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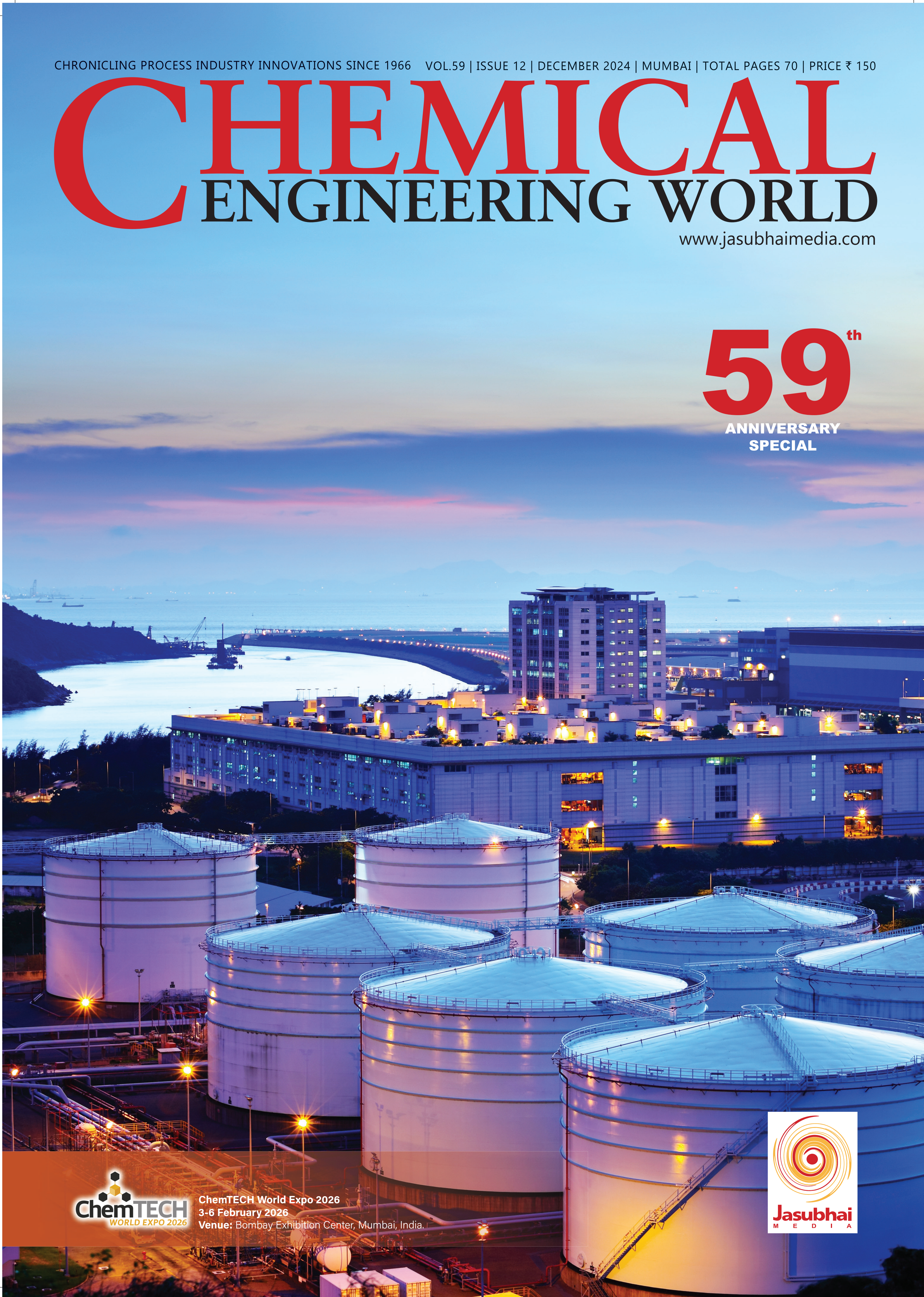

