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# Bioplastics-Opportunities and Challenges

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**Bioplastics are plastics, which are derived from natural renewable resources and are biodegradable. They are of current interest in the field of polymeric materials to combat the drawbacks of conventional petroleum-based plastics. Plastic waste management is a critical issue for these petroleum-based non-biodegradable plastic articles, especially 'single-use-plastic' products. They create environmental pollution, and risk to humans as well as other living systems, and hence reached alarming anxiety across the globe towards environmental and health issues. Thus, an alternative to such plastics is essential for eliminating or at least minimizing these detrimental issues. In this milieu, bioplastics not only remove the non-renewability issue for petrochemicals but also minimize the pollution and carbon footprint problems of petroleum-plastics. However, these bioplastics, in general, suffer from processing difficulties and inferior mechanical performance compared to the corresponding petroleum-based plastics and hence demand more comprehensive research and awareness in the field. Fortunately, recent research showed that appropriate modifications of such bioplastics can eliminate most of their material-related shortcomings. But details of life cycle assessment analyses are required to prove their significance and environmental superiority over petroleum-based plastics. In this article, therefore, a general overview of bioplastics from basic concepts to future trends including significance, limitations, and conclusion is presented.**

**Keywords: Bioplastic, sustainable development, biodegradable polymers, 'single-use-plastic', application, market production, limitation.**

## Introduction

Sustainability is not a buzz-phrase, it is the essential requirement for this civilized society and hence considered as the 'order of the day'! Thus, nowadays all the developments in this society have to be sustainable, and the development of materialsis not an exception of that, as the materials are the backbone for developing the society. In fact, the importance of materials has been realized from ancient times and that is why a particular era was named after the most significant materials used in those periods of civilization, like the stone age, iron age, bronze age, etc. and now it is the age of polymers. More importantly, the advancement of materials in a particular era of a civilized society governed the status of that civilization. Furthermore, among different categories of materials, polymeric materials are considered the most advantageous, because of their easy processing, the lightweight character, favorable cost to performance ratio, versatility with respect to structure and property, and hence applications. Thus, in today's society, other categories of materials such as metals and ceramics are being replaced by polymeric materials for many applications. It is therefore noticed that these low-cost high-performing lightweight materials have been used recklessly (~3 kg/person/year for developing country to ~80 kg/person/year for the developed country) that created environmental pollution to an alarming state, especially in sewage and water bodies including oceans, where about 9 million tons of plastics are entered in each year. These plastic wastes caused land filling problems and created a risk to aqueous as well as terrestrial animals, as plastic/microplastic are found in the food chain as well as different animal bodies including humans. This is due to the fact that almost all polymers are produced commercially from non-renewable petroleum or fossil fuel resources (consummation increasing at high rate and estimated consumption is 20% of crude oil by 2050)[1], and they cause all sorts of environmental nuisance, health issues and ecological imbalances because of the non-biodegradability character of the resultant polymeric articles. The non-biodegradable plastics are disintegrated into small fragments when present in the environment (soil/water) for a long period of time, and these are ingested by smaller eukaryotes as food, which are taken by higher eukaryotes as their food, subsequently these microplastics are entire in food chain, and causing threatened situation for many species including higher animals[2]. Thus, these plastic articles are retained 'as they are' for long times in the environment and that is the reason for all such adverse and negative impacts. However, here it is pertinent to mention that this non-biodegradability of polymers was imparted during the initial development phase of such materials as, at that period other categories of used materials like metal-based articles were degraded fast due to corrosion and ceramic articles were broken easily due to their brittleness character. But nowadays this essential attribute of polymeric materials became a serious threat for some applications, especially for 'single-use-plastics'. Now, these single-use-plastic articles like poly-bags (plastic packets), poly-container (plastic jar/drum), poly-films (packing plastic wrapper), poly-commodity items (plastic bottles, caps, pipes, tubes, cutlery items, water packets, etc.) etc. are either banned or restricted for their uses by different countries, as otherwise, the society may face unrepairable damage. But this banning of plastics is found to be temporal in nature as it is extremely difficult to replace plastics by other categories of materials, rather reverse is true! In addition, although most of them can be recycled, reprocessed and reused, but the actual fact is not reflecting that strategy as most of such articles are thrown to the garbage or even 'here and there' causing environmental havoc. The report indicated that only less than 10% are recycled and about >78% are accumulated in landfills or in the natural environment, the rest 12% are incinerated (producing toxic gasses)[3]. It is pertinent to mention here that 4R protocol, i.e., Reduce, Repair, Recycle, and Reuse, is recommended worldwide to practice for any kind of plastic articles to minimize their waste, but unfortunately it is also not followed. Instead of reduced uses, people are using more than their required amount, repairable articles are almost never repaired, recycling is less than 10%, as already

