

**Review****Bioplastics advances and their role in the management of plastic pollution**

Nidhi Sharma, Salman Akhtar, Mohammad Kalim Ahmad Khan*

Department of Bioengineering, Integral University, Lucknow-226026, Uttar Pradesh, India

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ABSTRACT

Bioplastics are a type of plastic which are natural and renewable. These are made from raw materials such as sugarcane, corn starch, wood, wastepaper, fats, bacteria, algae. Bioplastics are eco-friendly as they can decompose back into carbon dioxide. Reduction of greenhouse gases through reduced carbon footprint occurs by the usage of renewable resources. In contrast to petrochemical plastics, bioplastics production is around 80% which is less than carbon dioxide. Bioplastics have been used as attractive materials for biomedical applications due to their physicochemical, biological, and degradation properties. Due to the widespread use of bioplastics, they are essential materials. Biowaste products should be designed correctly for the benefit of the environment and the utilization of these products. In composting and an anaerobic digestion infrastructure, a part of biorefineries, technology is beneficial. Enhanced production of plastics across the globe has been added more waste pollution. Recycling plastic waste is one solution to the increased plastic pollution, but it alone is not the only one. Decreased usage of fossil-based plastics is vital in the aspect of sustainability. This study aims to review the recent advances of bioplastics and their possible implications for controlling and managing plastic pollution.

Introduction

The plastics are typically organic polymers of high molecular mass, but they often contain other substances. They are usually synthetic, most derived from petrochemicals, but many are partially natural. The dumping of waste material like plastic, polythene bags, bottles, and other housewares generated in vast quantities causes environmental hazards. Discharge of plastics in water bodies can lead to severe water contamination affecting the food chain of marine life, thereby causing long-term carcinogenic effects due to the release of diethylhexyl phthalate, lead, mercury, and cadmium. Microplastic debris which floats on the sea surface also contaminates the oceans. To overcome plastic waste and pollution on our planet, we must reduce plastic consumption and raise awareness about plastic recycling. The crucial need to minimize the consumption of plastics has led to the broad expansion of bio-based plastics produced from renewable sources.¹⁻³

About 25.8 million tons of plastic are generated annually, 30% are recycled, and 40% are carbonized. Plastics such as polyethylene terephthalate (PET), polystyrene (PS), polyethylene (PE), Polypropylene

*Corresponding author at: Department of Bioengineering, Integral University, Lucknow-26026, India

E-mail address: mkakhan@iul.ac.in

<https://orcid.org/0000-0002-8004-1448>

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(PP) are petrochemically derived, but there is a current demand for plastics used by renewable resources. Bioplastics are essential and requisite materials for substantial and current living. They are also vital for the upcoming generations due to their vast growth and need to be preserved. Bioplastics are biodegradable, and so they can decay with the help of microorganisms in the environment into compounds like carbon dioxide, biomass under aerobic conditions, and methane under anaerobic conditions. Non-biodegradable bioplastics are durable. The intensity of bioplastics being biodegradable is influenced by temperature, polymer stability, and available oxygen content.

In emerging economies like India, Brazil, and China, there has been an increased demand for biodegradable polymers. Polyhydroxy and polylactic acid (PLA) is considered the main contributor to the growth of biobased biodegradable plastics, followed by starch known to have the highest share in biodegradable plastic production. The total percentage of bio-based bioplastics is around 2.11 million tons, out of which the PHA has a market share of 1.2%, whereas PLA has that of 13.90%. It is expected that there could be a 6.3-fold increase in the global production of PHA, i.e., from 25.32 tons in 2019 to 159.70 tons by 2024. In PLA, there could be a rise of 8% increased production 293.29 tons in 2019 to 317.00 in 2024.⁴⁻¹⁷

Maurice Lemoigne, a French chemist, and bacteriologist discovered the Gram-positive bacterium *Bacillus megaterium* producing intracellular polyester and polyhydroxybutyrate (PHB) while working at the Lille branch of the Pasteur Institute in 1926. Nowadays, around 100 PHAs have been discovered from a variety of microorganisms. The chemists and biologists only began to consider petroleum-based plastics as a gross waste product problem around the 1980s. After that, an intensive search began to look for new ways to make them degrade in municipal and industrial waste facilities. This experiment led to the invention that some genetically altered microorganisms and chemical compounds could help to accelerate the breakdown of petroleum-based plastics to a limited extent. In the upcoming years, these biodegradable polymers can replace conventional polymeric goods in packaging applications. Though it is crucial to characterize the biopolymers permeability to aroma and flavor compounds, little work has been done. Data suggests a limited supply of cost-effective, consumer, and environmentally friendly sustainable plastic alternatives as they are in huge demand.¹⁸⁻³⁰