The Future of Bioplastics : Focus on Polyhydroxyalkanoate

Since the mid-20th century, plastic production has surged to over 460 million metric tons annually, reshaping industries and modern life.[1] Yet, this convenience comes at a steep cost—these plastics are made from non-renewable, fossil fuels and only about 9 per cent of plastic waste is recycled around the world each year, with billions of tons accumulating in landfills and oceans.[2] Efforts to reduce, reuse, and recycle are vital but insufficient to curb the growing plastic crisis. To truly transform the future of plastics, we need innovative, biobased materials that can be made from non-toxic, renewable feedstocks, and support more circular solutions. One such breakthrough is polyhydroxyalkanoate (PHA), a biodegradable, compostable and biobased polymer poised to redefine the lifecycle of plastics from how they are made to how they are thrown away.

The first PHA, poly (3-hydroxybutyrate) was discovered in 1926 by the French scientist Maurice Lemoigne during his work with the bacterium Bacillus megaterium[3]. A PHA is a unique polymer made from annually renewable feedstocks that have sequestered carbon dioxide into sugars that are processed through large-scale fermentation. The sugars are fermented the same way you would ferment hops to make beer, but instead of beer, the microorganisms produce PHA that is recovered and turned into a functional polymer that can be used for a wide variety of applications. The raw materials for PHA are sugars sourced from plants, including sugar cane, tapioca, corn, or, in the future, cellulosic biomass. As a natural polymer, PHA offers an attractive alternative to petrochemical-based materials, such as polyolefins and polystyrene, that are used to make plastic products. It works well as a modifier to other polymers or biopolymers, increasing bio-based content, accelerating biodegradation, and improving the functional properties of resin and finished products.

PHAs are readily biodegradable in various environments, including marine and soil settings as well as industrial composting facilities. Because PHAs are compostable, they can be used to create certified compostable food packaging and serviceware that helps divert more food scraps away from landfills and into compost. Food scraps degrading in landfills are the third largest source of human-generated methane