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mentioned and hence reused is almost negligible! Under these circumstances, renewable resources modified biodegradable plastics (that is bioplastics) are happened to be the most appropriate alternative to overcome all the above shortcomings, and hence is the subject matter of this article.

Bioplastics are renewable resources-based plastics, which can be used as biodegradable plastics for different applications, especially in 'single-use-plastic' articles and biomedical uses. These articles are acceptable to the environment as they can be assimilated after their useful service life, and microbes can take them as their food with the production of $CO_2$, water and biomass. All these end products are utilized directly by plants and through plants to animals, where from the raw materials of bioplastics are obtained. This cyclic process initiates from plant/animal/microorganism and returns back to them through a cyclic process of renewable raw materials conversion to the production of desired plastic-based articles which are transformed to biomass, water and $CO_2$ upon biodegradation after their useful service life and the process can be continued endlessly (Fig. 1). Hence this development is a sustainable development, as it fulfills the demand of the present generation without compromising the needs of the future generation. These bioplastics are produced from different renewable resources, such as vegetable oils, polysaccharides like starch/xanthan/guar gum/locust bean gum/gum karaya/gum tragacanth/gum Arabic, cellulose like straw/wood/sawdust, carbohydrates like recycled food waste, etc. which are obtained from plants; while protein, lipid, fat, chitin, chitosan, gelatin, glutamine, poly(hydroxy-alkanoate)s, agar, etc. are obtained from animals/micro-organisms. These raw materials can be modified appropriately by using suitable conventional processes like similar kinds of polymers to produce bioplastics as biodegradable materials and can be used to reduce/eliminate the problems of petroleum-derived plastics. Through this approach, solid plastic waste that is suffocating this planet by polluting the environment can be minimized, eliminated, or even refreshed. Most importantly, this methodology follows the concept of the triple bottom line approach which concerns the balance of economy, ecology, and environment, and tents of Green Chemistry and is hence considered the most promising approach. A few examples of bioplastics are poly(lactic acid), polylactides, poly(hydroxy-alkanoate)s, and bio-based poly(butylene succinate), as well as plastics that are derived from starch, lignin, cellulose, chitosan, vegetable oils, carbohydrates, etc.[4]. According to a report, the total production of bioplastics was around 2.5 metric tons in 2021 and projected production in 2026 is around 7.5 metric tons, which reflects its market demands[5].

In this article, therefore, the author wishes to report an overview of bioplastics including their background, concept, significance, limitations, applications and conclusions with recommendations under the current scenario of polymeric materials.

## Background and basic concept

The bioplastics have started their journey from the day when life was created in this universe by the fantastic combination of

