

## REVIEW ARTICLE

# Nano-biofertilizers: A promising technology for sustainable soil fertility, soil health, and environmental protection

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**Abstract:** The rapidly increasing global demand for food security urgently calls for agricultural technologies that can boost productivity without contributing to environmental degradation. A group of fertilizers that combines nanotechnology with beneficial microorganisms – known as nano-biofertilizers – has shown tremendous potential to enhance plant growth, increase yields, and improve soil health. Controlled nutrient release, enhanced microbial activities, and improved nutrient-use efficiency are key benefits of these new fertilizers, collectively leading to higher crop productivity with reduced environmental impact. These advantages contribute to sustainable agriculture by reducing the use of chemical fertilizers, surface soil degradation, nutrient leaching, and greenhouse gas emissions. Recent research findings have also highlighted their role in increasing plant resilience to abiotic stress factors, enhancing soil microbial diversity, and supporting ecological balance. This paper presents a comprehensive analysis of the multifaceted roles of nano-biofertilizers in modern agriculture, focusing on their contributions to plant physiology, soil health, environmental sustainability, and long-term agricultural productivity. Through empirical integration, we argue that nano-biofertilizers could be a transformative tool in advancing sustainable farming and achieving global environmental conservation goals.

**Keywords:** Fertilizer innovation; Microbial bioinoculant; Plant growth and yield; Soil health and sustainability; Plant-microbe interaction; Nutrient efficiency; Microbial activity

## 1. Introduction

As a recent development, the integration of nanotechnology with biofertilizers is being practiced to promote soil health and environmental sustainability. Nanobiofertilizers combine the advantages of biological fertilizers with

advanced delivery mechanisms enabled by nanomaterials. As a result, they can increase nutrient efficiency, reduce the environmental impact associated with nutrient losses, and address potential environmental risks.

Chemical fertilizers have marked a breakthrough in traditional farming practices; however, their use

typically leads to nutrient leaching, soil degradation, and water pollution. On the contrary, nano-biofertilizers release nutrients gradually and more efficiently deliver the specific nutrients that plants need. This approach allows for reduced fertilizer application, thereby significantly decreasing potential environmental harm. Garg *et al.*<sup>1</sup> support the view that nano-biofertilizers enhance nutrient availability, resulting in improved plant growth and yield. The inclusion of beneficial microbes in nano-biofertilizers likely contributes to soil health, as these organisms are involved in nutrient solubilization, nitrogen fixation, and suppression of soil-borne pathogens. According to Sambangi *et al.*,<sup>2</sup> the application of nano-biofertilizers containing plant growth-promoting rhizobacteria improves microbial activity and soil fertility.

Another main benefit of the nano-biofertilizer is environmental protection. They help reduce greenhouse gas emissions and water pollution caused by nutrient runoff, as they lower the dependency on chemical fertilizers. Nanophosphorus fertilizers, for instance, enhance plant growth with minimal environmental harm, as the applied doses are not excessive, an effect demonstrated by Miranda-Villagómez *et al.*<sup>3</sup> Separately, Madlala and Khanyile<sup>4</sup> indicated that the physical properties of nanoparticles, such as size, shape, and crystallinity, significantly influence the efficiency of nutrient utilization by plants. The study also confirmed that agglomeration and nanoscale loss could reduce the effectiveness of nanofertilizers, highlighting the importance of standardizing preparation and analysis methods to ensure reproducibility.

In summary, nano-biofertilizers represent a forward-looking approach to sustainable agriculture. They enhance nutrient efficiency uptake, support soil microbial health, and are environmentally friendly, positioning them as a vital component of future farming practices.

## 2. The concept of nano-biofertilizers: A scientific perspective

The ever-increasing demand for sustainable agriculture worldwide has initiated a new trend: Nano-biofertilizers, which combine nanotechnology with biofertilization to improve soil fertility, enhance crop productivity, optimize nutrient use, and minimize environmental harm. Conventional fertilizers have been widely used for decades, but their overuse has led to soil degradation, water pollution, and loss of biodiversity.<sup>5,6</sup> In the context of nutrient management, the concept

of nano-biofertilizers has emerged. These involve the combination of microbial inoculants with nanoparticles to improve nutrient uptake, stimulate microbial activity, and maintain healthy, living soils.<sup>7</sup>

### 2.1. Defining nano-biofertilizers

Nano-biofertilizers represent a new generation of fertilizers that include:

