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Review article

Sustainable plastic waste management in a circular economy

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HIGHLIGHTS

- Plastics are not biodegradable in nature because they can live up to hundreds of years.
- Incineration of plastics is not environmentally healthy because of the harmful gases emitted during the process.
- The circular economy has provided the possibilities for recycling and sustainable management of plastic wastes.
- Waste pet bottles are used for arts, crafts and reinforcement aggregate for building construction.
- Plastics are also used as filaments for 3D printing of various items.

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ABSTRACT

The discovery of plastics as useful materials for human existence, providing comfort and ease has now turned into a menace in the society and a pain in the neck as plastics have also become co-habitat of the human ecosystem. Plastics were made by men, but plastics now live way longer than the men who gave them the privilege of existence. Since these colonies of materials cannot be eradicated, it is very pertinent to discover possible ways of useful diversion through recycling by converting plastic bottle waste into useful raw materials for other sectors of the economy. This paper has stirred the pool of relevant literature to extract some of the innovative efforts that have been deployed into redirecting the potential of plastic waste into useful applications like engineering and building construction, horticulture in agriculture, and the most advanced application is the 3D printing using plastics as filaments. Following the trend of technology, 3D printing is a grey area of plastic recycling, it is quite expensive however, it worth exploring.

1. Introduction

Waste could be referred to as any material that is unavoidable as a result of industrial or domestic activities which makes them of no demand economically and must for disposal (Sridhar and Hammed 2014; Park et al., 2007; Safavi et al., 2010). As a factor of significance, it is quite necessary to have a clear understanding of waste in terms of its natural disposition, associated environmental impact, hygienic disposal habits and many more (Prasad and Vinu 2012; Rani et al., 2019; Saldaña Durán and Nájera González 2019). Wastes are in various forms like the gaseous, liquid and solid-state which are generated from different production processes of human activities (Kayode, 2006; Ren et al., 2015). Plastic is another form of solid waste (Awasthi et al., 2017). Plastics take over a thousand years to degrade compared to other wastes (Hopewell et al., 2009) as shown in Table 1. Over 2 billion tons of municipal wastes (solid) are generated yearly with an estimated increase to 2.2 billion tonnes and 3.4 billion yearly by 2025 and 2050 respectively. Presently, plastics are accountable for about 7%–12% of the total municipal solid waste generated by weight. This data is subject to a possible increase owing to the consistent use of plastics for product packaging for end-users consumption.

Plastics are generally cheap which is why they are mostly abused by humans through indiscriminate use. However, some parts of the world especially those in the developed countries have implemented the

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Table 1. Selected wastes and their rate of degradation (Elekwachi et al., 2019).

s/n	Waste	Period of degradation
1	Glass	Not yet determined
2	Plastics	100–1000 + years
3	Aluminium, tin and other metals	200–500 years
4	Woollen cloth	12 months
5	Cotton cloth	2–5 months
6	Paper	10–30 days
7	Organic waste	7–15 days

initiative of adding cost to the use of plastics as plastic bags are now paid for during shopping in malls. Plastics are very unique materials that have prominent attention in the global economy as a result of their ubiquity. There are certain issues around the existence of these materials with a major concern of the impact of the plastic disposal method on the environment. In the middle of the 19th century, Bakelite amongst other plastics was not known until 1950 when plastic became the common sort after materials on the planet, they are also very attractive in nature which encourages their usability. Plastic is an inevitable waste because it plays a major role in most of our daily activities such as packaging materials for daily consumables such as pet bottles for drinks, plastic containers for edibles and plastic bags for groceries amongst other shopping activities (Idumah and Nwuzor, 2019).

According to Lundell and Thomas (2020), the amount of plastic products that is manufactured globally in metric tons is over 300 million. It was also estimated based on different countries that plastics are recycled between 9 to 10% of the yearly production, about 10% burnt and an average of 80% of the generated plastics are discarded without giving them a second chance for reuse, this is known to be the case due to the fact that they are cheap to manufacture and in bulk usually through injection molding technology. To this end, this paper is assigned to extract from literature the updated study on the efforts made to manage plastics from production to usage, disposal and post disposal behavior of plastics through various recycling approaches and elimination methods.

