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(Review Article)

Bioplastic for future: A review then and now

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Abstract

Petrochemical based plastics have been widely used as packaging materials, as they have good barrier properties, stiffness, tensile strength & tear strength. Although in great demand plastics have many disadvantages like very low water vapour transmission rate, non- biodegradability etc. which further causes environmental pollution. Keeping in mind about the pollution and harm caused to the nature, newer concepts about the use of bio-plastics came into force. Bio-plastics are produced from the biological sources such as potato, potato peels, corn, sugarcane, wheat, rice, banana peels etc. These plastics are environment friendly & biodegradable, and are safer option than the petroleum-based plastics. These biodegradable plastics break down into carbon dioxide, water & inorganic compounds and degrade completely. The time-line, sources and other important details about the bio-plastics have been presented in this review paper.

Keywords: Bioplastic; Biodegradable; Renewable; Eco-friendly; Plasticizers

1. Introduction

Due to their versatile, inexpensive, lightweight and excellent thermal properties; petrochemical based plastics such as Poly Ethyl Terepthalate (PET), Poly Butylene Terepthalate (PBT), Polypropylene (PP), Polystyrene (PS), Polyvinyl Chloride (PVC) are widely used in our day-to-day life [1,2,3].

Plastics are used to make products such as water bottles, coffee cups, forks, knives, plastic bags to carry groceries, etc. Petrochemical based plastics are not eco-friendly because of their high content of carbon footprint [4]. Properties like cheapness, durability and lightness make plastics far more useful than the metals, wood, papers etc. They are useful in almost all the industrial fields. Excessive use of plastics has caused severe impacts to the environment, and it is estimated that about 34 million tons of plastics are produced per year by humans. Out of that only 7% is recycled and the remaining 93% is dumped into the landfills, oceans and seas [5]. In 2015, more than 300 million tons of plastic was used in the world [6]. The incineration or burning of plastic liberates various toxic emissions such as carbon dioxide and methane, these greenhouse gases affect the climate worldwide [7]. Petrochemical based products cause many problems like accumulation of waste in land area, in natural habitats like sea, oceans etc [8]. Due to plastic pollution, humans are also suffering from the disturbance of thyroid hormone levels [9]. Due to the use of chemical additives during the production of plastic, they are toxic and carcinogenic. Efforts to reduce plastic consumption has occurred in many areas which have further promoted the recycling of plastic. Additives such as phthalate plasticizers and brominated flame retardants are used in the production of plastics [10]. Plasticizers are substances that are added to plastics to increase their flexibility, durability, transparency and longevity. Therefore, now scientists are looking for other alternative options.

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2. Timeline of plastics

2.1. Parkesine: In 1862, Alexander Parkes produced first man-made plastic called as Parkesine. It was a biological material derived from cellulose that once prepared and molded, it maintained its shape as it cooled down.

2.2. Celluloid: In 1868, John Wesley Hyatt invented celluloid (resultant from cellulose and alcoholised camphor) as an alternative for the ivory in billiard balls. But the flexible film he developed was not strong enough to be used as an alternative to billiard balls. The newly formed substance i.e., celluloid was easy to be modeled with heat and pressure and it became famous as it was the 1st flexible photographic film used for still photography and motion pictures [11].

2.3. Bakelite – Formaldehyde Resins: Formaldehyde was the next foundation that evolved in the technology of plastics after cellulose nitrate. In 1897, many struggles were done to produce white chalkboards directed to casein (milk protein mixed with formaldehyde) plastics. Galalith and Erinoid were the two examples of synthetic plastic materials of that time. In 1899, Arthur Smith established British Patent for "phenol formaldehyde resins" and in 1907, Leo Hendrik Backeland improved phenol formaldehyde resin and invented 1st synthetic resin, called as Bakelite [12].

2.4. Polyvinyl chloride (PVC): French physicist Victor Regnault discovered PVC in 1912.

2.5. Cellophane: Edwin Brandenberger used viscose to form cellophane in 1913. It was his idea that created transparent packaging for food items.

Polymethyl methylacrylate (PMMA): Barker and Skinner created PMMA. In 1924 it was sold by Rohm, under the name of Plexiglas.

2.6. Polyethylene (PE): It was discovered by E.W. Fawcett and R.O. Gibson in 1933. It is the most commonly used plastic in the world.