- (i) Nanoparticles: Serve as nutrient carriers, enhancing bioavailability and enabling controlled nutrient release.
- (ii) Biofertilizers: These are microbial substances containing beneficial microorganisms such as *Rhizobium*, *Azotobacter*, *Mycorrhizae*, and phosphate-solubilizing bacteria, which play crucial roles in biological nitrogen fixation, phosphorus solubilization, and plant growth promotion.<sup>8</sup>

### 2.2. Mechanisms of action

Nano-biofertilizers function through multiple mechanisms, including nutrient delivery, soil retention, and plant uptake, which collectively make them superior to conventional fertilizers.<sup>9</sup>

- (i) Controlled nutrient release: Nanoparticles, particularly in nanofertilizers, enable a slow and controlled release of nutrients, thereby reducing leaching losses and enhancing nutrient-use efficiency.<sup>10</sup> A critical aspect is the improvement of nitrogen and phosphorus use efficiency, as both nutrients are commonly lost through volatilization and runoff.<sup>11</sup>
- (ii) Enhanced microbial activity: Nano-biofertilizers can improve the viability and effectiveness of beneficial soil microorganisms. For example, nano-silica and nano-chitosan support microbial safety and promote the growth of probiotic bacteria.<sup>12</sup> Enzyme activity in soil, which contributes to enhanced nutrient bioavailability, is also improved by nano-zinc biofertilizers.<sup>13</sup>
- (iii) Improved plant nutrient uptake: Nanoparticles promote better root penetration and improved mobility of nutrients in the soil, leading to more efficient uptake of essential elements by plants.<sup>14</sup> Studies have shown that nano-biofertilizers increase root biomass and chlorophyll content, two effects directly linked to enhanced crop yield.<sup>15</sup>

### 2.3. Types of nano-biofertilizers

Table 1 presents the development of nano-biofertilizers targeting different nutrient deficiencies and soil conditions.

## 2.4. Advantages of nano-biofertilizers

Table 2 summarizes the various environmental and agricultural benefits of nano-biofertilizers compared to their conventional counterparts.

## 3. The role of nano-biofertilizers in soil fertility and health

Soil fertility is a crucial factor influencing soil health and its capacity to support productivity. It has been recognized that while conventional fertilizers have been widely applied to improve soil fertility, over-reliance on them often results in soil compaction, which can contribute to nutrient leaching and environmental pollution.<sup>20,21</sup> Nano-biofertilizers, which combine nanotechnology with biofertilizers, have therefore been proposed as an environmentally friendly alternative that stimulates microbial activity and enhances overall soil health.

### 3.1. Nano-biofertilizers and mechanisms in soil fertility

The use of nanoparticle-based formulations combined with biofertilizers to enhance nutrient availability and microbial activity in soil is referred to as nano-biofertilizers. Nanoparticles serve as carriers for nutrients and beneficial organisms, improving their stability and efficacy.<sup>22,23</sup> For example,<sup>24</sup> observed increased nitrogen availability in soil through slow-release techniques, which consequently decreased dependency on chemical fertilizers. Nano-biofertilizers also stimulate soil enzyme activity, a primary factor in nutrient cycling. Specifically, urease and phosphatase

activities in the soil increased after nanobiofertilizer application, making nitrogen and phosphorus more available.<sup>25,26</sup> Such improvements in nutrient efficiency directly contribute to increased agricultural output and soil fertility.

### 3.2. Impact on soil microbial communities

Microbial populations are key determinants of soil health due to their diversity and functional roles. Nano-biofertilizers elevate populations of beneficial bacteria such as *Rhizobium*, which fixes nitrogen, and *Pseudomonas*, which solubilizes phosphates.<sup>27,28</sup> The use of nano-biofertilizers has been shown to improve microbial biomass and enzymatic activities critical for the decomposition of organic matter and nutrient recycling.<sup>29</sup> In addition, nanoparticles such as nano-silica and nano-zinc have been reported to suppress pathogenic microbes while promoting the growth of beneficial ones. This dual effect supports soil health and reduces the incidence of soil-borne diseases.<sup>30,31</sup>

