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From Soil to Sustainability: Multifaceted Applications of *Azotobacter*

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Abstract

Azotobacter is a free-living, nitrogen-fixing bacterium with diverse applications in agriculture, biotechnology, and environmental remediation. Beyond its well-established role as a biofertilizer, *Azotobacter* produces a wide range of bioproducts such as polyhydroxybutyrate (PHB), alginate, exopolysaccharides (EPS), and siderophores. These compounds have applications in sustainable farming, bioplastics, pharmaceuticals, and pollutant removal. Recent studies highlight its use in pesticide degradation, nanoparticle synthesis, biofuel precursors, and as a microbial chassis for synthetic biology. This review discusses the biological features, mechanisms, and multifunctional applications of *Azotobacter*, while also exploring recent advances, challenges, and future perspectives for its industrial and environmental use.

These include biodegradable polymers such as poly-β-hydroxybutyrate (PHB), alginate, exopolysaccharides, biosurfactants, vitamins, and enzymes with applications in agriculture, medicine, and industry. Recent advances have highlighted its potential in bioremediation through heavy metal sequestration and pesticide degradation, as well as in emerging fields such as nanomaterial synthesis, bioenergy, hydroponic farming, and synthetic biology. Genomic and metabolic engineering studies further position *Azotobacter* as a promising microbial chassis for sustainable fertilizer and biofuel production. This review synthesizes current knowledge on the biological traits, biotechnological applications, and environmental significance of *Azotobacter*, while critically examining recent developments, limitations, and future prospects for its large-scale utilization in green and climate-smart technologies.

Keywords: *Azotobacter*, Biofertilizer, Nitrogen fixation, Bioplastics, Alginate, Bioremediation, Sustainable biotechnology

Introduction

Azotobacter are free-living bacteria that can fix nitrogen from the air and make it available to plants. Because of this, they are considered very important plant growth-promoting bacteria (PGPR). They also produce plant hormones like indole acetic acid (IAA), gibberellins, and cytokinins, as well as siderophores that help plants take up iron. These features improve crop growth and protect plants from harmful microbes (Bhattacharyya & Jha, 2021; Arora, 2020).



Apart from helping plants, *Azotobacter* can make useful bioproducts. They produce biopolymers such as alginate, which is widely used in food, medicine, and industry, and polyhydroxybutyrate (PHB), which is a biodegradable plastic. Both alginate and PHB from *Azotobacter* are now studied as eco-friendly alternatives to synthetic materials (Peña & Galindo, 2021; Campos & Galindo, 2019; Guzmán et al., 2020).

These bacteria are also important for cleaning the environment. Their exopolysaccharides and biosurfactants can trap heavy metals like lead and cadmium, and can also help break down oil and other pollutants. This makes them good candidates for bioremediation of contaminated soils and wastewater (Bafana et al., 2019; Agbabiaka & Oyeyiola, 2022).

Because of all these properties, *Azotobacter* can be seen as a multipurpose microorganism useful in agriculture, biotechnology, and environmental protection. Recent research shows their potential not only as biofertilizers but also as producers of high-value bioproducts, making them a strong candidate for sustainable applications (Chouhan & Sharma, 2022).

Biological Features & Mechanisms:

Nitrogen fixation and plant growth promotion:

Azotobacter are free-living bacteria that can fix atmospheric nitrogen and change it into a form that plants can use. This helps improve soil fertility without adding chemical fertilizers. They are also known to make plant hormones such as indole acetic acid (IAA), gibberellins, and cytokinins. These hormones support root and shoot growth. In addition, *Azotobacter* produces siderophores that bind iron and make it available to plants, and antifungal substances that protect crops against soil pathogens (Bhattacharyya & Jha, 2021; Arora, 2020).

Stress resistance and survival traits:

One special feature of *Azotobacter* is that they can form cysts. Cysts are protective structures that allow the bacteria to survive in tough environmental conditions like drought, high salt, or nutrient-poor soils. This ability makes them reliable candidates for biofertilizer production because they can remain active in the soil for a long time and continue to benefit plants (Bhattacharyya & Jha, 2021; Chouhan & Sharma, 2022).

Biotechnological Applications

Azotobacter is not only useful in agriculture but also has many applications in biotechnology.

Bioplastics (PHB and PHAs):

One of the most important products of *Azotobacter* is poly- β -hydroxybutyrate (PHB). This is a type of polyhydroxyalkanoate (PHA), which is a natural plastic. Unlike normal plastics made from petroleum, PHB is biodegradable and does not harm the environment. It can be used to make packaging materials, coatings, and medical products such as sutures and drug carriers. Researchers have also shown that *Azotobacter vinelandii* can grow on cheap waste materials like crude glycerol to produce PHB, making the process more sustainable (Campos & Galindo, 2019; Guzmán et al., 2020).

