Zernab Fatima¹ and Roohi¹,*

¹Protein Research Laboratory, Department of Bioengineering, Integral University, Lucknow, India

Abstract: Background: The world’s annual utilization of plastic materials is growing day by day and simultaneously solid waste management is becoming one of the major environmental concerns throughout the world. Current approach for their usage and disposal is not sustainable because of the durability of the polymers involved.

Methods: Partially digested products of these plastics in the form of micro-plastics are accumulating as debris in landfills and in natural habitats because of their remaining in the environment for millions of years. Easy availability, low cost and ubiquitous applications make the plastics most attractive polymer whose proper disposal through specific technology seems the only alternate and that may lessen down the pollution over the next decades.

Results: Recycling as a waste management strategy provides opportunities to reduce the use of petrochemical resources and improving environmental conditions. Reuse of bulky plastic wastes in concrete and Wood Plastic Composites (WPC) seems a smart approach for solving the problem of disposal. The development of new construction materials using recycled plastics is important to both the construction and the plastic recycling industries.

Conclusion: This review article presents the details of recycling of waste management, their probable application for concrete and WPC production, types of recycled plastics, role of microbes and microbial enzymes for recycling of plastics and emphasis on use of biodegradable plastics to make the environment green.

Keywords: Recycling, plastic concrete, wood plastic composites, biodegradable plastics, solid-waste management, polymers.

1. INTRODUCTION

Plastics have become one of the basic needs for our day to day lives, nowadays. It has become our necessity. There are various forms of plastics used such as:-

1.1. Types of Plastics

- **Polystyrene (PS)** - It has been produced in a massive form since 1930s. It may be clear, rigid and brittle. It is used to make less costly packaging materials such as pens, electronic devices, and safety razors, also used in materials for construction of jewelry boxes. It mostly used in restaurants because of its lightweight and high insulating capacity.

- **Polyethylene (PE)** - It has mass production since 1939. It is a largest used variety of plastic which is used in making beverage bottles, gas tanks, fibers for making clothes as well as toys etc.

- **Polyvinyl Chloride (PVC)** - Its mass production took place since 1938. It is used in making water pipes, electric wires, also used in various medical applications, packaging, etc.

- **Polypropylene (PP)** - Its mass production took place since 1950s. PP is resistant to water, acid and salts which can cause damage to metals. It is used to make ketchup bottles, medicinal bottles (syrup bottles), medical syringes, yogurt containers, battery cases used in automobiles etc.

- **Polyethylene Terephthalate (PET)** - Its mass development started in 1941 used for making carbonated beverages and food containers. It is also used to make fibers for clothing, carpets, and engineered plastics for the precision of molded parts.

- **Acrylonitrile-Butadiene-Styrene (ABS)** - It has been developed in 1960s used in electronic housings, fittings, pipes, various parts of the telephones, interior and exterior components of an automobile [1].

- **Miscellaneous** - Recycling type includes multi-gallon water bottles, ‘bullet-proof’ materials, sunglasses, DVDs,
Recycling of Polymers

The consumption of plastic products used in different forms and styles is soaring worldwide. There are near about 300 million tons of plastics produced every year and approximately 33% plastics are used for one-time use and then discarded. Plastic usage is so rampant that the generation of plastic by the huge mass desperately calls out for painstaking disposal. Disposal of plastic products further wreaks havoc in the environmental air and makes our stint on the earth a problematic one. Therefore, recycling of plastic has become one of the main concerns nowadays. The concept of recycling came into picture since the Industrial Revolution. Although plastics are durable and play a significant role in our mental pollution. Table 1 describes the list of countries where plastic production reaches till 2030. In this context, it should be noted that China has already banned plastic waste imports [2].

Therefore, if plastic waste once discarded, it may take several centuries to disintegrate and break down [3]. The toxins of partially disintegrated plastic break down and seep into the earth. These toxins are noxious and capable of contaminating groundwater. Hence, its toxicity level has gone beyond our imagination. Fortunately, the alternative of recycling plastic products keeps them out of landfills and also reduces the amount of new materials spent on a variety of objects [4].