### 3.3. Sustainability and environmental benefits

Conventional fertilizers, in addition to supplying nutrients, often cause nutrient runoff, leading to eutrophication. On the contrary, nano-biofertilizers enhance nutrient use efficiency, reducing nutrient losses to the environment. Their slow-release properties ensure that nutrients are supplied to plants over an extended period, reducing the frequency of applications and minimizing environmental contamination. Nano-biofertilizers also promote microbial decomposition of plant residues and organic fertilizers, thereby increasing soil organic matter content. This, in turn, improves soil

**Table 1. Types and main functions of nano-biofertilizers with key references**

Type	Main function	References
Nano-nitrogen biofertilizers	Enhance biological nitrogen fixation and minimize Nitrogen losses	10
Nano-phosphate solubilizing bacteria	Increase phosphorus solubilization and availability	9
Nano-potassium biofertilizers	Improve potassium uptake and soil cation exchange capacity	16
Nano-zinc biofertilizers	Boost enzyme activity and micronutrient absorption	15
Nano-silica biofertilizers	Increase plant resistance to drought and pathogens	17

**Table 2. Environmental and agronomic benefits of nano-biofertilizers compared to traditional fertilizers**

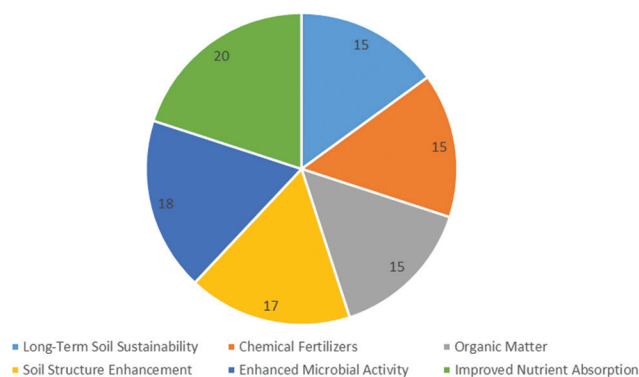
Benefit	Description	References
Higher nutrient efficiency	Reduces nutrient losses and improves plant uptake	5
Enhanced microbial function	Promotes soil biodiversity and nitrogen fixation	18
Reduction in chemical fertilizers	Decreases synthetic fertilizer dependency	12
Eco-friendly and sustainable	Limits soil pollution and groundwater contamination	19

structure, enabling better water retention to support root growth and facilitating the gaseous exchange necessary for healthy crop development.<sup>32,33</sup>

A quantitative representation of the role of nanobiofertilizers in sustaining soil fertility is shown in Figure 1. The chart illustrates six key functional contributions: (i) “Improved nutrient absorption” (20%) highlights the enhanced efficiency of nutrient uptake due to nanoscale delivery systems; (ii) “Enhanced microbial activity” (18%) refers to the stimulation of beneficial soil microorganisms facilitated by nano-encapsulated inoculants; (iii) “Soil structure enhancement” (17%) includes improved soil porosity and aggregation resulting from increased microbial exudates; (iv) “Long-term soil sustainability” (15%) reflects the cumulative effect of balanced nutrient release and ecological compatibility; (v) “Reduction in chemical fertilizers” (15%) demonstrates how nano-formulations reduce the need for synthetic inputs; and (vi) “Increase in organic matter” (15%) indicates the build-up of carbon and organic residues due to microbial and plant-soil interactions. These interconnected roles reinforce the multifunctional benefits of nano-biofertilizers in improving soil health over time.

#### 4. The role of nano-biofertilizers in plant growth and yield

Over the years, nano-biofertilizers have attracted mounting attention as a sustainable approach to stimulate plant growth and improve agricultural output. This is due to the synergistic effects of nanotechnology and biological fertilizers, which enhance nutrient availability and strengthen plant growth and soil health while minimizing pollution from fertilizer applications.<sup>34</sup> In this paper, the critical role of nano-biofertilizers in



**Figure 1. The role of nano-biofertilizers in sustaining soil fertility**

enhancing crop productivity, their mechanisms of action, and their advantages over conventional fertilizers are discussed.