Alginate production:

Another important product of *Azotobacter* is alginate, a polysaccharide that has wide use in food, medicine, and industry. In the food industry, it is used as a thickener and stabilizer. In medicine, alginate is used in wound dressings, controlled drug release, and tissue engineering. Recent studies have found that alginate production in *A. vinelandii* is controlled by special regulatory molecules like c-di-GMP, which help the bacteria adjust production according to environmental conditions (Peña & Galindo, 2021; Núñez et al., 2019).

Biosurfactants and exopolysaccharides (EPS):

Azotobacter produces extracellular polysaccharides (EPS) and biosurfactants that have strong environmental uses. EPS can bind heavy metals such as lead (Pb) and mercury (Hg), which helps in cleaning polluted soil and water. Biosurfactants lower surface tension and help in breaking down oil, which makes them useful in treating oil spills and petroleum-contaminated sites (Bafana et al., 2019; Agbabiaka & Oyeyiola, 2022).

Other products:

Besides these, *Azotobacter* can also produce useful enzymes, vitamins (like vitamin B12), pigments, and antifungal compounds. These products have potential use in the pharmaceutical and biocontrol industries (Chouhan & Sharma, 2022).

Overall, the ability of *Azotobacter* to make such a wide variety of valuable products shows its importance as a “green factory” for future sustainable industries.

Applications:

Agriculture:

Azotobacter is widely used as a biofertilizer because it fixes atmospheric nitrogen and makes it available to plants. This reduces the need for chemical nitrogen fertilizers. The bacteria also produce growth-promoting hormones and siderophores, which improve nutrient uptake, root growth, and crop yield. In some crops, the use of *Azotobacter* biofertilizer has been shown to increase yield by up to 40%. They also act as biocontrol agents by producing antifungal compounds and competing with harmful microbes in the soil, making them a sustainable option for farmers (Bhattacharyya & Jha, 2021; Arora, 2020).

Bioremediation:

Another important use of *Azotobacter* is in cleaning polluted environments. Their exopolysaccharides (EPS) can bind heavy metals such as lead (Pb) and mercury (Hg), reducing their toxicity. Biosurfactants produced by these bacteria lower surface tension, which helps break down oil and pesticides in contaminated soils and water. Because

of these features, *Azotobacter* is considered a useful microbe for bioremediation of industrial waste, oil spills, and agricultural pesticide pollution (Bafana et al., 2019; Agbabiaka & Oyeyiola, 2022; Kumar & Singh, 2020).

Bioplastics and alginate:

Azotobacter can make high-value industrial bioproducts. They produce poly- β -hydroxybutyrate (PHB), a natural plastic that is biodegradable and eco-friendly. PHB has many applications in packaging, medicine (sutures, implants), and drug delivery systems. Another important product is alginate, an extracellular polysaccharide widely used as a thickener in food, in wound dressings, and in tissue engineering. Both PHB and alginate are considered promising alternatives to petroleum-based products, and their production using *Azotobacter* is seen as a step toward sustainable industries (Campos & Galindo, 2019; Peña & Galindo, 2021; Núñez et al., 2019).

Miscellaneous products:

In addition to bioplastics and alginate, *Azotobacter* can produce other valuable compounds such as vitamin B12, melanin pigments, and enzymes like amidases and phenol oxidases. These products are of interest in biotechnology, pharmaceuticals, and industrial enzyme applications (Chouhan & Sharma, 2022). Summary of Applications of *Azotobacter* is presented in Table no. 1.