Recycling of plastics has immense potential to mitigate environmental pollution by utilizing various eco-friendly techniques and it also helps in providing certain economic opportunities. Due to the scarcity of space for landfilling and ever-increasing cost, utilization of waste has become an attractive alternative to disposal and reuse of bulky waste like plastic is the best example for this [5]. One can also identify recyclable plastic by the recycling triangle symbol which is usually found imprinted somewhere on the bottom of a bottle with a numbered and lettered abbreviation to label its type.

2. PLASTIC PRODUCTION

The rate of plastic production in the previous 65 years largely exceeded to approximately 8.6 billion tons since the beginning of 1950s, for manufacturing of quality products. Plastic production is increasing in a very fast pace annually. It was estimated that 275 million metric tons of plastic waste was produced in the year 2010 and 4.8 to 12.7 million metric tons entered into the world's oceans [6]. Hence if plastic production will continue in this manner then by the end of the year 2050, mankind will produce up to 6,000 Mt of polypropylene fibers, 2,000 Mt additives and 26,000 Mt of resins. This leads to accumulation of billions of metric tons of plastic across the globe that also includes the aquatic and terrestrial ecosystems. Approximately, more about 33,000 Mt plastic waste is generated including resins, PP, fibers and additives, out of which, 9,000 Mt of plastics has been recycled, 12,000 Mt are been incinerated and, 12,000 Mt has been discarded in natural environment and landfills (Fig. 1) [7].

3. EFFECTS OF PLASTICS ON HUMANS, ENVIRONMENT AND WILDLIFE

Since the majority of the products we use in our day to day lives are made up of plastics. From the jewelry we wear to the buttons on our shirts, from the keyboard to the food packaging materials, hence its use just cannot be deniable. We have so much delighted and confident about the use of recycled plastics, but we can’t refute the deleterious effects of the plastic usage on humans, animals, plants or in totality on environment. Some of these harmful effects are mentioned here;

3.1. Effects on Humans

There are various harmful raw materials used for manufacturing of plastics so called as plasticizers such as bisphenol A (BPA), a monomer of polycarbonate which is used as a softening agent. It is also used as fungicides, making plastic bottles, perfumes, medical devices, cosmetics, toys, etc. Possible daily exposures of BPA can be via air, dust, food, or drink. It can leach into food from the protecting internal epoxy resin coatings of canned foods, meal boxes, cash and ATM receipts, infant’s milk bottles and water bottles. The degree to which BPA leaches from polycarbonate bottles into liquid may depend upon the temperature of the liquid or bottle.

BPA is also found in breast milk. BPA plays a key role for disrupting endocrine system in humans. According to the recent studies, BPA is said to be a carcinogen [8, 9]. It does not directly cause cancer but its presence can enhance the formation of tumor in a living system. BPA exposure may also cause heart disease, diabetes, early puberty, even learning disabilities, etc. And most striking point is that the damage is taking place by in taking its microscopic doses every day.

Therefore, it is a controversial matter whether to ban BPA completely or not. Food and Drug Administration (FDA) declines the ban over BPA but mentioned that the studies done on BPA are too less to declare it as a “ban”. “Evidence from some studies have raised questions as BPA may be associated with a variety of health effects, but there remain serious questions about these studies, particularly as they relate to humans”, as per the FDA statement. Moreover, it is emphasized by some research that BPA was metabolized and eliminated from the body very quickly before taking place of damage. Whatever contentious scenario is going in India, the Canadian government has already declared BPA as a toxic substance [10].

Likewise, BPA, di(2-ethylhexyl)phthalate (DEHP) or diocetyl phthalate (DOP) is used in the production of polyvinyl chloride (PVC). DEHP is another softening agent mainly used as a plasticizer, roofing, flooring and for making surgical instruments. High exposure of DEHP causes chronic toxicity. It may also cause gastrointestinal distresses in humans [11].
Table 1. Global import and export of Plastic until 2030 [2].