2. Global production of plastics

Ángeles-Hurtado (2021) reported that there is a proportionate relationship between the rate of global population increase and plastic disposal from end-users. This was corroborated by the world population sensor report of the United Nations which was 7.7 billion in 2019 as the mid-year report. A data forecast for the world population was estimated by the United Nations to be 8.5 billion and 9.7 billion for 2030 and 2050 respectively (United Nations and Affairs, 2019). Considering a relative growth and projection in the global production of plastics, Sahin and Kirim (2018) reported that plastic production reached a total of 280 million metric tons globally in the year 2011 with a significant increase to 322 million metric tons in the year 2015 and a final estimate of 400 million tons to 414 million metric tons in 2021 which was without consideration of the COVID-19 impact. This increase in demand for plastic can be attributed to the stupendous growth in the world population. The rapid growth in the production of plastics can also be a result of the uncommon attribute of plastics such as very high strength-to-weight ratio, high resistance to chemical and physical degradation, not permeable to liquids and easy formation into varying shapes. The cost of producing plastics is relatively low with makes it a considerable substitution for other traditional materials such as glass, paper, fibres, wood, metals and concrete. Plastics are used in various applications like industrial machinery, construction, electrical, transport, consumer goods, textiles and packaging. The use of plastics as packaging materials by weight still remains the largest application amongst other sectors as shown in Figure 1.

The use of plastic by many households around the world has been on the increase (Dutta et al., 2016) with a severe impact which led to the ban of use in some countries like China to be able to reduce the amount of plastic in circulation because it has been proven over the years that polymers are excellent pollutants in seas and cities (Shen et al., 2020).

2.1. Environmental impact of plastics

Plastics have a life cycle that now poses a threat to planetary boundaries which means that the pollution from plastics could be overboard a certain threshold that becomes very critical with an irreversible global impact on the climate, ecosystems and biodiversity levels (Villarubia-Gomez et al., 2018). About 14 million tons of plastics gets into the ocean majorly from the coastal areas of Asia yearly. An estimate of about 700 species of aquatic life has been affected by the deadly impact of plastic pollution over the years (Schmaltz et al., 2020). Hence, it is projected that almost all the seabird species all around the planet will start consuming wastes from plastic by 2050 (Parker 2019). It has been discovered that most plastics residues that find their way into the oceanic regions carry some harmful species of viruses, algae and microbial communities that transports with ease some toxic substance that eventually changes the ecosystems and alters genetic diversities (Villarubia-Gomez et al., 2018). If preventive or damage control measures are not taken, there is a likelihood of an increase in the mass of plastics in the ocean by 2040 to be an estimate of 30 million tons yearly which would conversely increase the effect on the environment (Parker 2020).

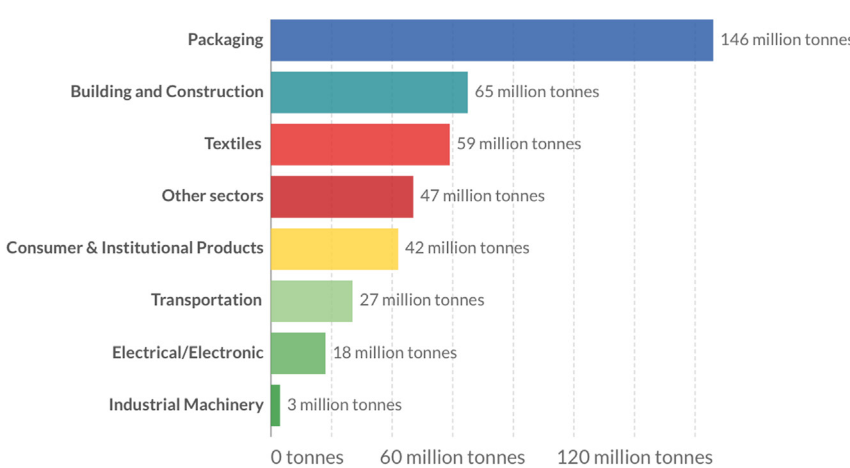


Figure 1. Global plastic use by sectors (Geyer et al., 2017).

2.2. Impact of plastics on humans

Most of the chemicals that give the defining qualities of plastics like hardness, durability, malleability, colour and plasticity are given off into the atmosphere when they are burnt openly. This constitutes a number of toxic substances in the air that affects the human skin, and eyes, increasing the risk of cancer and heart disease, headaches and nausea which could also damage the nervous and reproductive system (Verma et al., 2016). Mismanaged plastic wastes can block drainages and waterways which could also result in flooding, a breeding ground for mosquitoes, breeding of flies that carry diseases and vermin (Kehinde et al., 2020).