2.7. Polyurethane (PUR): In 1937, Dr. Otto Bayer developed PUR.

2.8. Polystyrene (PS): Ray Mclntire developed Polystyrene in 1944 by chance when he was working on flexible rubber.

2.9. Polypropylene (PP): Working for Montedison, Giulio Natta (1963 Nobel Prize with Karl Ziegler) discovered a catalyst what is dubbed as the "Ziegler-Natta". This catalyst was able to produce polypropylene with high mechanical resistance, inert to chemical aggression, and able to withstand temperatures above 100° C [13].

3. Bioplastic and its sources

Bioplastics are biodegradable plastics made from the renewable sources [4]. Renewable sources such as potato starch, corn starch, fibres obtained from pineapple, jute, hemp, banana stems [14,15] cassava [16], newspaper pulp [17], waste paper [18], Prosopis juliflora [19], citrus waste [20], cyanobacteria [21], Pseudomonas putida [22,23], Bacillus sp. [24] Employment of new techniques for manufacturing of bioplastics that promote sustainable solution and reduce the plastic waste has been greatly encouraged in recent years [25]. Important source of starch is corn but now-a-days, starches from potato, wheat, rice, barley, oat etc. are also being used [26,27,28]. Bio-based plastics can be degraded by algae, fungi and bacteria [29,30,31]. These plastics are novel materials of the 21st century and have great importance [32]. These are currently used as packaging materials, but in future these will be used in forming various products such as electronics and vehicle parts [33]. Figure 1 represents classification of bioplastics [34].

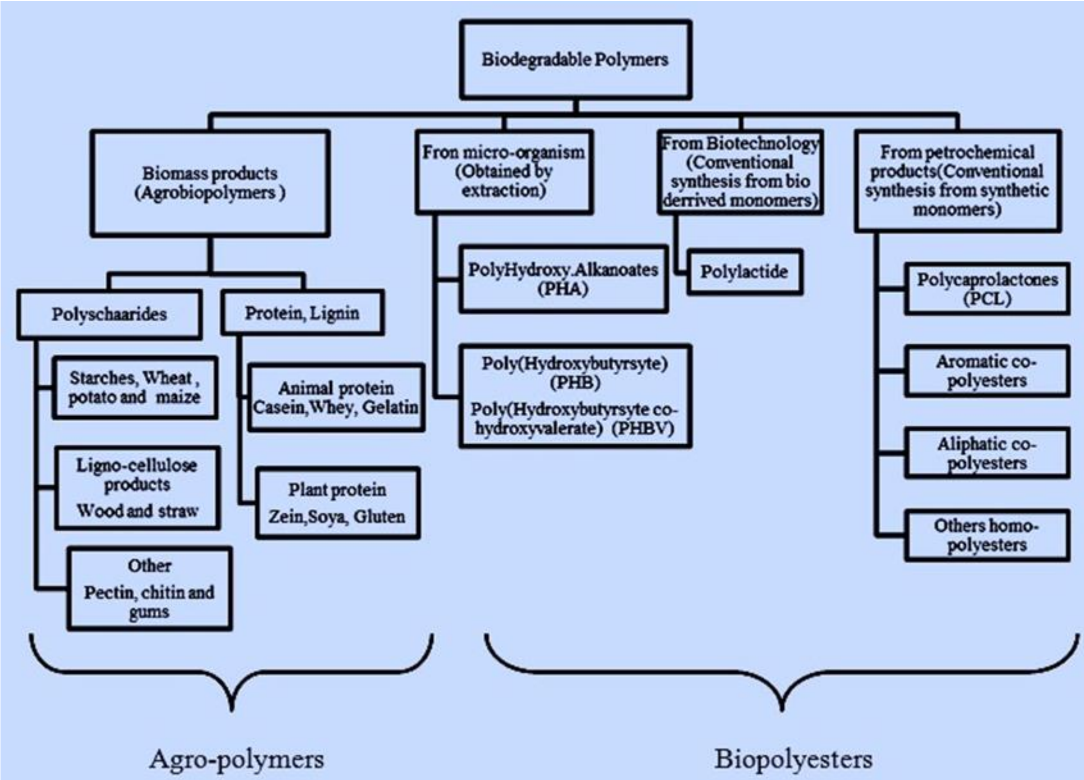

Figure 1 Bioplastic and it's sources

4. Classification of bioplastic

Plastics can be manufactured from bio-based or fossil based materials and can be biodegradable or non-biodegradable. While bioplastics are only made from renewable materials, biodegradable plastics are made from fossil based or are made with mixture of renewable and fossil-based materials. Figure 2 represents classification of bioplastic. Three types of Bioplastics are as follows:-

- Biodegradable and Bio-based.
- Biodegradable and fossil-based.
- Non-biodegradable and petroleum based called as plastics [35].