#### 4.1. Mechanisms of action of nano-biofertilizers

The primary functions of nano-biofertilizers are improving nutrient use efficiency in crops, inducing beneficial microbial activity, and enhancing soil structure. Simply put, these fertilizers are engineered to deliver nutrients to plants in controlled and targeted manners at the nanoscale.<sup>35,36</sup> Due to their small size, nanoparticles have a large surface area that allows close contact with roots for more effective nutrient uptake by plants.<sup>37</sup> In addition, biofertilizers contain beneficial microorganisms, such as nitrogen-fixing bacteria and phosphate-solubilizing fungi, which enhance nutrient availability and absorption.<sup>38,39</sup>

One of the most important mechanisms through which nano-biofertilizers act is by releasing essential nutrients from otherwise inaccessible forms. For example, nano-encapsulated nitrogen fertilizers reduce nitrogen losses due to leaching and volatilization, ensuring a steady supply of nitrogen to crops. Similarly, nano-phosphorus fertilizers increase phosphorus solubilization and uptake, promoting proper root growth and higher crop yields.

#### 4.2. Advantages of nano-biofertilizers over conventional fertilizers

Conventional fertilizers have a significant drawback compared to nano-biofertilizers: They are often highly inefficient in nutrient delivery and can be detrimental to the environment, as well as less effective in helping plants cope with stress conditions. Conventional fertilizers frequently leach nutrients, causing pollution of both soil and water. In contrast, nano-biofertilizers release nutrients in a controlled manner, thereby reducing environmental degradation caused by nutrient wastage.<sup>40,41</sup> Moreover, the microbial components of biofertilizers improve soil organic matter and soil fertility, providing long-term benefits for sustainable agriculture.<sup>42,43</sup>

Another major advantage of nano-biofertilizers is their potential to increase plant tolerance to abiotic stresses such as drought, salinity, and metal toxicity. Studies have shown that plants treated with nano-biofertilizers exhibit improved drought tolerance linked to increased activity of antioxidant enzymes.<sup>18</sup> This effect is particularly important given the increasing impacts of climate change on agriculture.

Various studies have also demonstrated that nano-biofertilizers significantly enhance crop yield and productivity. For example, Meena *et al.*<sup>44</sup> showed that applying nano-biofertilizers to wheat increased grain yield by 20 – 30% compared to traditional fertilizers. Similar trials conducted on maize and rice reported higher biomass, increased chlorophyll content, and greater grain yields following nano-biofertilizer application.<sup>45,46</sup> These findings clearly indicate that nano-biofertilizers can play a major role in improving food security through sustainable agricultural practices.

Nano-biofertilizers combine nanoparticles with biological agents, including plant growth-promoting bacteria, which have been widely observed to stimulate plant growth and productivity (Table 3).

These studies indicate the potential for enhancing certain plant parameters and yields by combining biofertilizers with nanoparticles. However, in practice, the effectiveness of nano-biofertilizers may vary under the same conditions in which conventional fertilizers often fail. Therefore, further organized research is imperative to test formulations and application methods, with the aim of optimizing their performance across different agroecological zones.

#### 4.3. Comparison: Nano-biofertilizers versus conventional biofertilizers (yield and soil health)

The integration of nanotechnology with biofertilizers aims to overcome some limitations of traditional biofertilizers. In terms of crop yield under field conditions, nano-biofertilizers demonstrate a clear advantage. Conventional biofertilizers (microbial inoculants) can improve yields by enhancing nutrient availability and soil biological activity. However, their effects are often gradual and variable, as they rely on living organisms whose performance may be inconsistent due to environmental stress or poor survival in the soil. In contrast, nano-biofertilizers typically

exhibit faster and stronger impacts on crop growth, as nano-carriers provide immediate and efficient nutrient delivery in addition to microbial benefits. For example, field trials have reported that applying nutrients in nano form (like nanourea) can achieve yields comparable to or even higher than those achieved with standard fertilizer rates, despite using smaller quantities.<sup>50</sup> In one study, foliar application of nano-urea allowed a 25% reduction in conventional urea usage with no yield loss in wheat and rice. Another experiment on soybeans showed a ~20% higher seed yield when using nano-hydroxyapatite (a nano-phosphorus fertilizer) compared to traditional phosphate fertilizer.<sup>51</sup> These results suggest nano-enhanced biofertilizers can outperform traditional biofertilizers in terms of immediate yield gains, owing to the controlled nutrient release and targeted uptake. However, recent evidence also cautions that nanofertilizers are not a complete substitute for bulk fertilizers in all cases. Adequate macronutrient supply is still required, and nano-formulations are most effective as supplements to optimize efficiency rather than as replacements.