2.3. Circular economy

The theory of circular economy and its practice focuses on how never making plastics become waste (Qu et al., 2019). But despite the fact that plastics are kept away from the stream of waste and rechanneled into useful economic activities through the circular economy, plastics are still found to be a significant cause of environmental and social harm (Geyer et al., 2017). This is however referred to as the lubricant of globalization. Some critics of plastics are of the school of thought that the circular economy (CE) is a possible distraction from the root causes of pollution and plastic consumption that has resulted in a widespread destructive effect across the earth. Sequel to this, some organizations with global references such as Story of Stuff, Break Free from Plastic, GAIA and Local Futures strive for feasible movement way beyond the call to recycle and focus more on the phasing out of plastics through a major emphasis on the reduction of plastics altogether (Monbiot, 2018). In the low and middle-income countries (LMICs), the adoption of solutions from the circular economy model has very promising advantages although quite nascent. This solution-based method is premised on the waste separation tradition at the source, improved consciousness of resources, the birthing of recycling innovations and small-scale initiatives for plastic recycling (Pagliaro, 2020).

3. Plastic waste management techniques

3.1. Recycling

Waste from plastics can be converted into useful products like toys and bags (Ángeles-Hurtado 2021). Plastics have contributed to the deteriorated level of the environment. However, it is very important to establish the policies of the circular economy by recycling the household waste in a bid to prevent the advert effect of pollution (Sadat-Shojai and Bakhshandeh 2011; Sahin and Kirim 2018).

Some innovative steps have been taken thus far to recycle plastic waste through massive industrialization which has created job opportunities for many. But these processes have further created multiple plastics as new products which get more difficult to be classified.

3.2. Landfills

According to Ragaert et al. (2017), an approximate metric ton of 150 million plastics always end their cycle in landfilling because it was discovered that open landfills pose more environmental danger about 23 times more than the effect of carbon dioxide. Gases generated from landfill has been reported to have contributed to over 50% of the gas emissions from greenhouse. However, it is still the most adopted method globally for the management of solid waste. Plastics used for landfills have a shelf life of 500year before they fully decompose in any landfill and a plastic bottle can decompose in the ocean into micro-plastics which could last for over 500 years (Ángeles-Hurtado 2021). Owing to the landfilling effect of solid waste as a management strategy, some countries like Denmark, Austria, Sweden, Belgium, Germany, Netherlands and Switzerland have been able to control the disposal rate of waste in landfills to about 5% unlike a nation like Mexico that disposed 78.54% of waste into disposal sites (Lima et al., 2014).

3.3. Incineration

Plants for incineration can work continuously for a year except for a few days of scheduled maintenance (Pascoe and Connell 2003). However, the adoption of incineration for plastic waste management has adverse effects on the environment due to the release of very toxic substances that eventually pollute the atmosphere through air contamination (Jeswani et al., 2021). Incineration could be practised in two ways such as gasification and combustion.

3.4. Mechanical recycling

Mechanical recycling could also be referred to as secondary recycling and a plastic waste recovery process that can be reused through mechanical means. This method is only used for plastics that contain a single polymer. Some plastics are recovered through processes of mechanical manufacturing which is also referred to as a physical-mechanical recycling. Mechanical recycling could only become difficult and complex when the waste is contaminated with green waste particles (Al-salem et al., 2009). A conventional process of mechanical recycling involves the waste collection, separation, cleaning, crushing, pelletizing for required conversion and re-processing which ends up in the production of new products without altering the material's chemical composition (Hamad et al., 2013). However significant changes only occur in the plastics during the mechanical recycling process based on the substances that have been exposed to through treatment by using some wetting agents which could alter the composition of the polymers (Scavino et al., 2009). This shortcoming was further elucidated by Arun Kumar (2017) through the highlighting of some issues that occurs during the recycling process which could be the heterogeneity and degradation of plastics waste as a result of the addition of polycondensation and polymerization because of the chemical reaction (Ragaert et al., 2017).

3.5. Chemical recycling

Monomers are produced by depolymerizing polymers through chemical recycling and decomposing of plastic into valuable raw materials. Numerous chemical reactions are adopted in the decomposing of polymers but the most commercialized ones are methanolysis and glycolysis. Gasification and pyrolysis are quite outstanding polymer decomposing techniques in areas of degradation research questions. Pyrolysis is the most adopted technology that explains the process of crushing sorted plastics, melting them for proper refining for conversion into useful diesel and some other products of petrochemical applications (Kumagai et al., 2020). Gasification on the other hand is another technique that converts waste into useful energy by melting plastics in oxygen and high-temperature steam of 1,200 to 1,500 °C

Pyrolysis: It involves the heating of plastics without the presence of oxygen until the decomposition of the plastic waste into gas and oil. This process breaks down all plastic polymers into quite small molecules. Viscous liquids are produced more favourably during the pyrolysis procedure at a temperature as low as 400 °C or less. While small gas molecules are produced during the pyrolysis process at a high temperature of 600 °C or more. The entire process of pyrolysis has a couple of advantages like CO_2 emission reduction, reduced landfilling, speed up product commercialization, production of products that could be useful in electricity production and heat generation.