Table 1 Types of bioplastics

	Bio based	**Petroleum based**	**Reference**
Biodegradable	Bioplastics e.g.:- Starch, Cellulose, Polyhydroxy alkanoates, Polylactic acid	Bioplastics e.g.:- Polycaprolactone, Polybutylene succinate, Polybutylene adipate Terephthalate	[36,37,38,39]
Non-biodegradable	Bioplastics e.g.:- Bio-polyethylene, Bio-polypropylene	Conventional Plastics e.g.:- PVC, Polypropylene, Polyethylene	[37,38,40]

Both cellulose and starch are not plastic but can be transformed into plastics by polymer technology or fermentation [41] by using various techniques like casting [42], mixing, extrusion [43], injection molding, etc. [44] Bio-ethylene and Bio-propylene have the prefix "bio", indicating that they are made from renewable materials, and have identical properties to that of petrochemical based plastics [45]. Figure: 2 represents classification of bioplastics [46].

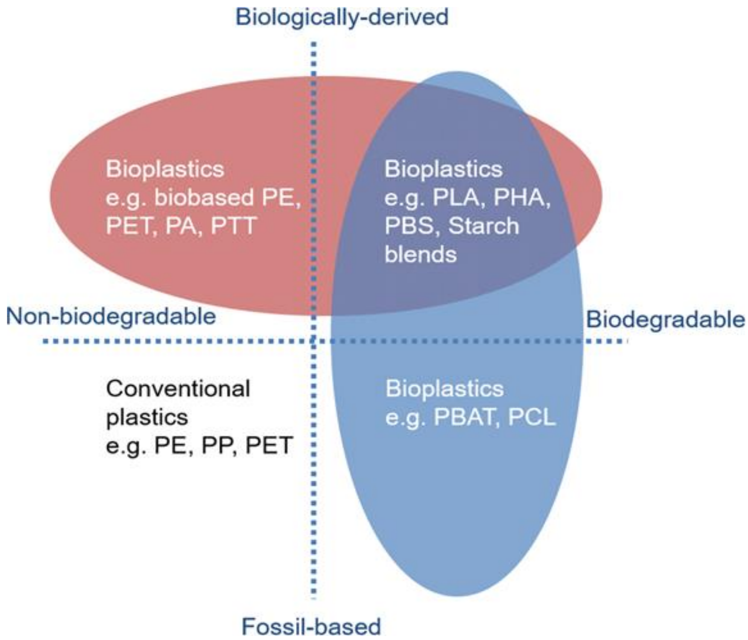

Figure 2 Classification of bioplastic

5. Bioplastic production

5.1. Cellulose

Cellulose occurs as natural polymer and consists of glucose monomer units that are linked together by Glycosidic linkages. Cellulose is extracted from its crystalline state in microfibrils, it is soluble in solvent such as N-methylmorpholine N-oxide. However, it is quite difficult to use for packaging because of its certain properties like poor solubility, hydrophilic nature and highly crystalline structure. Poor moisture barrier characteristic is present because of alternating hydroxyl side chains along with cellulose. Due to highly crystalline structure, the resulting packaging material is brittle with poor flexibility and tensile strength [47]. As a result, now research has been focused on cellulose derivatives for the purpose of packaging.

5.2. Cellulose derivatives

They are polysaccharide consisting of linear chains linked together by beta (1-4) Glucosidic units. Following cellulose derivatives are used for edible films/coating: Hydroxypropyl cellulose, Hydroxypropyl methylcellulose, Carboxymethylcellulose and Methylcellulose. They show thermo-gelation i.e., when suspensions are heated, they form gel and in return gain their original consistency when cooled [48]. Such films are poor water barriers because of hydrophilic nature of molecules, and show poor mechanical properties [49].

