plastic [18]. In agriculture, aside from industrial sludge, plastics mulch is an important source of microplastics [41]. Plastics mulch has been widely adopted to increase crop yields by reducing evaporation and increasing temperature. These products can also produce a high amount of microplastics when the plastics cannot be recycled efficiently [41]. Greenhouse materials, soil conditioners, manure, irrigation, garbage, atmospheric deposition, and debris from the friction of plastics products are other sources of microplastics, which primarily accumulate in agricultural soil [42], resulting in a mixture. These mixtures can result in 0.08 - 6.3 kg ha^{-1} per year of visible plastics in arable soil, with annual microplastics input reaching 0.6 - 4.3×10^5 and 0.4 -3.0×10^5 tonnes in European and North American agricultural soils, respectively, higher than that in the surface water of the ocean [43-44]. Discarded plastics also contaminate a wide range of natural terrestrial, freshwater and marine habitats. There is also some data on littering in the urban environment, for example compiled by EnCams in the UK (http://www.encams.org/home). Plastics have become a menacing pollutant in the environment because of the very high rate of production and also their improper disposal via indiscriminate dumping (unsanitary landfilling). When plastics get dumped at an unsanitary waste site, they get dispersed, blown and washed away into various channels. According to the U.S. Environmental Protection Agency, Americans recycled only 9.1% of their plastics in 2015. Waste-to-energy facilities combusted 15.5%. But the most likely destination for the plastics discarded in the U.S. is the landfill; it is the final resting place for three-quarters of it. The incidental presence of microplastics in aquatic habitats (surface water, the water column or sediments) facilitates the intake of microplastics by organisms. The spatial overlap between the microplastics distribution and the physical presence of biota is the major contributing factor for microplastics influx into food webs [45]. Microplastics enter into food webs via a prey's ingestion (trophic transfer), entanglement, respiratory intake (inhalation) or adherence of microplastics [46]. There are accounts of inadvertent contamination of soils with small plastic fragments as a consequence of spreading sewage sludge [47], and of fragments of plastic and glass contaminating compost prepared from municipal solid waste. Also, plastics are carried into streams, rivers and ultimately the sea with rainwater and flood events [48]. A summary of worldwide microplastics contamination is shown in Table 2.

5. Decomposition of plastics

Plastics tend to be exceptionally stable and durable, which is why they have gained popularity and a wide application in society; however, these same qualities render them persistent in the environment, and resistant to decomposition when discarded [56]. In the environment, plastics may undergo degradation by four principal mechanisms : photodegradation, thermo-oxidative degradation, hydrolysis and biodegradation by microbes [57]. Photodegradation by sunlight is generally the initial event, which primes the material for subsequent thermo- oxidative degradation [57-58]. As a result of these processes, the plastic becomes brittle and steadily dissociates into increasingly smaller fragments: finally, down to the molecular level, such that they can be metabolised by microbes [57,59], which either incorporate the carbon atoms from the polymer chains into biomolecules, or oxidise them to CO_2. The overall process of decomposition is very

Table 2. A summary of microplastic contamination in various estuarine water/sediments reported worldwide.

SI. no.	Location	Microplastics range/ave.	Method	Particle size (mm)	Sample type	Polymer types	Reference
1	Vembanad Lake, India	252.8 particles m^{-2} (average)	Van Veen grab (25 cm^2) Sieve: 5 mm	<5 mm	Sediment	HDPE, LDPE, PP, PS	Sruthy and Ramasamy [49]
2	Lake Huron, Canada	3209 plastic pieces 85 m^{-2} (total)	Grid: 2 m x 2 m Sample collector: Stainless steel trowel Depth: N/A	5 ± 0.5 mm	Sediment	PE, PP and Polyethylene terephthalate (PET)	Zbyszewski and Corcoran [50]
3	Pearl River Estuary, Hong Kong	5595 ± 27,417 items m^{-2} (average)	Quadrat: 0.25 m^2; Depth: 4 cm; Sieve: 0.315 & 5 mm	0.315–5 mm	Sediment	Expanded polystyrene (EPS), fragments and pellets	Fok and Cheung [51]
4	Five urban estuaries of KwaZulu-Natal, South Africa.	745.4 ± 129.7 particles per 500 ml	Beach and Estuary sample; Corer: 50 mm diameter Depth: 10 cm. Surface water sample; 300 µm mesh of diameter 30 cm.	20–5000 µm	Sediment & Water	Not identified	Naidoo [52]
5	Gulf of Mexico estuary	5–117 items m^{-2}	Quadrat: 0.25 m^2; Depth: 6 cm	2.5 ± 0.48 mm	Sediment	PP, PE, PS, polyester and aliphatic polyamide	Wessel [53]
6	Lake Garda, Italy	1108 ± 983 microplastic particles m^{-2} (average)	N/A	0.781 – 3.016 mm	Sediment	LDPE, PS, PE, PP, polyamide and PVC	Imhof [54]