<table>
<thead>
<tr>
<th>List of Countries</th>
<th>Imported Plastic Produced (~ in million metric tons)</th>
<th>Exported Plastic Produced (~ in million metric tons)</th>
<th>Displaced Exported Plastic Produced (~ in million metric tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada</td>
<td>4</td>
<td>4</td>
<td>7.5</td>
</tr>
<tr>
<td>Mexico</td>
<td>1</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>US</td>
<td>8</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>UK</td>
<td>1</td>
<td>9.5</td>
<td>12</td>
</tr>
<tr>
<td>Belgium</td>
<td>4</td>
<td>7.5</td>
<td>12.5</td>
</tr>
<tr>
<td>Netherlands</td>
<td>7</td>
<td>8.5</td>
<td>10</td>
</tr>
<tr>
<td>France</td>
<td>2</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Germany</td>
<td>6</td>
<td>17.5</td>
<td>24</td>
</tr>
<tr>
<td>Thailand</td>
<td>1</td>
<td>3.5</td>
<td>9.5</td>
</tr>
<tr>
<td>Indonesia</td>
<td>2</td>
<td>2.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Philippines</td>
<td>0.2</td>
<td>2.5</td>
<td>6</td>
</tr>
<tr>
<td>South Korea</td>
<td>2</td>
<td>3.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Australia</td>
<td>0.2</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Japan</td>
<td>0.1</td>
<td>22</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Fig. (1). Progressive production and disposal of plastic waste; solid lines show Chronological data from 1950 to 2015 and the dash lines show estimation of the past years until 2050. *(The color version of the figure is available in the electronic copy of the article).*

3.2. Effects on Environment and Wildlife

Plastic debris is harmful and can cause aesthetic problems to maritime activities like fishing, tourism, water sports, etc. Discarding fishing nets may result in losses commercial fisheries [8, 10]. More than 260 species which include invertebrates, fishes, turtles, seabirds and other mammals, were been reported to ingest, result in impaired movement and reduced reproductive output damaging, and death [9, 12, 13]. The latest report suggests that plastic debris found in the aquatic animal body which remained 11 km deep in the ocean. After reading this news, even a common man can think about the extent of severity of plastic pollution at each and every part of this Earth.
4. SMART ALTERNATE FOR MINIMIZING PLASTIC POLLUTION USING BIOPLASTICS

As per the statement of Brendan Morris, (CEO, Plantic Technologies Limited), “We must all begin to live in a smarter materials world. Bioplastics innovation isn’t the total solution to the problem of plastic waste, but it’s a critical start.” Therefore, keeping all these points in mind, the concept of bioplastics came, that are not only biodegradable but also sustainable through its lifespan. The petroleum-based plastics which are degradable, the plant-based plastics which have no compulsion for degradation and a mix of these two comes under bioplastics [13]. Bioplastics are mainly made up of plant biomass like cellulose, sugarcane, corn, etc. and hence they can easily degrade by microorganisms which can convert them into compost, water and carbon dioxide, which further can be utilized. Bioplastics may be divided under three groups:

**Group 1:** Plastics that are based on fossil fuels and are biodegradable.

**Group 2:** Bio-based or moderately bio-based nonrecyclable plastics.

**Group 3:** Bio-based plastics which are biodegradable at the same time [14].

4.1. Various Ways for Plastic Recycling Management

Different ways, which are available for recycling of solid wastes, are mentioned in Table 2 [15].

4.2. Stages of Plastic Recycling

1) **Collection:** Plastic collection can be done by two methods. The one is the kerbside collection, where recovery of plastics from homes, which were used for beverages or foods, is performed. The other is the ‘bring-schemes’, where for example, buying drink in the plastic bottle, some charge for bottle is added to the product price at the time of buying. And this charge will refund if the bottle is returned to the store. However, this result in low collection rate either because of the less committed public behavior or by less funding.

2) **Sorting:** It can be done either by the automatic method or manual method. Automated sorting of containers is widely used by various plastic recycling facilities. The system used mostly is Fourier Transform Near Infrared (FT-NIR) spectroscopy for polymers type analysis. To sort the streams into clear and colored fractions, optical color recognition camera systems are currently been used. Optical sorters can be used to differentiate between different colors (light blue, dark blue, green, red, etc.) of the PET containers. By using multiple detectors and doing sorting in series, sorting performance can get enhanced. X-Ray detection is another sorting technology that helps in separation of PVC containers having 59% of chlorine by weight, hence can easily be distinguished.