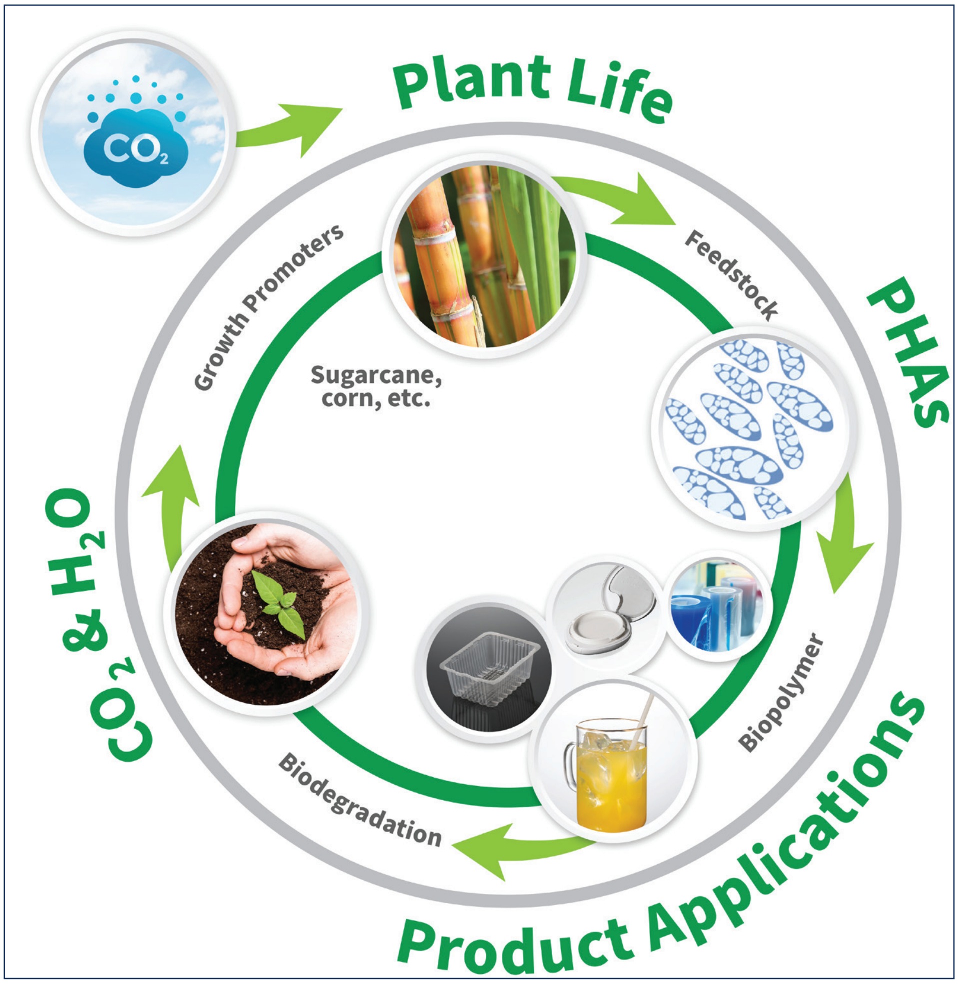

Chart 1: Bio-circle diagram *(Credit: CJ Biomaterials).*

emissions in the US. However, in compost, food scraps and compostable packaging breakdown and become part of a nutrient-rich soil amendment that improves soil's health, biodiversity, and carbon sequestration capability. In the US, access to industrial composting facilities that process food waste is growing quickly with the number of households with access to food waste collection growing by 49 per cent from 2021 to 2023 — from 10.0 million to 14.9 million households .[4]

Environmental conditions, such as temperature and pH, and PHA properties, likewise monomer type, molecular weight, crystallinity, and surface area, directly influence the degradation rate of PHAs. In the environment, PHAs are observed to have a relatively fast degradation mostly via microbial activity.[5] Therefore, if products made entirely with PHA are littered, they will biodegrade naturally, leaving behind no persistent microplastics or long-term impacts to the environment. This is why PHAs offer a safer, and more circular alternative to incumbent fossil-based plastics. At the beginning of life, PHAs accelerate the decoupling of materials from fossil fuels like oil or natural gas, instead using plants to capture and sequester atmospheric CO_2 into sugars that can be used to produce PHA. At the end of life, products made with PHA-modified biopolymers biodegrade into CO_2 and water, which are ultimately sequestered into compost or returned to the atmosphere to be used by plants again. (See Chart 1.)

Improving Functional Properties of other Biopolymers

During the past 50 years, extensive research and many development projects have been dedicated to the ever-growing class of PHAs.[6] To date, the number of known PHA monomers has increased to more than 150, including unsaturated and aromatic monomers.[7]

Amorphous PHA is a more recent innovation. It is a tough, ductile, pliable material that offers fundamentally different performance characteristics than the crystalline or semi-crystalline forms of PHA that currently dominate the market. Amorphous PHA (aPHA) is a thermoplastic material that can be compounded with other biopolymers and processed into various applications including fibers and nonwovens for hygiene products, flexible and rigid food packaging, foams, straws, and injection molded cutlery or profiles.

Significant progress has been made over the last 20 years in using biopolymers to reduce the use of fossil-based plastics and address the accelerating levels of plastic waste on our planet. Polylactic acid (PLA), in particular, has made significant inroads, and it is the biomaterial of choice for the plastics industry. The challenge PLA faces is that it is very brittle, stiff, and can be slow to compost, limiting its usefulness for certain applications.

The aPHA biopolymer works well as a modifier to PLA as well as other polymers or biopolymers and can be used to increase bio-based content, accelerate biodegradation, and improve functional properties of resins and finished products. For example, in rigid food packaging, aPHA improves the impact resistance of polylactic acid (PLA) thermoforms so they can be used in automated food packaging systems while maintaining high levels of biobased content and passing 3rd party compostability testing. aPHA also improves the softness of spunbond PLA nonwovens by 40 per cent, which is a critical attribute for nonwovens used as the topsheet, or layer that touches the skin, in diapers.