One method for improving the quality of moisture barrier can be performed i.e., by addition of hydrophobic compounds such as fatty acids into cellulose matrix to develop the films [50].

5.3. Starch

All the green plants produce starch which is white in color, granular, organic chemical, soft, tasteless powder, and insoluble in cold water, alcohol or other solvents. Basic formula of starch is $(C_6H_{10}O_5)_n$ [51]. It is polysaccharide consisting of amylose and amylopectin linked together by glycosidic bond [52]. Commercially, starch and its derivatives are produced from various raw materials such as, potato & its peel, corn, wheat, pea etc. Beyond food industry, it has many applications like, in pharmaceutical sector it is used as binding agent, it has its application in the textile industry, in the paper and board sector [53]. Because of its natural abundance, low cost as well as major carbohydrate content it is considered useful for preparing biodegradable plastics [54].

Source	Amylose (in %)	Amylopectin (in %)
Banana	20.5	79.5
Potato	17.8	82.2
Corn	28	72
Rice	35	65
Wheat	20	80

In the above table the concentration of amylose and amylopectin present in the various plant products has been mentioned. It is observed that when the concentration of amylose is high the tensile properties of the bioplastic rises [56]. It has been also observed that the biodegradation tendency increases because the amylose molecules loose water and the plasticizer property increases due to the presence of the amylopectin molecules [57].

5.4. Starch based plastics

Starch based plastics are safer option than the petroleum based, because they are produced from the natural resources such as corn, potato etc., and are easily degraded. Many countries like Europe have started to implement the idea of starch-based plastics. After degradation, the remaining waste part will be reused and recycled for future use. By using starch-based plastic, we can protect our environment from hazardous chemicals. Commercially 50% of bioplastics are prepared from the various starches [3,58].

5.5. Poly-Beta-Hydroxyalkanoates (PHB)

PHB, degrades under the presence of micro-organism that comes in contact with the polymer, secrete enzymes and breakdown into smaller parts. Properties of PHB are (1) 100% resistance to water (2) 100% biodegradability (3) ability to process thermoplastic [1].

5.6. Polylactide Acid (PLA) Plastics

PLA is the most attractive material from the packaging point of view, because of its excellent biocompatibility, biodegradable and processing ability. It is processed by injection molding, blow molding, thermoforming & extrusion. It is composed of lactic acid (2-hydroxy propionic acid) and contains methyl group on alpha C atoms [59]. Commercially, it was the first biobased polymer on a large scale, which could be shaped into various objects, films [60]. It has replaced HDPE (High density polyethylene), LDPE (Low density polyethylene), PET (Polyethylene terephthalate) & PS (Polystyrene) as packaging material.

5.7. Chitin/Chitosan

It is the second most abundant natural polymer occurring in the nature after cellulose [61]. Chitosan is obtained from Chitin. Chitosan is prepared by deacetylation process in the presence of alkali and it is an important waste of fishery industry [62]. It forms films without any addition of additives, consists of excellent mechanical and microbial properties against bacteria, molds, yeasts. It also exhibits good oxygen & carbon dioxide permeability, but major drawback is that it has poor solubility in neutral solutions. To obtain a soluble product, the required degree of deacetylation must be 80-85% [63]. It forms transparent films which improves the quality as well as storage life of the products [64].

6. Different kinds of plasticizers used for the production of bioplastic:

Plasticizers are organic molecules, that are added to polymers, to reduce brittleness, reduce crystallinity; improve durability, toughness; lowering melting temperatures [65]. These reduce polymer-polymer contact hence the rigidity of the 3D structures is also reduced, allowing deformation without rupture [6]. In the production of bioplastic, different kind of plasticizers are used that includes polyols such as glycol, glycerol, sorbitol, fructose, sucrose, and mannose, fatty acids such as palmitate or myristate. Out of these, glycerol is most widely studied & used plasticizer because of its non-toxicity, low cost and high boiling point(292°C) properties [66].

7. Bioplastic from uneatable substances

In today's world where food is a scare resource, we can produce bioplastics from non-edible portions too. Things such as orange peel, pomegranate peel, banana peel, potato peel are used for the production of bioplastic. In the latest trend bioplastic films from polysaccharide residue feedstock is in great demand. Cellulose, hemicelluloses, starch, pectin make these lignocellulosic feedstocks useful for the production of bioplastic.