Gasification: The gasification process encourages the reduced adoption of landfilling process of waste management and accrued cost that results from the incineration of plastic solid wastes. Gasification makes use of air instead of oxygen O_2 which makes it less cost incurring and more simple. However, a major disadvantage of the gasification

Table 2. Difference between bricks wall and PET bottle wall (Jalaluddin, 2019: Muntean and Cazacu, 2017).

S/N	Description	Bricks	Pet Bottle
1	Load carrying capacity and strength	Lower strength and more wall thickness	About 20 times more than a brick wall
2	Appearance (work beauty and neatness)	Immense material waste incurred during project execution	Neat execution without wastage of materials
3	Cost of execution	More manpower at a higher cost is required	Fewer resources and Indigenous manpower are required at a low cost
4	Project execution speed and time	Takes longer time than plastic bottle wall	15% faster than brick wall
5	The purchasing cost of equipment and materials	Brick wall takes more materials and has more weight.	Saves the supposed cost of water, fittings, grinder and cement.

process is the impact of the nitrogen element present in the air during the procedure.

4. Adoption of plastic waste in different sectors

4.1. Concrete admixtures

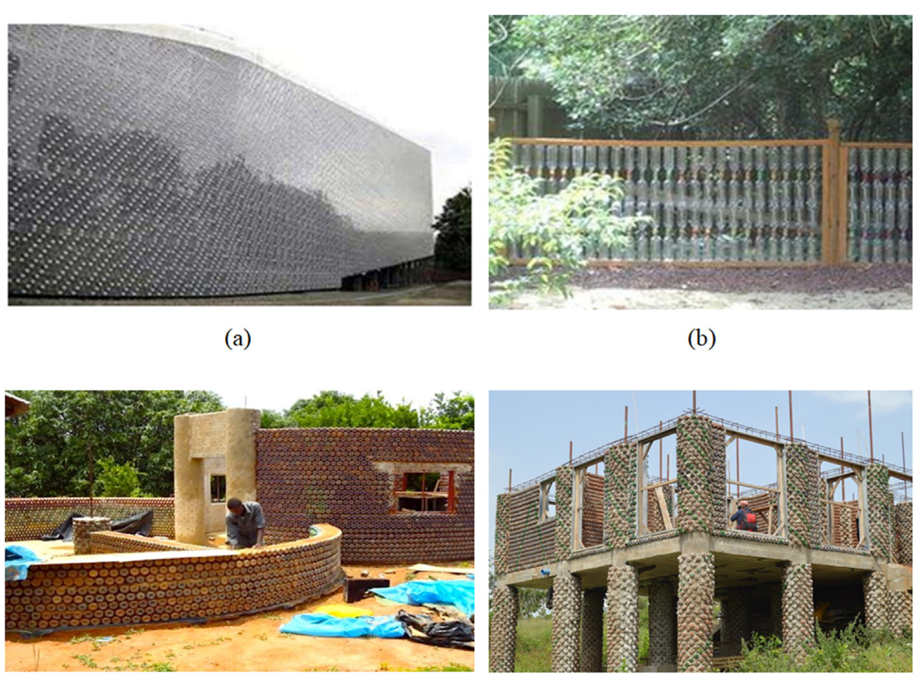
Naik et al. (1996) applied some plastics in a shredded form in the concrete aggregate to understudy the possible effect it could have. It was reported to have improved the compressive strength of the structure. Prahallada and Prakash (2009) further adopted the same method of admixtures to examine the impact of shredded buckets as a form of plastic waste converted into a supposedly useful aggregate in the making of concretes but the outcome was a decrease in compressive strength which was contrary to the finding of Naik et al. who also considered the same approach. However, the studies of Gowri and Rajkumar 2011 who used raw plastics and shredded polythene sheets corroborates the findings of Prahallada and Prakash (2009) who also got decreased compressive strength of concrete in their findings. Amongst other related works are (Raghate 2012: Anum et al., 2019) who also attained the same result. However, Cordoba et al. (2013) gathered PET bottles, crushed them into flakes and used them for similar studies to other researchers mentioned above. The findings of the study revealed the increase in compressive strength alongside the modulus of elasticity with maintained values for the young modulus. In summary, the fluctuation in the result of the considered studies that used different types of plastics can be attributed to the variation in the chemical composition of the different polymers.