PE — Polyethylene, PP — Polypropylene, PS — Polystyrene, LDPE — Low-density polyethylene, HDPE — High-density polyethene, PET — Polyethylene terephthalate, Source: Laskar & Kumar [55] slow, however; an estimated 50 years for a foam plastic cup, 400 years for a plastic drinking cup, 450 years for a disposable nappy, and 600 years for a fishing line [60]. The persistence of plastics in the oceans is enhanced by the limited availability of oxygen, and by the cooling effect of the water; also, rates of hydrolysis are too low to provide an effective route for the decomposition of most polymer components of plastic debris [57]. To consign plastic waste to landfills involves rendering unavailable land that might otherwise be more productively used, such as for agriculture [61], and in combination with the fact that most plastics degrade but slowly, especially in landfill environments, the land is necessarily thus occupied for a longer term. When such degradation does occur, the plastic may discharge a host of secondary pollutants, such as benzene, xylenes, and trimethylbenzene isomers, either as gaseous components or via leachate [62], along with various other substances, including bisphenol A (BPA) [62-64], with the risk of groundwater contamination. In addition to its acknowledged role as an endocrine disruptor, BPA has been demonstrated to promote the production of hydrogen sulphide by sulphate reducing bacteria that are present in soil [64].

6. Plastic waste handling

Before 1980, plastic recycling and incineration were negligible. Since then, only non-fibre plastics have been subject to significant recycling efforts. The following results apply to non-fibre plastic only: Global recycling and incineration rates have slowly increased to account for 18 and 24%, respectively, of non-fibre plastic waste generated in 2014. On the basis of limited available data, the highest recycling rates in 2014 were in Europe (30%) and China (25%), whereas in the United States, plastic recycling has remained steady at 9% since 2012 [65-69]. In Europe and China, incineration rates have increased over time to reach 40 and 30%, respectively, in 2014 [66, 68]. However, in the United States, non-fibre plastics incineration peaked at 21% in 1995 before decreasing to 16% in 2014 as recycling rates increased, with discard rates remaining constant at 75% during that time period [67]. Waste management information for 52 other countries suggests that in 2014, the rest of the world had recycling and incineration rates similar to those of the United States [70]. To date, end-of-life textiles (fibre products) do not experience significant recycling and are thus incinerated or discarded together with other solid waste.

7. Threats, risks, and environmental burdens

A recent analysis by the State University of New York on plastics water bottles made a shocking report as it found twice as many microplastics in bottled water as compared to tap water on average. The samples were collected from 19 locations from different countries including India, Brazil, China, Kenya, Lebanon, Mexico, Thailand, USA and Indonesia. It was found that 93 percent of the samples collected contained microplastics particulates ranging from 1 to 10,000 in a single water bottle [55]. The food safety authorities of the entire advanced developed nations do not have any residue limit for microplastic as of now. The World Health Organization started to review the potential risk of plastic pollutants across the world to bring down the use of plastics. The environmental fate of a plastic product includes the processes by which both the plastic material and the chemicals released during the preproduction and production phases are moved and transformed. Hazardous substances may be emitted during all phases of the life cycle of a plastic product and may consist of nonpolymeric substances (e.g., raw materials, monomers, catalysts, solvents, by-products from production, and additives), as well as degradation products of the nonpolymeric substances and from the polymer itself. It should be emphasised that a polymer ranked as hazardous is not the same as the polymer being hazardous. The ranking means that the polymer is made from hazardous substances (the greatest part being transformed during polymerisation). Release of these hazardous substances or degradation products may occur during production, use and end of life phase, and thereby there is a hazard associated with the ranked polymer type. These plastics are made from depletable resources (fossil fuels) as mentioned earlier on and are not sustainable as they pose more environmental burdens that arise from continued production. Some of the raw material substances, intermediate substances or by-products in the synthesis of monomers are sometimes more toxic than the monomer itself. Besides the residual monomers, other polymerisation impurities can also be present in a plastic product. These include oligomers, low molecular weight polymer fragments, catalyst remnants, and polymerisation solvents, as well as a wide range of plastic additives including processing aids and end-product additives [71]. All these non-polymeric components are usually of low molecular weight and may, therefore, migrate from the plastic product [71] to air, water or other contact media (e.g., food). Two very hazardous raw material substances are benzene and butadiene, which are both classified as carcinogenic (category 1A) and mutagenic (category1B). During production, the size and type of emissions to water and air varies between different polymers and between different production sites, according to EU risk assessment reports (European Commission Joint Research Centre, e.g., 2009, 2010, 2017). During use and end of life, many factors determine the type and size of emissions from plastic polymers and products.