7.1.1. Pomegranate peel

Has rich source of bioactive compounds [67]. It consists of lignin-5.7% and hemicelluloses-10.8%, cellulose-26.2% and pectin-27%. On acid hydrolysis, the polysaccharides present in peel are converted into monosaccharides which can break down into cellulose, hemicelluloses and lignin components. These components further are used to develop bioplastic [25].

7.1.2. Orange peel

The peel contains carbohydrates which can be used for the production of biomolecules. Careless discharge of unprocessed peels causes many environmental problems [25]. Therefore, it is recommended to collect the waste and convert it into bioplastics.

8. Life cycle of bioplastic

Figure 3 shows life cycle of bioplastic

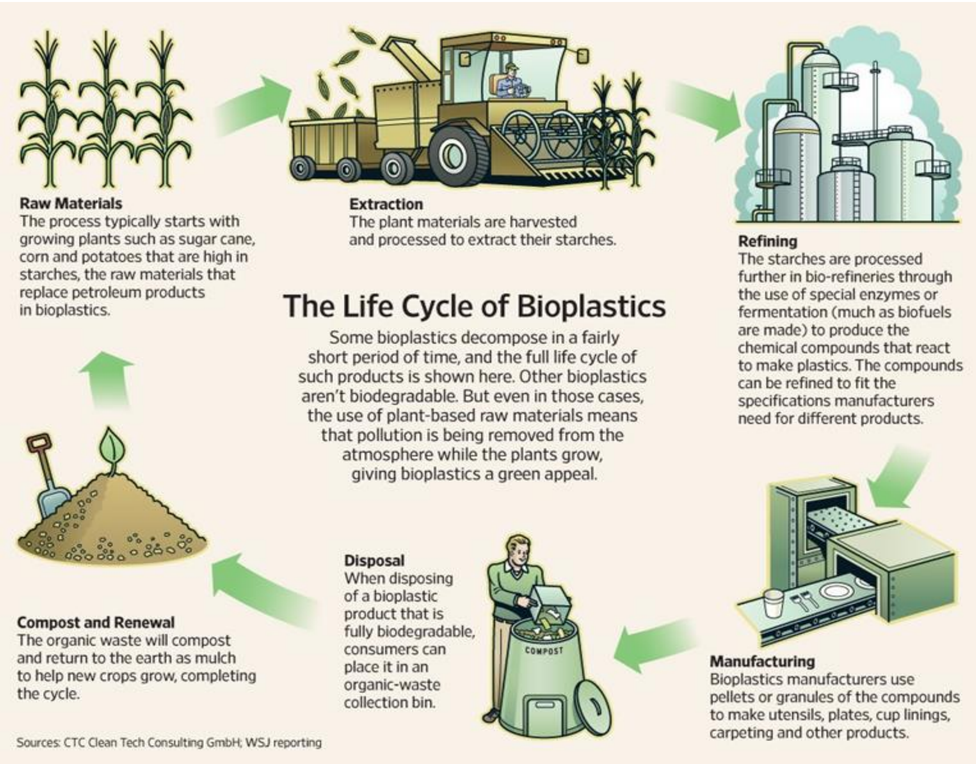

Figure 3 Lifecycle of bioplastic (http://www.sciepub.com/reference/84613)

9. Bioplastic market

Figure 4 represents the lifecycle of bioplastic[69]. This figure depicts how bioplastic production and degradation goes on simultaneously. Many researchers have developed tools to assist in decision making about the selection of plastic. One of them is the "Plastic spectrum" [68,69].