Types of bioplastics

As per the European bioplastics Organization (EBO), a material is called bioplastic if it is either bio-based, biodegradable, or features both properties. The term bio-based is defined as the materials or products entirely or partially acquired from renewable resources. It is why petrochemical resin, typical in standard plastic, is replaced by vegetable or animal polymers, and the compounds like glass or carbon fiber or talc are replaced by natural fibers (wood fiber, hemp, flax, sisal, jute). On the other hand, the term biodegradable refers to the material that can undergo degradation by biological processes at the time of composting to yield CO₂, inorganic materials, biomass, water, and other compounds without producing any toxic chemicals or wastes. These materials are made up of different compounds describe above about biodegradable and non-biodegradable bioplastics listed in Table 1.³¹⁻⁴¹

Table 1: Types of bioplastics based on biodegradability and bio-based content

Biodegradable	
Bio-Based	Petroleum-Based
Polylactic acid, Polyhydroxy alkanooates, Cellulose, Starch (bioplastic)	Polybutylene succinate, Polybutylene adipate terephthalate, Polycaprolactone (bioplastic)

Non-biodegradable	
Bio-Based	Petroleum-Based
Biopolypropylene, Biopolyethylene (bioplastic)	Polypropylene, Polyethylene, Polystyrene, Polyvinyl chloride (conventional plastics)

Due to the environmental implications of non-biodegradable plastics, significant strides have been taken in the past few years. The best alternative to this is biodegradable plastics as they are environment friendly, with excellent reusable potency that can be produced from natural sources, including waste materials, methane, and other carbon sources. Even though biodegradable plastics are eco-friendly, they risk emitting methane under anaerobic conditions in landfills. Biodegradable plastics produced by methanotrophs are used for landfill methane.⁴² The morphology of bio-based material, investigated by scanning electron microscopy, showed a uniform and compact surface structure. 2D X-ray Diffraction analysis reveals that bioplastic is essentially amorphous. Mass loss test noted that it is wholly decomposed after being embedded in soil for 105 days.⁴³ A few examples of bioplastics are described below.

PHA: PHA is manufacture with the help of microbial fermentation processes, and it was extracted by microbial cells. The diversity in their monomeric compositions causes variations in their physical properties, and thus, it introduces a wide variety of applications.⁴⁴

PLA: PLA is transparent and is manufacture by corn and dextrose. PLA has a similar character as that of petrochemical-based plastics, and it can be manufacture by a similar method as that of conventional plastic.

PHB: The production of poly-3-hydroxybutyrate certain bacteria producing glucose and corn starch is used. PHB has the same characteristic as that of plastic polypropylene. PHB has a higher melting point than 130 degrees C, is biodegradable, and can be processed into transparent films. PHB is used for packaging purposes in South American industries.⁴⁵

PA11: Derivation of PA11 is derived from natural oils and has the triad name *Rilsan v*, manufactured by Arkema. PA11 is non-biodegradable and shows similar properties to PA12. Automatic fuel lines, pneumatic airbrake tubing, flexible oil and gas pipes are some of the applications of PA11. The manufacturer of polyamide 410 (PLA410) is BSM, and its trade name is EcoPaXX.