4.2. Column casting and bricks molding

Construction engineers are now very creative with the use of Plastic bottles for several parts of project execution such as a fence, columns, bricks, warehouses, schools, amusement parts, residential structures and many more (Raghatate, 2012). Mohammed (2017) reported that the first house that was built in Africa with plastic bottles was a project that was initiated by the Butakoola Village Association for Development with the acronym "BUVAD" in Uganda in the year 2010. This project was an innovative solution that was birthed from the problems facing several farmers in that village regarding the negative impact of plastic on the fertility of the soil which kept reducing crop productivity yearly. This challenge was discovered through a survey carried out in the community of farmers Kayunga by BUVAD in 2009. They began to gather all the available plastic bottles about 1.8 million used plastics and processed them into honeycomb-shaped bricks. The total cost of the project cost about a third of the cost of the conventional structures. Plastics have been proven over the years to be a better substitute (Dadzie et al., 2020) for the contemporary bricks quality used for the construction of structures as shown in Table 2 and the image representation in Figure 2a-d.

4.3. Plastic bottles in agriculture

It is no doubt that plastic waste bottles have become highly toxic to the entire space of human existence because of their intense resistance to bio-degradation over the years. During random disposal of PET bottles after use, some end up on the farmland owing to erosion or flood action



(a) (b) (c) (d)

Figure 2. a–d. Pet bottles are used for the construction of buildings (Nováková et al., 2017).

Figure 3. Plastics converted into a horticultural flower vase.

by rainfall but they never decompose even when immersed into the soil. This has also contributed to the low fertility level in soils which affects the productivity rate of crops cultivated on the farmland. In a bid to cub, reduce or eliminate these shortcomings, plastic waste bottles are now redesigned to serve as a support system for cultivating flowers, vegetables and other suitable crops. This is achieved by cutting the pet bottles into desired shapes that will accommodate the required quantity of soil needed for the germination and survival of the plant. It also gives room for flexibility of design in the arrangement and alignment of the bottles when used for planning flowers in horticulture (see Figure 3).

4.4. Plastics in 3D printing

In line with circular economy theory, plastics have gained further relevance in 3D printing through filament extrusion from plastic waste which is presently available commercially in some variants. There are several types of filament available for 3D printing like polyethylene terephthalate (PET), polylactic acid (PLA), and nylon, acrylonitrile butadiene styrene (ABS). Car dashboards, automobile parts and the HIPS from refrigerators are the major sources of ABS filaments. The choice of materials for the production of 3D printing filament depends on the parameters of the available technology and the producer's preference. Extruders are good for all 3D printer users because they have been proven to be high saving generating up to 80% proving a self-sufficient satisfaction to all end users. Considering the size of extruders which is relatively small, simple operations and significantly low price, they are user friendly without a need for an expertise skill set to operate them. Mikula et al. (2020) reported that PLA is reduced in mechanical strength through recycling. To overcome this challenge, Zhao et al., (2018) recommended the possibility of coating the polymer filament after recycling with polydopamine (PDA).

5. Conclusion

These reviews have exposed the derivable advantages in the use of plastic bottles for innovative applications in terms of reuse and environmentally healthy recycling approaches. Adopting the ideology of using plastics as a replacement for the brick wall will gradually aid the reduction of CO emission into the environment that is generated during the production of cement which is used for the moulding of bricks (Etim et al., 2021). Plastic has also revealed its cost-saving dimension against using the conventional brick walls for construction. For instance, if it cost Rs. 14888.5 to make a $20m^2$ brick wall, it will cost a total of Rs. 7758.4 to make the same square meter of the wall using plastic bottles (Manjarekar, 2019). It is safe to conclude that the climate rescue goal is still very paramount to every human that still resides on the earth planet. Hence, the need to reduce or possibly eliminate activities that emit toxic and dangerous gas that poses threat to our climate. To this end, researchers are encouraged to come up with innovative discoveries to further help contain the circulation of plastics just as discovered from the bank of literature that plastics are now used in concrete aggregate mixtures, construction walls and structural columns, plant cultivating pots in horticulture, filament materials in 3D printing or production and other useful crafts.

Declarations

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

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Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

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