The major commercial polymers, polyethylene and polypropylene, are extremely resistant to biodegradation [72], i.e., degradation by micro-organisms. According to [73], only 0.1% of the carbon in a polyethylene polymer will be transformed into CO_2 per year by biodegradation, even under optimal laboratory exposure conditions. Most other plastic polymer types are resistant to biodegradation (non-biodegradable) (e.g. PVC, polystyrene, polyacrylonitrile, and polymethyl methacrylate; [74]). The few biodegradable polymers only have a minor share in the plastics market today, but this is growing. However, not all of them are completely biodegradable in the natural environment [75]. Non-biodegradable polymers can, however, be degraded by heat, oxidation, hydrolysis, and mechanical shear, but these means of degradation also produce pollutants such as carbon monoxide, sulphur dioxide, nitrogen oxide and ozone [76]. During thermal degradation, nitrogen-containing plastics (e.g. nylons and polyacrylonitrile) release hydrogen cyanide; chlorine-containing materials (e.g. PVC) release hydrogen chloride & dioxins; fluorine-containing polymers (e.g., polyvinylidene fluoride and PTFE) release hydrogen fluoride; and some polymers (mentioned above) are depolymerised into their monomers [76-78]. Carbon dioxide and monoxide are produced from any hydrocarbon material in fire [60]. Of these, hydrogen cyanide and hydrogen fluoride are fatal if inhaled and carbon monoxide may damage the unborn child as reported by the Stockholm Convention on Persistent Organic Pollutants (POPs) [21].

Microplastics are very much harmful to marine life as the pollutant travels all the way from rivers to seas or oceans. They are so light that they can be easily tossed around and for many water species, they look like their food and are thus consumed which then accumulates in their body. The sea fish sometimes consume such plastic waste and unknowingly human beings consume such seafood and the microplastics which contain toxins enters in the bloodstream and affects the health directly, and hence such contaminant poses a potential threat to the environment and mankind (A report on “Microplastic pollution in oceans, a menace which is far worse than feared, says, scientists”, Environment | The Guardian, 12 March 2018). Consumption of microplastics for a long period of time may change our human chromosomes and may lead to infertility, obesity, and even cause cancer [79]. A statement by the EU Commission, 2017 informs that "Microplastics are of particular concern due to the negative effects on marine and freshwater environments, aquatic life, biodiversity, and possibly to human health since their small size facilitates uptake and bioaccumulation by organisms or toxic effects from the complex mixture of chemicals these particles consist of." [80].

8. Comparative Life Cycle Assessment of petroleum-based plastics and bioplastics

Life cycle assessment (LCA) is a beneficial tool for assessing the environmental impacts associated with a material, product, process or service over the entire life cycle that is cradle to gate or cradle to grave [81]. LCA is a tool to evaluate the environmental aspects of the products or services over their entire life starting from the raw materials from which they are made until the final disposal. A full LCA would serve as an appropriate tool for environmental impact evaluation. The studies reviewed focused on the evaluation and analysis the environmental impacts from cradle to grave of bioplastics (agro material-based) and petroleum-based plastics by using packaging materials as the representative product based on a life cycle approach. These studies evaluated the environmental impacts in terms of global warming, fossil depletion, acidification, eutrophication, land occupation, water depletion, and toxicity for whole life cycle of petroleum-based plastics and bioplastics. They also identified the stages of the product's life cycle that contributed the most impacts [82-88].