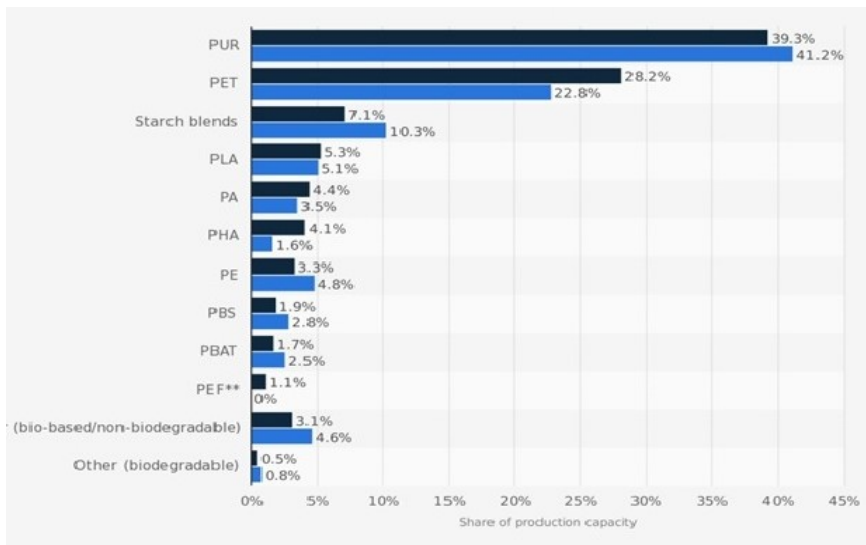
PHU: The reaction between polyamines and cyclic carbonates produces polyhydroxyurethanes. They have biodegradables and isocyanate. Cross-linked polyhydroxyurethanes can also be recycled.

Starch: The most widely used bioplastic is thermoplastic starch, consisting of about 50% of the bioplastic market. Due to the absorption of humidity by pure starch is used to produce drug capsules by the pharmaceutical sector. Pure starch-based bioplastic is brittle. Glycerol is added to starch as a plasticizer, and its tensile properties are suitable for packing materials.⁴⁶

Cellulose: There are two types of cellulosic plastic which are organic cellulose esters and regenerated cellulose. At present, around 20% of the global total chemical-grade pulp is utilized to produce organic cellulose ester. Cellulose regenerates manufactured from cellulose by dissolving by chemicals and then newly restructured in fibers or film. More than 60% of the global total chemical-grade pulp is used to form cellulose regenerates.³⁵

GM bioplastics: GM crops are being used to obtain genetically modified bioplastics. In the upcoming generation, the plant factory model might use GM crops of GM Bactria to optimize the efficiency of GM bioplastics.⁴⁷ Bioplastic production capacity global distribution by the material is shown in Figure 1.

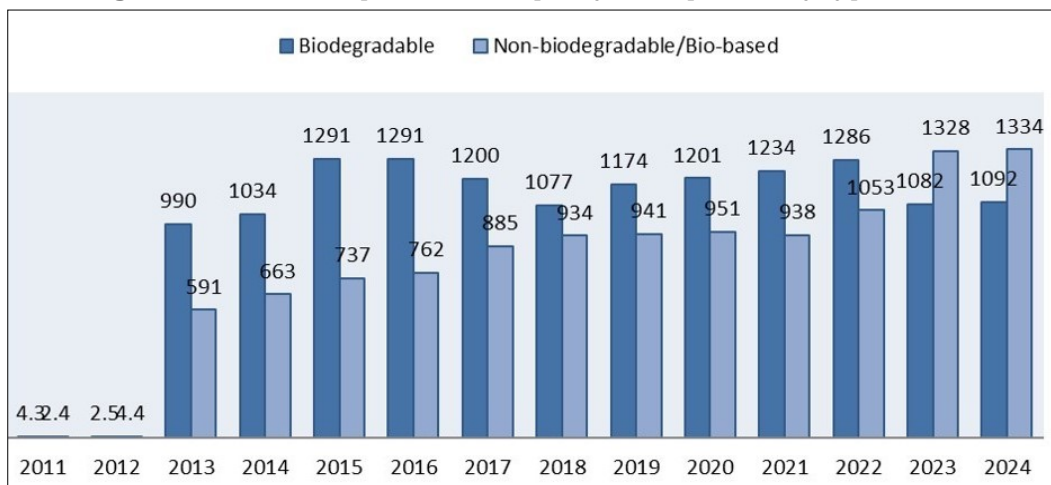
Figure 1: Production capacity and material-wise distribution of bioplastics. The blue and black shows the year 2016 and 2021 respectively.⁴⁸



Bioplastic market and production

It is predicted that the bioplastics packaging market will grow at a considerable rate from 2021 to 2024. Biodegradable, compostable, and degradable where the aspects examine by the bioplastic for agribusiness. The biodegradable bioplastics are expected to grow at the fastest rate during the forecast period. The Global Bioplastics for Agribusiness Market is expected to grow from USD 1,673.85 Million in 2020 to USD 3,411.10 Million by the end of 2025. The rise of biopolymer capacity and manufacture displace healthy growth in demand from our society. The global bioplastic utensils market declares information based on current market trends, restraints, and drivers.