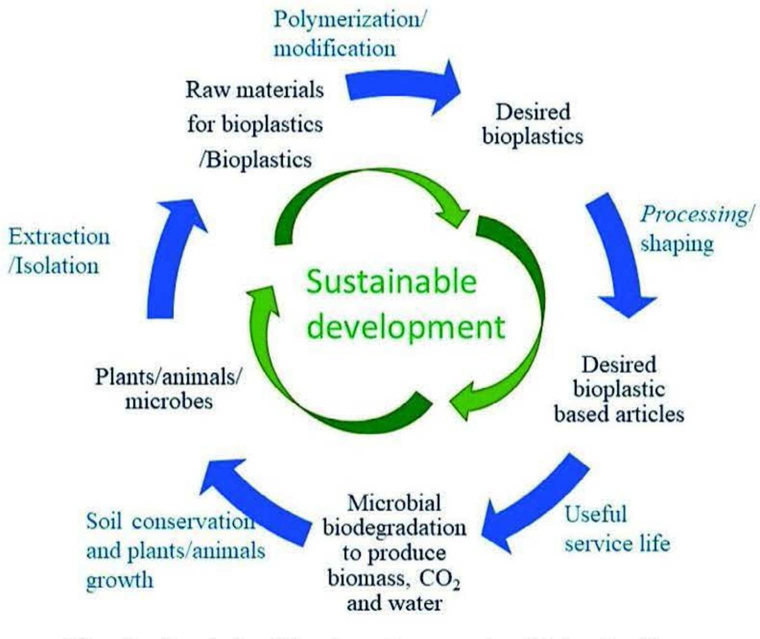


**Fig. 1.** Sustainable development of bioplastics.

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carbon, hydrogen, nitrogen, oxygen, etc.[6]. Polypeptides are part of animals, while cellulose and poly-saccharides are present in plants, and all of these are bioplastics. However, Galalith first produced bioplastic like casein from milk in 1897, while Maurice Lemoigne established poly(hydroxybutyrate) from bacterium *Bacillus megaterium* in 1926. On the other hand, Rilsan first introduced aliphatic polyamide as the industrial bioplastic in 1947, and polylactides, poly(hydroxy-alkanoate)s, etc. became well-known bioplastics since 1990[7].

Unlike petroleum-derived plastics, bioplastics are only obtained from natural renewable resources and modified to fit the applications with the desired biodegradability in the final products. These naturally renewable biomass-derived organic compounds/materials like starch, protein, cellulose, poly(hydroxy-alkanoate)s, aliphatic polyesters, etc. are transformed or modified through various processes to obtain the desired compostable bioplastic made products. These are ecologically advantageous and reduce pollution of natural ecosystems, hence shrinking the carbon footprint on the earth. Here it is pertinent to mention that biodegradable polymeric products are degraded by the combined action of mechanical (strain in the product), chemical (oxidation and hydrolysis during exposure) and biological (action of microbes) factors under open atmospheric conditions within three months to maximum one year, after their useful service life. On the other hand, petroleum-based non-biodegradable polymer-made products are required hundreds of years for their degradation and hence causing microplastic generation and environmental pollution. Bio-degradable materials are compostable, that is, they can be degraded by microorganisms present in the open atmosphere, into nutrient-rich biomass within the stipulated time which is not more than 12 months and should not leave behind any toxins or residue. It is also necessary to know that a few compostable bioplastics required elevated temperatures for their decomposition and such conditions must be provided for their biodegradation.

However, bioplastics also include the non-biodegradable plastics that are obtained from biobased origin like bio-polyethylene, bio-poly(ethylene terephthalate), etc. and bio-degradable plastics like poly(ε-caprolactone), petroleum aliphatic polyesters, etc., in addition, featuring both bio-degradability and biobased origin like polylactides, poly(hydroxyalkanoate)s, etc. by a few countries. But as non-biodegradable plastics and petroleum-derived plastics cause serious environmental pollution and generate a carbon footprint on the earth, so in this article, biobased biodegradable plastics are only considered bioplastics.

## Significance

Biobased biodegradable plastics have a number of great significances under the present scenario of polymeric materials in varieties of applications[8]. These significances are summarized in this subsection, as follows.

i. The raw materials are obtained from natural resources like microorganisms, plants and animals, hence there is no scarcity of raw materials, as the resources are naturally renewable and sustainable.

ii. More plants can be grown in agriculture or forest, both of which are beneficial towards the refreshment of environment and economic points of view.

iii. The approach for obtaining bioplastics from their raw materials is simple and required less energy, and hence mass production is easy.

iv. Bioplastics produced significantly lower greenhouse gas and carbon footprint than the corresponding conventional petroleum-based plastics over their complete lifecycle.

v. They are biodegradable under open atmospheric conditions and maintain carbon neutrality as $CO_2$ production during biodegradation is equal to $CO_2$ absorption by the plants during the generation of the raw materials.

vi. The approach is environmentally friendly and maintains the concept of the triple bottom line approach, i.e., making a balance of economy, ecology and environment.

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vii. The overall cost of bioplastic is relatively lower in most cases than the petroleum-based plastics, as the cost of petroleum is increasing day by day, and also crude oil reserves are shrinking.

viii. The development of bioplastics from natural products is sustainable, as the raw material to product cycle can be continued endlessly.

ix. Bioplastics are much safer than conventional petroleum-plastics, as bioplasticsare compostable under open atmospheric conditions, and marine-degradable, that is even in the ocean, they serve as foods for fish or bacteria and have no adverse toxic effects or residue.

x. They can fulfill the requirements of various biomedical applications as they are not only biodegradable, but they are also biocompatible, even some are edible[9].