3) **Washing:** To increase the quality of the final product of sorting, washing is done thoroughly. In this way, removal of various unwanted impurities takes place like adhesives, pulp fibers, food residues and labels. Wash plant uses 2-3 meter cube of water per ton of material.

4) **Shredding:** It may also be called as a size reduction step. Hence, here the plastic waste is loaded on the conveyor belts that run the waste through different shredders. The shredders tear up the plastic waste into small pellets and flakes. Followed by technologies such as dry cleaning, which is used to remove contaminants from the surface of the flakes, and performed by creating friction without using water.

5) **Identification and classification of plastics:** It is done to test the shredded product’s quality and class. Raman emission spectroscopic detectors are used to enable flake rejection and to differentiate the electrostatic properties. Laser sorting uses emission spectroscopy to differentiate polymer types (for Waste Electric and Electronic Equipment (WEEE) and automotive plastic).

6) **Extruding:** After shredding, many separation techniques can be followed. Here, melting of shredded plastics takes place so that they can be converted into pellets and then used to make various types of desired products [16, 17].

According to the United States Environmental Protection Agency, EPA (2012), 32 million tons of plastic waste was generated, and only 9% of that was recycled. But some innovative crafters are doing their part to make use of all that plastic. Turns out plastic doesn’t just have to be turned into more milk jugs. Recycled plastics are used for making various things like lamps, jewelry, and wall hangings [18].

5. ROLE OF MICROORGANISMS IN PLASTIC RECYCLING

Microbial biotechnology is one of the most retentive technologies for recycling of plastics. It is not only the most environmentally favored way of dealing with plastics but also economical and sustainable. Plastic waste should establish as the next generation carbon source in the field of biotechnology. Plastic waste is simply said to be a carbon-rich polymer. The biotechnological and environmental technologies turns plastic waste into a valuable resource in the various fields of chemicals and materials in order to seek bioeconomy and advantageous for the society and the ecosystem [19]. Best examples of microbes which are successfully involved in plastic recycling are as follows;

- **Pseudomonas:** This is a bacterial strain having unique stress resistance and metabolic competence [19]. This genus is commonly known for its efficient degradation of polyurethane (PU, a polymer of carbamate). Although it can degrade PET, it uses terephthalic acid as a carbon source for catalyzing PET into polyhydroxyalkanoate (PHA) instead [20]. *Pseudomonas putida* can be utilized for production of biopolymer, biosurfactant (like rhamnolipids) and natural PHA, i.e. a bioplastic [21]. PHA can also be produced by engineered microorganisms [5, 15]. PHA not only used in biodegradable packaging but also in surgical equipments and nanomedicines preparation [22, 23].

- **Ideonella sakaiensis:** A new type of bacterial strain has been discovered by the team of Kyoto University, Japan, after searching through 250 microbes which took about 5 years and finally isolated from a heap of wastes products. This strain lives on Polyethylene- Terephthalate (PET), a
6. COMMERCIAL APPLICATIONS OF RECYCLED PLASTICS

6.1. Wood-plastic Composites (WPCs)

A plasticized wood, like WPC, is an imperishable and roseate green material, having maximum durability without any usage of toxic reagents, and does not emit any harmful gases in the environment. It is a hybrid of wood, and plastic and occupies an important position in replacing woods in various applications. These are made up of mixing of thermoplastics or thermosets, wood flour and plant fibers which are reinforced by lignocellulosic components. Wood flour comprises cellulose, lignin and hemicelluloses. Whereas the plant fibers are used in order to attain flexibility and they are inexpensive having low density and good tensile strength, high biodegradability and low carbon dioxide emission. The wood parts of WPCs may also include sawdust and bamboo that form fiber fillers mixed with new or old plastic powder from different polymer materials. Once these materials are homogeneously mixed, they are further extruded to improve its characteristics. There are various methods adopted to improve the mechanical and physical properties of WPCs which include heating and chemical treatment with sodium hydroxide. Hybridization process, where two or more types of filler materials are mixed, helps in reinforcing of the thermoplastic matrix. By meeting all these requirements, the final material can be available for its practical and economical applications [25].