Figure 2: Worldwide production capacity of bioplastics by type.^{54,55}



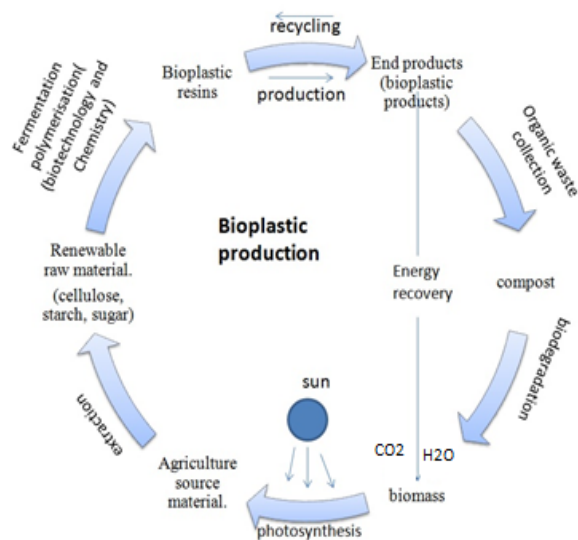
Bioplastics market size worldwide was estimated at over 1220 kilotons in 2020 and projected to be increased the CAGR (Compound Annual Growth Rate) by over 16% during the forecast period (2021-2026). In 2020, the market was heavily impacted by the COVID-19. The demand for flexible packaging has increased, accounting >45% for bioplastics due to an upsurge in demand for various usages including personal, healthcare products, pharmaceuticals, food, and beverages packing. According to JEITA (Japan

Electronics and Information Technology Industries Association), global electronics products such as laptops, mobiles, and semiconductors, amongst others, and information technology have increased. It is expected to reach USD 3,175 billion by the end of 2021, positively impacting bioplastics' demand. While there have been struggles for the bioplastics to deliver the same performance as fossil-based plastics, though the technology is increasingly closing the gap, creating highly functional plastics that do not cost the Earth.⁴⁹⁻⁵³ Bioplastics production capacity worldwide is shown in Figure 2.

Production and Life Cycle of Bioplastics

Potential environmental impact is attributed to the life cycle of products or survives, and it is a standard methodology for life cycle assessments (LCA). LCA can acknowledge the materials or products on the environment, optimal use of resources, and the impact of different processes. For example, conventional and biodegradable plastic, use of plastic waste, or natural fiber-based bags and textiles can be determined by LCA. Treatment of PLA waste in a Municipal Solid Waste Incinerator (MSWI) plant is compared to the recently developed recycling processes such as mechanical recycling, chemical recovery, and solvent water recycling. One way to specify problematic environmental hotspots in the manufacture of significant biochemical, which here also are chemicals produced from renewable biomass with microbial fermentation. LCA shows some hotspots for enhancing biomass input, even if the biochemical does not arrive in an oil-derived version.⁵⁶⁻⁶¹ Bioplastic production and its life cycle are shown in Figure 3.

Figure 3: Bioplastic production and its life cycle.⁵⁸



Biodegradation of plastics

When the partial or complete breakdown of a polymer occurs due to microbial activity into carbon, hydrogen, oxygen, hydrolysis, photodegradation, microbial action (enzyme secretion), and within-cell processes, the biodegradation process is temperature-dependent. It sometimes requires conditions like industrial composting units with a prolonged temperature of above 50°C to be wholly broken down. Biodegradable plastic is usually created from natural by-products and is controlled by temperature and humidity in industrial environments. Plastic biodegradable and compostable are mostly called bioplastic, and they are generally made from natural resources, such as bamboo or sugarcane, instead of fossil fuels. The compostability of bioplastics needs to be confirmed if the bioplastics are to be pretty and effectively

biodegradable to make sure they can be handled in industrial composting plants.⁶²⁻⁶⁴ The degradation of bioplastics in the soil environment is shown in Table 2.