When considering long-term soil health, nano-biofertilizers offer additional advantages beyond conventional formulations. Conventional biofertilizers are well-known for their contribution to long-term soil health. They help build organic matter, improve soil structure, and increase microbial diversity. Their effects on soil fertility are cumulative over multiple growing seasons through mechanisms such as nitrogen fixation or phosphorus solubilization, and they are valued for being eco-friendly. Nano-biofertilizers aim to combine these long-term soil benefits with more immediate nutrient delivery. As they incorporate beneficial microbes and/or organic compounds, they continue to support soil biological health in much the same way as traditional biofertilizers. In addition, nano-carriers can protect microbes from environmental stress and ensure

**Table 3. Summary of different types of nano-biofertilizers and their observed effects**

Nano-biofertilizer composition	Observed effects on plants	References
Mesoporous silica nanoparticles with <i>Bacillus</i> sp. CP4 and AHP3	Enhanced plant growth and nutrient uptake	47
Zinc oxide nanoparticles with <i>Bacillus</i> sp. CP4 and AHP3	Improved plant growth and nutrient absorption	47
Copper oxide nanoparticles with <i>Bacillus</i> sp. CP4 and AHP3	Increased plant growth metrics and nutrient uptake	47
Silicon dioxide nano-fertilizers	Increased nitrogen and phosphorus content in plants; decreased sodium content; improved plant growth and yield	48
Nano-biofertilizer capsules	Enhanced plant growth physiology and yield	49

more effective delivery to the rhizosphere. Some studies have reported that nano-biofertilizer application leads to higher soil enzyme activities and microbial biomass compared to conventional treatments, indicating a stimulated soil microbiome alongside crop growth promotion. Over multiple growing seasons, this may translate into improved soil structure and nutrient cycling. However, definitive long-term field studies are still limited. One concern is the potential for negative effects on soil properties from the accumulation of nanoparticles (e.g., heavy metal buildup or pH shifts). So far, short- and medium-term field data are promising, showing maintained or improved soil fertility and no adverse effects on soil biota, but ongoing monitoring is necessary. Farmer adoption of nano-biofertilizers may ultimately depend on their consistent field performance across varied environments. While traditional biofertilizers can fail under suboptimal field conditions such as drought or poor soils, nano-biofertilizers have demonstrated greater resilience by continuing to release nutrients and support microbial activity even under stress. For instance, polymer-encapsulated biofertilizer nanoparticles can stabilize microbes against heat and desiccation, delivering better results than free microbial inoculants. This suggests that nano-based formulations may provide more reliable long-term benefits in heterogeneous field environments. Overall, nano-biofertilizers appear to match or exceed conventional biofertilizers in enhancing crop yields while also sustaining soil health. They combine the slow-building advantages of biofertilization with the rapid nutrient availability offered by nanotechnology. Nevertheless, agronomists emphasize the need for more multi-season

trials to assess long-term impacts on soil quality indicators such as organic carbon content and microbial diversity. Such data will be critical in establishing whether nano-biofertilizers can sustain or even improve long-term soil health compared to traditional biofertilizers.

## 5. Nano-biofertilizer manufacturing technologies

Nano-biofertilizers can be manufactured using several methods, as outlined in Table 4, which integrate nanotechnology with biological agents for nutrient delivery, thereby supporting sustainable agriculture.

### 5.1. Encapsulation with nanomaterials

Encapsulation is one of the most widely used manufacturing techniques for nano-biofertilizers. In this approach, microbial inoculants or nutrient formulations are enclosed within nano-sized carriers, often made from biopolymers such as chitosan, alginate, or starch. This method improves the stability and viability of microbial strains and allows for the gradual release of nutrients into the rhizosphere.

A practical example is the use of chitosan–alginate nanocapsules embedded with nitrogen-phosphorus-potassium nutrients and plant growth-promoting rhizobacteria, which have been successfully employed in field trials. The inclusion of humic acid as a cross-linker produced porous capsules with extended nutrient availability and improved root colonization. These nanocapsules can be applied as soil granules, seed coatings, or foliar sprays. Uniform-sized beads can be produced using a sodium alginate–calcium chloride