Different countries have already tried to find the best solution for the grocery bag by using life cycle assessment. For example, the American Chemical Council Plastics Division concluded a comparison of paper and plastic bags using LCA in the USA [89]. The result demonstrated that plastic bag manufacture demands less energy, water and fossil fuel than paper ones. Moreover, the amount of solid wastes and greenhouse gases are also less. Also, several LCA studies about bioplastics in the past have shown their advantage as compared to conventional plastics particularly in the environmental impacts of global warming and fossil depletion [90-91]. However, many studies have also argued that bioplastics have a negative effect on the environment such as land use change [60] due to land expansion and land required for feedstock cultivation for bioplastic; ozone depletion, eutrophication, acidification impact due to the fertilization. [82-83, 92-93].

In the first case, an LCA research work on bagasse and PS foam carried out by Fangmongkol & Gheewala [84], the environmental life cycle impacts of bagasse lunch boxes were evaluated and compared to PS foam lunch boxes. The results show that bleached bagasse pulp production has a significant contribution to almost all the impacts. The major contributor to the global warming of bagasse lunch boxes is bleached bagasse pulp production (69% of total) due to the utilization of chemicals at plant, accounting for 84% of the total global warming impact from bleached bagasse pulp production and sodium chlorate production (3.9%).The major reason that makes the environmental impacts of bagasse lunch boxes larger than PS foam lunch boxes is the weight of bagasse lunch boxes, which are five times that of PS foam lunch boxes. The second reason is the use of chemicals in the bleaching process.

Similarly, an LCA research work involving Bioplastic (PLA) and conventional plastic (HDPE) by [85] showed that petroleum plastic bags perform better than bioplastic bags in all categories and are quite similar in term of fossil depletion impact. The major stage contributing to the impacts of bioplastic bags is the PLA production stage which is particularly due to the higher resin requirement for bioplastic bag production as compared to plastic bags. The life cycle global warming impact from the raw material acquisition to the production of the bioplastic bags was higher compared to the plastic bags. The major contributor of global warming impact for bioplastic bag was PLA resin production, especially from the utilization of chemicals and energy. The second largest contributor was sugarcane cultivation and harvesting (14%) due to the production and utilization of nitrogen fertilizers. Meanwhile, the main contributor to global warming impact of the conventional (HDPE) bags was ethylene production (monomer), accounting for 37%. Additionally, a research work by [86] employed LCA to determine the environmental impacts and economic sustainability of bioplastics production with various end-of-life options. The results showed that the environmental and economic sustainability could be enhanced with 100% mechanical recycling of all kinds of studied plastics. It is also important to highlight that mechanical recycling showed a better performance in terms of environmental and economic sustainability than composting of bioplastics. This result shows that the end-of-life of these materials must be considered before production. Furthermore, in the United Kingdom a comparative research of carrying bags was made by the Environmental Agency in 2011 [87]. They looked at environmental impact of the whole life cycle. The results showed that the environmental impacts of carrier bags are dominated by resource use and production. Another study showed the Australian experience; Consulting Pty Ltd compared high-density plastic grocery bags with several other bags made from paper, compostable plastic, cotton, and polypropylene. The reusable polypropylene bags had the least impact on the environment [88].

As stated earlier, marine plastic littering and landfilling of plastics can cause major impacts on ecological, social and economic values. In the case of ecological impacts, the individual organisms like marine mammals, reptiles, birds and fish, may entangle or ingest floating litter. Marine litter can also damage their habitats, like coral reefs. However, the amount of literature that quantifies the extent of plastic wastes pollution in these niches is limited. This limitation has also carried over on assessing the environmental impacts of the plastic waste in landfills and marine habitats. Hence, it is worthy to state that several research articles [2, 84-86, 94-95] on plastic waste LCA and management acknowledged that impacts related to marine plastics debris, and plastic landfilling are not properly addressed in LCA. Very recently, in a workshop on marine littering and landfilling of plastics [96-97], it was agreed that addressing these limitations within LCA methodology would be meaningful and feasible; however, the methodology needs to be further developed. To this effect, a lot of works are on-going to help address these limitations of the LCA methodology.