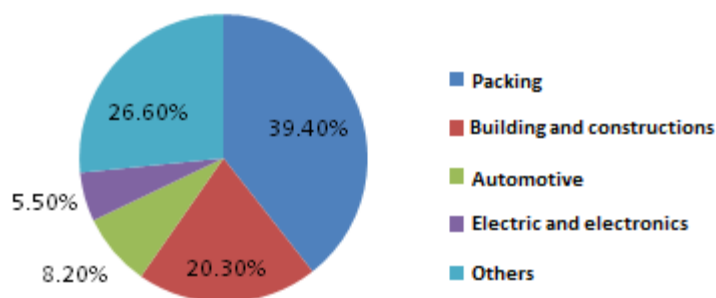
Table 2: Degradation of bioplastics in the soil environment.

Source	Types	Environmental Condition	Biodegradability (%)	Biodegradability (days)
Bio-based	PLA-based	Soil	10	98
	PHA-based	Microbial culture from soil	35	60
	Starch-based	Compost soil	14.2	110
	Cellulose-based	Soil	≈100	103
Petroleum-based	PBS-based	Soil	16.8	28
	PCL-based	Soil and leachate	22	60

Bioplastics Increase Recycling Efficiency

The circular use for biodegradable plastics and the creation of a solid secondary raw material market, and an opportunity for renewable energy generation all come under organic recycling. Life cycle assessment (LCA) helps to reduce contamination of mechanical recycling streams by facilitating separate collection of bio-waste and diverting organic waste from other recycling streams. Investments into sound waste management infrastructure and comprehensive projects to increase the consumer's knowledge about correct disposal must be considered. By following the above methods, recycling can become more efficient, contamination can be limited, and the solid secondary raw material market in a circular economy can thrive. Commonly, most household packaging is already recycled today, more than half of which (56%) are made from materials (around 20 years ago, it was only 3%).^{65, 66} The application of bioplastics in different areas are shown in Figure 4.

Figure 4. Bioplastics from renewable biomass and their applications in different sectors.⁶³



Microbes Used In Biodegradation

Bioplastics can degrade naturally and entirely to carbon dioxide and water with the help of the enzymatic reaction of the microorganisms. Data suggests that 313 microbes were isolated from 52 soil samples from the Arctic region and out of these, 121 (38.66%) showed biodegradation activity. The ability of precise zone formation on emulsified poly (butylene succinate-co-adipose) (PBSA) was observed for 116 microorganisms (95.87%), on poly (butylene succinate) (PBS) for 73 microorganisms (60.33%), and poly (ϵ -caprolactone) (PCL) for 102 microorganisms (84.3%). Nowadays, out of approximately 300 million tons globally, bioplastics constitute only 1 percent of produce annually.⁶⁷⁻⁶⁹ Table 3 shows the microbes used in the biodegradation of bioplastics.

Table 3: Types of bioplastics and the microbes used in biodegradation.⁷⁰⁻⁷⁶

Type	Microbes	Use
PHB	<i>Rhizosphere</i> , <i>Alcaligenes eutrophus</i> , <i>Azotobacter beijerinckia</i> , <i>Pseudomonas oleovorans</i> , <i>Rhizobium sp</i>	Soil <i>Rhizosphere</i> of maize, wheat and trefoil eighteen PHB producers
Cellulose	<i>Pseudomonas strains</i> , <i>Neisseria sicca</i> , <i>Alcaligenes xylosoxidans</i>	Degrade cellulose acetate with DS1.8 And DS2.3. The highest degradation rates reported were 60 and 45% within 20 days.
Starch	<i>Pseudomonas aeruginosa</i>	Produces Polypropylene
protein base	<i>Bacillus subtilis</i> and <i>Escherichia coli</i>	Using cane molasses as an inexpensive substrate.
Polylactic acid	<i>Rhizopus delemar</i>	Pure lactic acid production, end product of fermentation
Polyurethane	<i>Pestalotiopsis microspora</i>	Ability to degrade the synthetic Polymer Polyester polyurethane (PUR), useful for bioremediation
Polydiethylene adipate	<i>Comamonas acidovorans</i> , <i>Pseudomonas aeruginosa</i> , <i>Pseudomonas stutzeri</i> , <i>Streptomyces badius</i>	Waste management, and their Consumption is increasing day by day at a rate of 12% per annum

Environmental Effect

The environment-friendly rebound to plastic is bioplastics, which can quickly degrade through the enzymatic action of microorganisms. Examples of environmental effects are summarized as follows.