**Table 4. Summary of common nano-biofertilizer manufacturing methods, along with references to relevant studies**

Manufacturing method	Description	References
Encapsulation with nanomaterials	Biofertilizers are encapsulated within nanomaterial coatings, such as chitosan and alginate crosslinked with humic acid, to improve stability and controlled nutrient release	49
Green synthesis using microorganisms	Microorganisms such as bacteria, fungi, and algae are used to biosynthesize nanoparticles, which are then combined with biofertilizers. This eco-friendly approach leverages the natural reducing agents produced by these organisms	52
Chemical methods (e.g., sol–gel, hydrothermal)	Chemical techniques such as sol-gel and hydrothermal methods are employed to synthesize nanoparticles, which are then integrated with biofertilizers. These methods allow for precise control over particle size and composition	53
Top-down and bottom-up approaches	Top-down approaches involve breaking down bulk materials into nanoparticles, while bottom-up approaches assemble nanoparticles from atomic or molecular components. Both methods are used to create nano-biofertilizers with desired properties	1

cross-linking process, which ensures ease of handling and consistent field performance.<sup>54-56</sup>

### 5.2. Biological (green) synthesis

Green synthesis utilizes the natural biochemical pathways of living organisms – bacteria, fungi, algae, or plants – to reduce metal salts into nanoparticles. This bottom-up approach is eco-friendly, avoids the use of hazardous chemicals, and aligns with organic farming practices. Certain microbes, such as filamentous fungi or actinobacteria, can precipitate nanoparticles like zinc oxide (ZnO), iron oxide, or selenium through enzymatic activity. For example, extracts from *Chlorella vulgaris* have been used to synthesize iron oxide nanoparticles, which possess antifungal and plant-growth-promoting properties. In addition, *Aspergillus* species have been employed to produce nano-phosphate fertilizers, which have shown promising results in maize cultivation. Some key advantages of this method are its biocompatibility, low energy requirements, and sustainability. However, some challenges remain, including low productivity, variable particle size, and difficulty in large-scale standardization.<sup>57</sup>

### 5.3. Chemical synthesis methods

Chemical techniques such as sol-gel, hydrothermal synthesis, and co-precipitation are widely used in the production of nanofertilizers. These methods allow for precise control over particle size and purity. For instance, nano-hydroxyapatite, which is synthesized through hydrothermal methods, has demonstrated improved phosphorus availability and 20%–30% higher yields in soybean and wheat when compared to conventional phosphate fertilizers.

Another example is nano-urea, which has been commercialized by the Indian Farmers Fertilizer Cooperative (IFFCO) and is produced through industrial encapsulation and reverse osmosis. The main benefits include uniformity, effectiveness, and adaptability. However, there are some limitations associated with this method, such as high production costs, chemical residues, and the need for advanced equipment.<sup>58</sup>

### 5.4. Top-down versus bottom-up nanofabrication

In top-down fabrication, bulk materials are broken down into nanoparticles through physical methods such as ball milling or grinding. For example, rock phosphate has been milled into nanophosphate particles and combined with microbial solubilizers to improve nutrient availability in calcareous soils. Bottom-up approaches, as discussed above, assemble particles from atoms or molecules using biological or chemical processes.

In summary, Top-down fabrication is simple but energy-intensive and more challenging when it comes to controlling particle size, whereas bottom-up is more precise and controllable but may require complex inputs.<sup>59</sup>

### 5.5. Economic and scalability considerations

Each synthesis method varies in cost, efficiency, and scalability. Encapsulation and biosynthesis are eco-friendly but slower and less uniform. Chemical synthesis is effective and precise but costly and infrastructure-intensive. Top-down methods are straightforward but may not yield optimal nanostructures.

For large-scale farming, low-cost biological or precipitation methods may be best, whereas, for high-value crops, more expensive encapsulated fertilizers may be justified.

Overall, each method plays a specific role: Encapsulation combines slow-release with microbial protection; green synthesis is sustainable and chemical-free; chemical synthesis offers high precision; and hybrid methods strike a balance between cost and efficiency.<sup>60</sup>

Despite the diversity of methods used to manufacture nano-biofertilizers, there is significant variation in economic efficiency and industrial scalability. For example, chemical methods such as pyrolysis or co-precipitation are effective in producing homogeneous particles with high precision, but they are expensive and require complex technical infrastructure. In contrast, biosynthesis using microorganisms or plant extracts represents a lower-cost and more environmentally friendly alternative, but it still faces challenges in standardizing the physical properties of the produced particles. Therefore, evaluating the effectiveness of these technologies is not limited to release efficiency or stability. Economic factors, such as raw material and energy costs, and the potential for commercial scalability to meet the requirements of large-scale agriculture, must also be considered.