Therefore, bioplastics are considered naturally gifted plastics to service our demands. The common merits of bioplastics and demerits of conventional petroleum-based plastics are tabulated in Table 1.

**Table 1.** Merits and demerits of bioplastics and petroleum-plastics

| Merit of Bioplastics | Demerit of Petroleum-plastics |
|---|---|
| Renewable natural resources derived | Non-renewable fossil fuel derived |
| Biodegradable/compostable | Non-biodegradable/non-compostable |
| Do not produce microplastic | Produced microplastic in the environment |
| Non-toxic and environmentally benign | Environmentally pollutant |
| Carbon neutral product, no carbon footprint | Carbon positive, create carbon foot print on earth |
| Sustainable approach, endless cyclic process | Non-sustainable, non-cyclic process |
| Follow triple bottom line approach | Do not follow the triple bottom line concept |
| Follow maximum tents of green chemistry | May not follow any tents of green chemistry |
| Mostly safe to use and handle | Not fully safe |

**Production processes**

Bioplastics are generally produced by the conventional polymerization process like petroleum-based plastics from their corresponding monomers or raw materials. But some of them are also obtained directly from nature either from plants, animals or microorganisms like bacteria, fungi, algae, etc. A number of poly(hydroxyalkanoate)s like poly(3-hydroxybutyrate), poly(3-hyroxyvalerate), poly(4-hydroxybutyrate), poly(3-hydroxyhexanoate), etc. are directly obtained from microorganisms[10]. But polysaccharides and cellulose are obtained from plants, though bacterial cellulose is produced by specific bacteria.

Thus, bioplastics are generally produced either by chemical processes in the laboratory or by nature through microorganisms, plants, and animals. However, to obtain the desired articles the bioplastics numbers of other minor components like starch, chitosan, polysaccharides, etc. need plasticizers like glycerol, sorbitol, etc. along with other additives during processing. As an example, poly(3-hydroxybutyrate) is produced by a two-step process in nature. In the first step, natural photosynthesis converts $CO_2$ and water in the presence of sunlight to carbohydrates (equation 1), while in the second step, these organic substrates are converted into poly(3-hydroxybutyrate) by the microbial biochemical conversion process (equation 2).

$$CO_2 + H_2O = (CH_2O)_n + O_2 \quad (1)$$

$$(CH_2O)_n + \text{biochemical process} =$$
$$H\text{-}(O\text{-}CH(CH_3)CH_2C(O)=O)_n\text{-}, \text{ poly(3-hydroxybutyrate)} \quad (2)$$

However, researchers showed that this bioplastic can also be produced in the laboratory using an artificial photosynthetic process. Interestingly, the researchers claimed that the overall energy efficiency of the process is ranged from 2.9 to 7.1, and the average efficiency for the production of carbohydrate in this process is 5%, which is much higher than the conventional photosynthesis of plants (<1%) or even microalgae (2-3%). Furthermore, the yield of poly(3-hydroxy-butyrate) production per feed of $H_2$ is enhanced by 475%[11].

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The global production capacities of bioplastics as per the latest market data of 'European Bioplastics' as done by the nova-Institute is represented in Fig. 2[5].