With the help of LCA a task has been accomplished, which is to detect the phases of the product's life cycle that are contributing major environmental burdens. Identifying these phases will help push decision makers to find means and implement measures to cut down these impacts. The results of these LCA studies indicates that the bioplastics contribute more burdens in the production phase due to the use of bleaching chemicals, resins, and electricity for cleaning. Also, according to the results, the bioplastics are more sustainable in the long-run as they are mainly made from renewable resources as earlier stated in the introductory section and are more environmental friendly in terms of degradation and recycling. As a result of findings from the literature review of this study, it is imperative to raise awareness about plastic pollution and its adverse effects on the ecosystem. Therefore, it is necessary to make recommendations to help promote cleaner and safer production of these plastics, to promote proper plastic waste disposal and management. The following section will therefore attempt to make recommendations to sensitize every stakeholder.

9. Measures to control plastic, microplastic and polymer waste

To curb the effects of plastics (bioplastics, petroleum-based plastics) and microplastics in the environment, effective measures need to be adopted. This review study has identified hazardous substances (monomers, additives) used in polymer and bioplastics production for which the risks ought to be evaluated for decisions on need for risk reduction measures, substitution, or even phase out [21, 24]. There is also a need to assess the risks from exposure in a broader context, including plastic waste pollution, degradation products, additives and mixture toxicity. Environmental and human health hazard ranking models, as the one in this study, can be useful tools for comparing substances, mixtures or articles in hazard and risk assessment [7, 21, 57]. The end-of-life of these plastics should be factored into design and production so as to aid the process of recycling [91]. In the same vein of thought, an environment protection agency should be formed to regulate against unsanitary landfilling of plastics waste as some of these plastic wastes can be otherwise taken to recycling plants and recylcled into other useful items. Public awareness and public motivation must be done to judiciously use plastic items if they must use one, to properly dispose plastics waste, to promote the use of biodegradable bags and non-plastic materials through government approach and non-governmental organizations.

10. Conclusion of review results

There is no simple solution to this complex and global issue. Plastics and microplastics are growing contaminants affecting the whole world. Plastics offer considerable benefits for the future, but it is evident that our current approaches to production, use, and disposal are not sustainable and present concerns for wildlife and human health. We have considerable knowledge about many of the environmental hazards, and information on human health effects is growing, but many concerns and uncertainties remain. There are several solutions, but these can only be achieved by combined actions. There is a role for individuals, via appropriate use and disposal, particularly recycling; for industry by adopting green chemistry, material reduction and by designing products for reuse and/or end-of-life recyclability, and for governments and policymakers by setting standards and targets, by defining appropriate product labelling to inform and incentivize change and by funding relevant academic research and technological developments. Going by the ever-increasing volume of plastic production year in year out, combined with the low percentage of recycling which translates to a high percentage of landfilling and most importantly the non-biodegradable property of the plastics, it is apparent that plastics are not sustainable in the long-run, hence, the need to explore alternatives (e.g., bioplastics). These measures must be considered within a framework of lifecycle analysis and this should incorporate all of the key stages in plastic production, including synthesis of the chemicals that are used in production, together with usage and disposal. From the results of the above mentioned LCA analyses from different countries, it is valid to say that according to short-term environmental impact, petroleum-based plastics have a lower impact compared to bioplastics. Although if we are looking at landfilling, marine deposition and long-term harmfulness, biodegradable bags have less impact as they can decompose. Such results are not always apparent, therefore, measuring the impact on environment and human health is necessary and important. In addition, resource extraction and manufacturing processes create the biggest environmental impact among all the stages of production. Additives chemicals used in the production of bioplastics and petroleum-based plastics have been found to be potentially harmful to human health and the environment. Whilst staying conscious of the fact that bioplastics pose more environmental burdens, there is a lot of scope for improvement in production and processing, e.g., reducing the weight of the bioplastics, also the bleaching stage of production for some bioplastics can be phased-out or done in a more environmental friendly way to help reduce the overall environmental demerits of the bioplastic, with these wholesome improvements in production, processing, and proper waste managements (composting and mechanical recycling), bioplastics would be worthy alternatives / replacements to the petroleum-based plastics. These actions are overdue and are now required with urgent effect; there are diverse environmental hazards associated with the accumulation of plastic waste and there are growing concerns about effects on human health, yet plastic production continues to grow considerably. As a consequence, the quantity of plastics produced in the next years of the current century will keep rising continually.

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