6.1.1. Materials and Procedure of WPCs Production

Materials: Pinewood flour comprises small particles commonly used plastic in clothing and plastic bottles. The microbe was grown easily by leaving PET in a warm jar with bacterial culture and necessary nutrients and was left for few couples of weeks, later it was found that plastic was diminished. It has been researched that this microbe secretes an enzyme when it is in an environment rich in PET. Hence, the researchers identified the specific gene in bacteria’s DNA and found that this PETase enzyme can alone break down PET [24].

<table>
<thead>
<tr>
<th>Mechanical Recycling</th>
<th>Energy Recovery</th>
<th>Feedstock Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>This type of recycling includes the operation that intends to reform plastic wastes via mechanical process. The process involves grinding, washing, separating, drying, re-granulating and compounding. This subsequently produces recyclates that can be converted into new plastic products, often abolishing the nature of the previous plastic products. The process may apply for a high-value product, virgin plastic, which converts into same or similar kind of product. And low-value end-product, down-cycling, where the product is of low quality and its appearance as well as its finishing is unimportant.</td>
<td>Molecules that make up plastic products are a powerful source of energy. For example, in a facility that converts waste into energy; non-recycled plastics can supply more than 15,000 BTUs per pound. That is more energy per pound produced than any type of coal. And because plastics have a higher energy value than other garbage (or municipal solid waste), they help increase the efficiency of the energy recovery process in unconventional waste-to-energy facilities. Thermal energy production and recovery is achieved by performing the process of waste-to-energy facility. The process of energy recovery includes incineration, production of refuse-derived fuel (RDF) and direct incineration as a fuel.</td>
<td>This way is related to chemical recycling and is used in plastic recovery techniques that break down polymers into monomers which in turn can be used in different refineries, etc. For example, it includes thermal degradation, pyrolysis and gasification of plastic: e.g. biofuel mentioned later.</td>
</tr>
</tbody>
</table>
problem, nowadays research is focused on recycling of plastic or Plastic Bag Waste material (PBW) into concrete (a building material) and on the improvement of concrete is considered.

One of the proper utilization of plastic waste with non-degradable property is its inclusion in concrete to diminish environmental pollution. In 2005, approximately 3,315 tons of solid waste had been generated per day from the Dhaka city corporation area, 4.15% of which was composed of plastic waste. The utilization of various waste polymers in concrete may diminish not only waste disposal problems but also economical expenses at the same time. Therefore, various efforts are used for inclusion of the recycled plastics in concrete or asphalt concrete. Hence, these attempts might help the construction industries as well as the plastic recycling industries [5]. Very few information is available regarding recycling of polyurethane formaldehyde (PUF) based polymer wastes and its usage as a component in concrete.

6.2.1. Types of Recycled Plastic Used in Manufacturing of Concrete

1. Virgin Polypropylene- These strands are slender fibers of 19 mm long in size.
2. Melting-processed Plastic- These strands are slender fiber of 28 mm long and used for manufacturing of drawing automobiles bumpers.
3. Automobile Shredded Plastic- These particles include plastics and some rubber in flake form of 19 mm maximum dimension.
4. Shredded Plastic- The flakes made by shredding mixed plastic in flake form of 25 mm maximum with planar dimension.

6.2.2. Preparation of Concrete

Plastic wastes were used as a substitute of the sand in variable percentage in order to enhance the mechanical properties of the concrete. The concrete composition was determined by Dreux Gorisse method [5].

Recycled plastic based Concrete was produced by mixing (all values in kg/m³) cement; 400, water; 190, gravel (3/8 grade); 276, gravel (8/15 grade); 1064. Here in this mixture, ratio of Sand:PBW varies as per the Content Plastic Bag Waste (CPBW) concrete grade like for CPBW10%, CPBW20%, CPBW30% and CPBW40%, ratio of Sand:PBW was 420.3:16.25, 373.6:32.5, 326.9:48.75 and 280.2: 65, respectively.