Sustainability: Plastics can be made sustainable by simply adding less chemical diversity to them. Due to the micro partials of the plastic scattering can clog up the sewage drains and thus cause water and sewage problems. Organisms can swallow micro partials mistaking food, and it can cause death and injury to them. It can be stopped by controlling our actions by not littering our surroundings.

Worldwide conservation and environmental organization: Many organizations contribute to cleaning up the ecosystem, like Ocean Conservancy (international coastal clean-up), UNEP (United Nations environment programmed), Californians against waste, National wildlife federation, Rainforest Action Network, Tree people, WWF global.⁷⁷⁻⁷⁹

Recycling: The global average of plastic waste recycling is around 14-18%, and it is lower than expected in some countries. In Europe, recycling recently overtook landfilling in post-consumer waste treatment in 2016 with a recycling rate of 31.3% and a landfilling rate of 27.3%.⁸⁰ There are four main recycling mechanisms for thermoplastic, including closed-loop, mechanical, chemical, and quaternary.⁸¹⁻⁸⁴

Agriculture Waste

According to FAO, around 1.3 billion tons of food is lost or wasted every year globally. In the UK, 15 million tons of food were wasted annually. It is estimated that in Malaysia, around a 6.7million tons of FW are generated annually in 2020. About 567- 726 million tons of FW have been generated annually in the

USA. The government of France has introduced a policy for stimulating valorization of FW through the recovery of energy (e.g., biogas) and value-added materials (e.g., a bioplastic) with a punitive law amid an FW epidemic implementation of this policy was estimated to save 88 million tons of FW per year with a corresponding cost of USD 167 billion. Most parts of FW can be recycled (if separated), and recycling will help reduce the overall expenditures on waste management. Although many studies have reported the simultaneous conversion of FW into energy and bioplastics, most emphasized bioplastic production processes, new bacterial/archaeal species use in the fermentation process, and their operating conditions. According to the Ceresin in Constance, Germany, the world market for bioplastic in 2021 will be 3times larger than in 2014, generating a total of USD 5.8 billion in revenue.⁸⁵⁻⁸⁷ The disposal system of bioplastic should be technologically realistic and practical without risking the existing recycling system. Four main food waste valorization techniques have been adopted as a generation to biofuels, Recovery, and extraction of value e-added compounds, Production of bio-adsorbents for wastewater treatment, and Production of biomaterials.

Effect of Pandemic on the Globe

The King Abdullah University Hospital in Jordan produced tenfold higher medical waste (~650 kg per day, when considering an occupation of 95 COVID-19 patients) than the average generation rate during the regular operational day of the hospital. According to Central Pollution Control Board, India generated over 18,000 tons of COVID-19 related bio-medical waste. An extreme increase in medical waste was also disclosed in other parts of the world, as in Catalonia, Spain, and China, with an increment of 350% and 370%, respectively. Wuhan inhabitants in China (~11 M) produced 200 tons of medical waste on a single day (on February 24, 2020). It is four times higher than incinerated by the city's only dedicated facility, forcing authorities to deploy mobile treatment facilities. For example, around 129 billion facemask and 65 billion gloves would be essential to protect citizens worldwide.⁸⁸⁻⁹⁰

Conclusion And Future Perspective

This review paper includes the bioplastic, their type, degradability, standards, advantages, and disadvantages. There is an urgent need to standardize all details. A new guide and standard should be developed just for bioplastics' production, uses, and waste management worldwide. Also, labeling legislation may be improved based on a product's raw material usage, energy consumption, emissions from manufacture and use. Based on the advantages of bioplastics, there are certainly an abundant amount of materials and resources to create and find more uses for bioplastic. Based on the disadvantages of bioplastics, several parameters must be considered for sustainability, including the raw materials from which the bioplastic is generated, the energy consumed during bioplastic conversion, and its life cycle assessment analysis from production to ultimate disposal or recycle, and other several parameters.

Conflicts of Interest

The authors declare that there are no conflicts of interest relevant to this article.

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