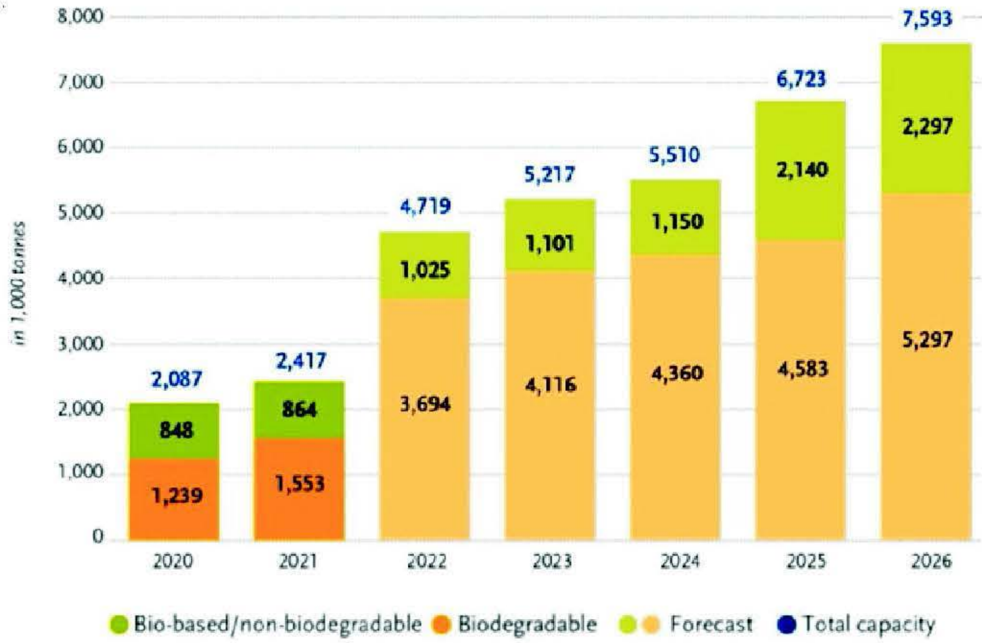


**Fig. 2.** Global production capacities of bioplastics (Courtesy: European Bioplastics, Copyright@nova-Institute).

## Limitations

Although bioplastics enjoy several advantages, researchers across the world have also shown that bioplastics may not be the silver bullet to all the issues in plastic waste. They claimed that the production of bioplastics resulted in more pollutants indirectly as the crops/animals/microorganisms need some toxic chemicals such as fertilizers, pesticides, herbicides, hormones, micronutrients, etc. for their growth and high yield. From such resources, only raw materials are obtained for the production of bioplastics. Further, some other chemicals are also used in the processing of bioplastics during the manufacturing of articles. As an example, the plasticizer is essential from pro-

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cessing of starch. Most importantly, a considerable area of land needs to be used to produce raw materials for bioplastics and this also contributed more towards ozone depletion, as well as some cases create conflict between food and non-food applications. Even some people argued that there may have a food crisis with the increasing production of bioplastics, as demand is huge. So, it is necessary to perform more research on bioplastics to address all such issues!

The biodegradability of a few bioplastics does not happen under open atmospheric conditions, and they need some special conditions for their biodegradation. Like petroleum-based plastics, bioplastics also possess a high amount of hydrogen in their structures and may catch fire easily and hence littering may also happen due to the unawareness of common people, which generates a lot of toxic gases/chemicals to the environment. Issues related to recycling plastics like contamination, segregation, identifications, etc. be remained true for bioplastics too.

## Applications

In recenttimes bioplastics are becoming the most popular plastics as they can find many applications without creating as such any solid waste disposal problems as well as do not consume fossil fuel, in general. Bioplastics are mostly used in single-use-disposable articles including packaging for food and other items, containers for commodity usages, straws for soft drinks, caps, bags, cups, trays, bowls, vegetable wrapping foil and bottles for common uses, coatings for phones and DVDs, etc. (Fig. 3). However, the applications of bioplastics now cover almost all areas of uses of polymers from packaging to biomedical including cutlery, automobile components, agriculture, horticulture, consumer electronics, hydrogels as super absorbent, heavy metal ions and dyes remover, consumer goods and household appliances, building construction, coatings, adhesives, etc.[12–15]. It is interesting to know that bioplastic obtained from the milk protein casein is used as a biodegradable and edible food wrapper, which is 500 times better

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for keeping food fresh than the conventional plastic packaging film. Furthermore, specially designed bioplastic-made food packaging materials not only protect them from mechanical, physical, and chemical attacks but also protect them from microbial attacks[16]. In addition, because of their significant advantages, they are also used in non-disposable multipurpose products like carpets, piping, casings, 3D printing items, car components, etc. As the bioplastics are biodegradable and many are biocompatible too and hence, they can find applications in the biomedical field from the scaffold to suture including lenses, bone plates and skin substitutes. The estimated global bioplastic market is exponentially growing, and about $44 billion is estimated for consumption in 2022.