Table No. 1: Summary of Applications of *Azotobacter*

Application Area	Product / Function	Benefit	Key References
Alginate production	High vs. low OTR control of molecular weight & G/M ratio	Tailor-made biopolymer properties for hydrogels, drug delivery	Díaz-Barrera et al. 2007; Ponce et al. 2025 (PubMed , Frontiers)
Pesticide bioremediation	Degradation of chlorpyrifos, pendimethalin, chemosate	Detoxifies soil, reduces toxicity, improves organism survival	Conde-Avila et al. 2021; Mousa 2021; (PMC , accscience.com , ResearchGate , Frontiers Publishing Partnerships),
Bioplastic & biofertilizer	PHB, alginate production	Eco-friendly materials and crop growth enhancement	Campos & Galindo 2019; Peña & Galindo 2021; Arora 2020
Nanomaterials	EPS-based silver chloride nanoparticles	Antimicrobial biomaterials	Rasulov et al., 2016
Pollutant degradation	Breakdown of 2,4,6-TCP and endosulfan	Expands bioremediation spectrum	
Synthetic biology	Engineered strains for biofuels, urea, and ammonia	Green energy and fertilizer production	Sánchez-Clemente et al. 2023; Ren et al. 2024; Kim et al. 2024
Hydroponic farming	Diazotroph biofertilizers for soilless agriculture	Reduces synthetic input and enhances indoor crop growth	Renganathan et al. 2025; Far future applications
Agriculture / Biocontrol	Nitrogen fixation, IAA, hormones, siderophores, cysts formation	Better plant growth, yield, and stress resilience	Bhattacharyya & Jha 2021; Arora 2020; Chouhan & Sharma 2022

Recent Developments and Future Perspectives

Modern research is moving beyond the traditional view of *Azotobacter* as just a biofertilizer. With the help of advanced biotechnology, this bacterium is now being explored as a platform for renewable energy, sustainable agriculture, and industrial biotechnology.

One promising area is bioenergy. *Azotobacter vinelandii* has been engineered as a microbial chassis for producing biofuel precursors and lipids. These engineered strains can accumulate fatty acids that can later be converted into biodiesel, making *Azotobacter* a candidate for renewable energy industries and an eco-friendly alternative to fossil fuels (Sánchez-Clemente et al., 2023).

Another breakthrough is in bio-based fertilizers. Producing synthetic fertilizers such as urea requires large amounts of energy and contributes to greenhouse gas emissions. Recent studies have reprogrammed diazotrophic bacteria, including *Azotobacter*, to directly produce urea as part of their nitrogen metabolism. This could reduce reliance on synthetic urea fertilizers and make agriculture more sustainable (Ren et al., 2024).

Genomic and pan-genomic studies have provided important insights into the diversity and potential of *Azotobacter*. Sequencing different species and strains has revealed genes responsible for nitrogen fixation, alginate biosynthesis, PHB production, and stress resistance. These findings allow researchers to design improved strains with better nitrogen-fixing efficiency, faster growth, and higher yields of valuable bioproducts. They also show that natural diversity within *Azotobacter* can be harnessed for applications in different soils, climates, and industries (Kaur et al., 2024).

In the field of synthetic biology, researchers are mapping out the regulatory networks that control *Azotobacter*'s metabolism. For example, the c-di-GMP signaling pathway regulates alginate and biofilm production. By targeting such pathways, scientists can develop tailor-made strains optimized for the large-scale production of alginate, PHB, or other valuable compounds (Núñez et al., 2019).

Recent studies also highlight the role of *Azotobacter* in climate-smart agriculture. Engineered and naturally stress-tolerant strains have shown potential to support plant growth even under drought, salinity, and poor soil conditions. This opens the possibility of using *Azotobacter* in degraded soils or marginal lands where crops usually fail, contributing to food security under climate change (Chouhan & Sharma, 2022).

Despite these advances, challenges remain. Scaling up the production of PHB and alginate is still costly compared to petroleum-based plastics. Progress in fermentation technology, cheaper raw materials, and metabolic engineering will be essential to make these products competitive (Campos & Galindo, 2019; Peña & Galindo, 2021). Similarly, the effectiveness of *Azotobacter*-based biofertilizers in the field can vary with soil, climate, and microbial competition, which often limits farmer adoption. Improved formulations, carrier materials, and longer shelf life are needed for consistent results (Bhattacharyya & Jha, 2021; Arora, 2020).

Another gap lies in bioremediation applications. Laboratory studies show that *Azotobacter* can bind heavy metals and degrade pollutants, but large-scale field studies are still rare. Pilot projects are needed to confirm its usefulness in real-world contaminated soils and wastewater systems (Bafana et al., 2019; Agbabiaka & Oyeyiola, 2022).

While genetic engineering has opened up new opportunities, stability, biosafety, and regulatory approval remain major hurdles. Careful evaluation of engineered *Azotobacter* strains will be crucial to ensure safe application in agriculture and industry (Sánchez-Clemente et al., 2023; Ren et al., 2024).

In conclusion, *Azotobacter* is emerging as a multi-purpose green biofactory that can contribute to renewable energy, sustainable agriculture, bioplastics, and bioremediation. With continued investment in genomics, synthetic biology, and large-scale trials, this versatile bacterium could become a key player in the future of green biotechnology and climate-smart solutions.

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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