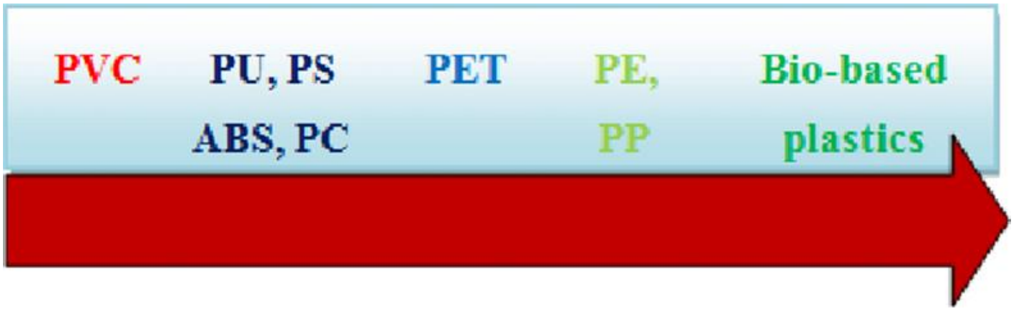

Figure 4 Plastic spectrum

In this spectrum, Bio-based bioplastics indicate that they are more preferable, as they are produced from renewable sources, they are biodegradable and compostable [70]. Bioplastic containers and packaging films and are more appropriate option because these products have a relative short service life and easily end up in landfills. Biodegradable bioplastics have many applications in the biomedical field like in drug delivery carriers, tissue engineering scaffolds and in making bone plates and screws [68,71]. McDonald in America already started to make biodegradable containers for their fast-food service and delivery. Many companies like Dupont, Nike, Danone, Bayer, Dow Cargill etc. are producing biodegradable packaging materials [72].

About 20%-25% per year global bioplastic market is growing. In 2020, approximately 10%-15% bioplastics of the total plastics market increased and its share went up to 25%-30%. The bioplastic market reached up to 1 billion US$ in 2007 and 10 billion in 2020. Many companies are investing in bioplastic market which is a good indication for our environment.

9.1. Advantages and Disadvantages of bioplastic

Plastic is the main pollutant in the environment which is used on the daily basis [73]. Therefore, to decrease environmental pollution, we should switch to bioplastic rather than the petrochemical based products. By doing this, many environmental issues can be solved [74]. Bioplastics have unique characteristics such as eco-friendly, compostable, biodegradable as well as energy efficient [75].

Future of biodegradable plastics shows great potential. Here are some of the advantages of the bioplastics:

- Reduced carbon foot print [33,75,76].
- Energy efficiency [33,75,76].
- Partly based on natural feedstock [33,75,77].
- Eco-safety [78].

However, problems might occur with the use of bioplastics. Here are some of the disadvantages of bioplastics:

- High cost [77,79].
- Brittleness [37,80].
- Thermal instability [33,80].
- Various recycling problems [77].

9.2. Applications

Bioplastics are used as packaging material for both short shelf-life products like vegetables and fresh fruits, and long shelf-life products, like potato chips and pasta [80].

Applications of bioplastic based on the materials from which they are prepared are as follows-

- Cellulose – packaging, disposal household, electronic devices [81,82,83,85].
- Starch – food packaging, agriculture foils, textiles and construction [83,84,85,86].
- PLA – films, food packaging [88,89].
- PHA – food packaging [75,87,88].

Table 2 Current applications of bioplastic [80] based on biopolymer are listed as follows-

Packaging	Biopolymer	Company
Starch based		
Milk Chocolates	Cornstarch trays	Cadbury Schwepps
Organic Tomatoes	Corn-based packaging	Iper Supermarkets (Italy) Coop Italia
Cellulose based		
Kiwi	Bio-based trays wrapped	Wal-Mart
Organic Pasta	Cellulose based packaging	Birkel
Sweets	Metalized cellulose film	Qualitystreet, Thomton
Potato chips	Metalized cellulose film	Boulder Canyon
PLA		
Beverages	PLA cups	Mosburger (Japan)
Yogurt	PLA jars	Stonyfield (Danone)
Bread	Paper bags with PLA Window	Delhaize (Retailer)
Fresh salads	PLA bowls	McDonald's

10. Conclusion

This review has covered classification, sources, life cycle, advantages, disadvantages and applications of bioplastic. Utilization of renewable resources for the production of bioplastics rather than Petro-chemical ones are more beneficial for our environment as well as for other lives on the earth. Since Petro-chemical based plastics have many disadvantages i.e., they cause environment pollution, from the manufacturing to recycling they produce toxic gases, etc. Moreover, eating food from plastic containers may cause cancer as it is widely used in packaging. We should switch to bioplastic, as it is renewable, bio-degradable, eco-friendly and sustainable option in comparison to Petro-chemical plastics. Hence, the research and development in the field of bioplastics is much needed & should been encouraged.

Compliance with ethical standards

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Disclosure of conflict of interest

Hereby I declare there is no author conflict.

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