These bioplastics are commonly used in almost all kinds of packaging including flexible and rigid; varieties of biomedical applications including regenerative medicine and controlled drug delivery systems; electrical and electronic industries including optoelectronics, circuit boards and data storage; consumer market including serving of food and soft drink; automobile and aerospace industries including lightweight vehicle components and paintings; agriculture and horticulture including seed storage, mulching, nursing packets, super-absorbents, agrochemicals carrier and greenhouse; building and construction including flooring, roof, admixtures, interior decoration and 3D printing; paints and surface coatings including decorative, architectural, protective and industrial; and many others.

In addition, modified bioplastics like biocomposites/nano-composites with improved performance without deteriorating the advantageous properties of original bioplastics found numerous advanced applications in smart packaging, building construction, electrical and electronic, automobile and aerospace, etc. applications. For example, the items used in building construction include fencing, railing, framing, common and insulating wall, door, window frames, flooring, ceiling panels, decorative panels, etc., which are manufactured from such green composites[17]. Besides these, biocompatible such bioplastics have also been used in different biomedical applications including tissue engineering or regenerative medicine, controlled drug delivery system, wound healing materials, fibrous and porous scaffolds, orthopedic devices, etc.

The importance of bioplastics, particularly their nano-composites in the field of food packaging, including active and intelligent packaging has increased manyfold because of their environmentally friendly and biodegradability attributes. These smart packaging materials not only provide the protection, preservation and marketability of food, but they also function to improve food quality, extend food shelf life, protect food products from spoilage and damage by environmental factors including the attack of microbes, insects, oxygen, moisture, sunlight, heat energy, fouling smells, dust, dirt, etc.[18]. Interestingly, they may also provide authentication and anti-counterfeiting ability to the food products. Such packaging materials should have smart attributes like antimicrobial, antioxidant, microwave resistance, UV-resistance, thermostable, selective barrier property, biochemical sensing, hydrophobicity, desiccant, self-cleaning, self-healing, printability, anti-


**Fig. 3.** Common applications of bioplastics in everyday life (Courtesy: European Bioplastics).

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counterfeiting, etc. In general, bioplastics like starch, chitosan, protein, cellulose, gelatin, polyester, poly(lactic acid), polylactides, etc. have been utilized for these purposes.

## Conclusion and recommendations

In general, bioplastics result in reduced $CO_2$ emissions compared to petroleum alternatives, and large production of bioplastics would strongly influence the global bioeconomy and most importantly contribute to the prevention of deforestation and soil erosion, which adversely affect water supplies and climate changes, across the globe. Thus, bioplastics are more environmentally friendly than petroleum-based plastics. However, it is important that all the aspects of their life cycle assessment from raw materials to after disposal towards energy, water, land, materials involved, disposal products, etc. are to be analyzed to properly understand the environmental and health impacts; to authentical the claims. Further, adverse impacts of bioplastic productions, especially secondary pollution generation during cultivation, poor performance, processing difficulties and conflict between food and non-food consumption need to be addressed before their widespread applications. However, greener and greener varieties and more efficient production processes for bioplastics are coming out from the active participation of dedicated researchers across the globe and help to minimize or even eliminate plastic pollution and reduce the carbon footprint in this universe. As an example, the fabrication of composites/nanocomposites using bioplastic as the matrix with suitable reinforcing agents/ nanomaterials improves the performance significantly. Further, it is expected that the governments of different countries across the globe should work together towards a pollution-free environment, zero-emission economy, maximized the reservation of fossil resources and most importantly focused on the sustainability of all sorts of developments.

Above all, the author personally feels that just replacing one kind of plastic with another may not be able to solve the plastic waste issues. The author suggests that all of the users need to change their mindset of not throwing them 'where and there', as well as keep them in the designated garbage bins after segregation for their recycling and reuse. Further, one should keep in mind that 4R protocol should be followed for the use of all sorts of plastics. Last but not the least, a combined heartfelt effort of scientists, engineers, politicians, policy-makers, producers, customers and common people can only transform back this 'plastic polluted planet' into a 'blue planet', again.

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Dr. Karak has credited two granted and three more filed India patents. He has executed 12 sponsored research and five consultancy projects. Prof. Karak guided 22 Ph.D. scholars, seven post-doctoral fellows and 42 MSc/MTech students. His fields of research interest are mainly based on biobased high performance hyperbranched polymers, nanomaterials and their nanocomposites as sustainable advanced multifaceted materials. Prof. Karak has been credited with nine national awards including visitor award by 'The president of India', and nine international recognitions (including listed among top world scientists, and top 2% scientists from India).

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