6.2.3. Specimen Preparation

Specimen preparation was done by the modified method of Ghernouti et al. [25] that is mentioned below;

1. Prior to the mixing of concrete, the vivid and circular moulds are prepared.
2. Every stage was preceded with the 20 seconds vibration of mould with the help of mobile stripe.
3. For every course, three vivid (70x70x280 mm) and three circular (160x320 mm) specimens were prepared by the same compositions.

4. After de-molding, specimens were deposited in water vat for about 28 days.
5. Lastly, its quantities were measured by various tests, such as
   • Freshness test
   • Hardness test
   • Compressive strength test
   • Flexural strength test
   • Ultrasonic pulse velocity test

The inclusion of plastic in concrete improves the property of concrete like the compressive strength decreases and its tensile strength and mechanical strength increases. There are also two basic advantages of using plastic waste, firstly it can solve the problem of disposal up to some level and secondly it diminishes the cost of production [27].

6.3. Biofuels Production Using Plastics

The concept of producing biofuels from recycled plastics by the industries is rising globally. Biofuel is an eco-friendly fuel which produces less pollution. It is basically produced by the contemporary biological process like anaerobic digestion.

For manufacturing biofuel, plastic material and pure hydrocarbons such as polyethylene and polypropylene are used so that fuel can burn easily. Avoidance of usage of too much of chlorine is appreciated as it may wear away the reactor and causes pollution to the environment.

6.3.1. Procedure

• Plastic wastes was shredded and heated in a chamber, where thermal degradation or pyrolysis takes place at the temperature of ~ 400°C. This step is known as feedstock recovery (Table 2).
• In the meantime, gases are taken out and used for the purpose of fueling the chamber.
• Then after, proper boiling is done, and the fuel is filtered by the process of distillation. Since the plastic is not burnt, there are no harmful toxins released into the environment. And all the gases and sludge released is utilized in the machine itself.

One gallon of fuel is recovered from 8.3 pounds of plastic. The whole process does not require much energy as the whole process utilizes energy from its own released gases. This is an outstanding process for recycling of synthetic plastics like polypropylene which is very difficult to recycle. In this way, 100% plastic is recycled without any deleterious effect of any kind [28].

CONCLUSION AND FUTURE PROSPECTS

Plastic recycling should be one of the major concerns, as pollution generated by plastics causes severe health problems and destroying the environment. Mainly the plastic monomers and various additive chemicals including plasticizers like DEHP, BPA, DINP (diisononyl phthalate), as well as flame retardants are causing harmful effects to our health.
Although plastic products supplies significant benefits now and in the future as well, on the other hand, the consumption of plastic is not considered to be sustainable and is the major cause of depletion of marine life. Hence, there must be various solutions taken out with combined action. There should be a role for every individual to use the plastic products appropriately and ensure its safe disposal, keeping recycling of plastic in mind. Use of biodegradable plastics in various sectors seems to be a good and sustainable approach that can be adapted to minimize this pollution. Industries should adopt green chemistry, and design their products in such a manner that they can be reused. Moreover, production companies should adapt all those features and relevant properties of their products that are capable of recycling.

There should be a proper collaboration between the government, the industries, and consumers. The industries should take care of their discard plastic material or maybe process the unwanted plastics into less harmful form before discarding away. Every industry should bear a mini burner or a chamber in order to degrade the plastic and should introduce recycling technology of plastic mentioned above. Laws and rules regarding plastic usage and safe plastic disposal should be enforced by the government. The plastic products that are extremely hazardous to health and the environment should be banned internationally. Awareness, regarding the harmful effects and proper disposal of plastics, to people should be provided through conducting seminars, workshops, street plays as well as advertisements on televisions, movie theatres, and holdings.

CONSENT FOR PUBLICATION

Not applicable.

FUNDING

Authors are grateful to Department of Science and Technology DST-SERB, ECRA scheme, Project no. ECR/2017/001001, for providing financial support.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

ACKNOWLEDGEMENTS

Authors are grateful to Integral University for providing necessary infrastructure.

REFERENCES

[22] http://dx.doi.org/10.1038/nrmicro3253 [PMID: 24736795]


[27] RaghateAtul M, Use of Plastic in a Concrete to improve its properties.