Furthermore, aPHA increases the rate of composting of PLA and other biobased polymers. Like PLA, aPHA is certified by the Biodegradable Products Institute (BPI) as industrially compostable. But, unlike PLA, it is also TÜV OK-certified biodegradable in soil and marine environments and also certified for home compost. These properties that make PHA biodegradable under a wider range of conditions are what help improve the compostability of PLA as well.

Using aPHA as a modifier can have a significant impact on the market. Global production capacity of PLA was approximately 675,800 tons in 2023,[8] and that is not enough capacity to begin replacing fossil-based plastics at scale. A conservative estimate is that half a million tons of PLA needs to be produced to satisfy market demand. Looking beyond PLA to all biopolymers (PBAT, PBS, PBST, etc.), European Bioplastics estimates that total global production capacity of bioplastics will eclipse 7.4 million tons by 2028[9] which is barely 2 per cent of the greater incumbent plastics market. The full portfolio of PHAs, from amorphous to semi-crystalline, will be needed to expand the functional capabilities of all biopolymers so that more applications and products can transition away from fossil-based plastics to safe, low carbon, biobased materials with extended capabilities for compostability and biodegradability.

Looking Ahead

The crisis the world is facing, from climate change to plastic waste demands immediate action and innovative solutions. From governments to brands to consumers, we are seeing unprecedented attention being paid to how plastics impact all aspects of the environment. PHAs represent a critical step forward to ensure we are able to meet the challenge of implementing a low carbon, fully circular bioeconomy for materials. As fully biodegradable, bio-based polymers, PHAs address the limitations of traditional plastics and even other bioplastics, offering a truly circular solution. With advancements like amorphous PHA, the potential for widespread applications is growing—from enhancing the performance of existing biopolymers to enabling home-compostable packaging solutions.

In addition to its environmental advantages, a cohesive regulatory framework is also essential for PHA to have an impact. While initiatives like California Senate Bill 54[10] represent significant progress, there are gaps in implementation that hinder the scalability of compostable materials. For example, the National Organic Program (NOP) standards, which restrict compostable packaging inputs for organic agriculture, create unintended roadblocks for advancing compostability. Updating these standards to reflect modern materials is critical to achieving alignment across industries and reducing dependency on landfills. Collaborative regulatory efforts, such as working with the National Organic Standards Board (NOSB) to revise these outdated standards, are key to addressing systemic challenges and ensuring compostable products achieve their highest value by aiding in the diversion of food scraps away from landfills and into compost.

The future of PHA and its ability to address plastic pollution depends on its scalability and its industry adoption as a replacement for conventional plastics. Achieving commercial scale production is difficult for newer biobased materials competing against the economics of fossil-based polymers where the production and value chain has been optimized over the last 60 years. However, despite the challenges, PHA manufacturers are seeing greater interest from the market, securing investments, and justifying reinvestment economics that will support the ongoing scale up of the industry. Recently, Mango Materials, a producer of PHAs in California, received funding via a USD26.9 million investment from BioMade to facilitate point-of-need production for biodegradable plastic replacements while enabling decentralized production of materials.[11] In April 2024, CJ Biomaterials announced additional capacity at its manufacturing facility in Pasuruan, Indonesia, specifically to expand production of both its aPHA and scPHA biopolymers.[12] The biotechnology company, RWDC, then announced an additional investment in June 2024 that will support construction of their new PHA manufacturing expecting to break ground in 2025.[13] While certainly challenges remain, the ongoing investment in PHA capacity and capabilities will underpin growth in the biopolymers market in 2025.

By integrating PHA into packaging, consumer goods, and industrial applications, manufacturers and brands can continue the journey to reducing the negative impact of plastics on our climate and environment. With increasing global capacity for bioplastics and ongoing innovations in PHA technology, the vision of a sustainable, circular bioeconomy is firmly within our reach. ■

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