These methods highlight the diverse approaches in the production of nano-biofertilizers, with each beneficial microorganism and technology used for nutrient nanoparticle loading playing a unique role in enhancing nutrient delivery and promoting sustainable agricultural practices.

## 6. The role of nano-biofertilizers in sustaining soil fertility

Soil fertility quite plays an important role in determining agricultural productivity as well as the sustainability of ecosystems. Conventional chemical

fertilizers have a long history of providing essential nutrients to crops; however, their overuse has led to soil degradation, disruptions to microbial activity, and environmental pollution. In contrast, nano-biofertilizers offer a sustainable alternative by maximizing nutrient efficiency and promoting microbial activity, ultimately enhancing soil health. These advanced fertilizers combine nanotechnology and biofertilization approaches to optimize nutrient delivery and ensure ecological sustainability.<sup>17</sup>

### 6.1. Nanotechnology innovations in nano-biofertilizers for improved nutrient use efficiency

The high surface area of nano-phosphorus helps control and reduces leaching and volatilization losses of the applied phosphorus source.<sup>15</sup> The slow and steady release of essential nutrients like nitrogen, phosphorus, and potassium improves plant uptake efficiency while minimizing environmental contamination.<sup>11</sup> For example, nitrogen nano-capacitated fertilizers can deliver nitrogen slowly and in a targeted manner, reducing nitrogen losses commonly associated with conventional mineral fertilizers.<sup>10</sup> Reducing the frequency of source material application can lead to significant cost savings by minimizing resource wastage, a common issue with traditional fertilizer use. This enhances resource efficiency and is considered an attractive investment factor, as optimal resource use is one of the most important determinants of successful and sustainable agricultural investment.<sup>61</sup>

### 6.2. Healthy soil microbiome

Nano-biofertilizers also play a crucial role in promoting a healthy soil microbiome. Conventional chemical fertilizers often harm beneficial microorganisms in the soil, leading to soil degradation and nutrient imbalances. Gold nanoparticles doped with essential elements such as zinc, iron, and silica have been shown to enhance microbial growth, enzyme activities, and nitrogen fixation.<sup>7</sup> Microbial strains such as *Azotobacter* spp., *Rhizobium* spp., and *Bacillus* spp. are commonly included in nano-biofertilizers to promote healthy soils and support plant growth.<sup>18</sup> These strains contribute to the soil by:

- (i) Biological nitrogen fixation, which reduces reliance on synthetic nitrogen sources.
- (ii) Phosphate solubilization, which increases the availability of phosphorus to plants.
- (iii) Supporting the plant in initiating and developing roots, enhancing nutrient uptake.

In addition, studies have shown that nano-biofertilizers improve microbial diversity, leading to better soil aggregation and more efficient decomposition of organic matter, both of which are key indicators of sustainable soil fertility.<sup>9</sup>

### 6.3. Improvement of soil structure and organic matter

Nano-biofertilizers may also indirectly improve soil structure, porosity, and aggregation. Increased porosity and aggregation result in reduced soil compaction and enhanced root-zone aeration. This, in turn, contributes to higher organic matter content by stimulating microbial-driven carbon and nitrogen cycling. Nano-based amendments can help sustain long-term fertility by reducing soil erosion, improving water-holding capacity, and enhancing the stability of organic matter. For instance, nano-clay and biochar-enhanced biofertilizers have reduced erosion while improving water retention and organic matter stability, leading to greater long-term fertility sustainability.<sup>62</sup>

### 6.4. Reduction in chemical fertilizer dependency

A key objective of sustainable agriculture is to reduce dependency on synthetic fertilizers. This goal is increasingly being achieved through the use of nano-biofertilizers due to the following factors:

- (i) Enhanced nutrient retention and the requirement for lower application rates of fertilizers.<sup>19</sup>
- (ii) Reduced environmental pollution due to decreased nitrate leaching and greenhouse gas emissions, thereby minimizing ecological harm.<sup>63</sup>
- (iii) Improved resistance of plants to abiotic stresses<sup>64</sup> such as drought and salinity, though not necessarily heavy metal toxicity.

For example, nano-zinc biofertilizers have been shown to mitigate zinc toxicity – commonly observed with conventional zinc sulfate fertilizers – while simultaneously promoting plant growth.<sup>15</sup> Another example is nano-silica biofertilizers, which enhance resistance to disease and drought in crops by strengthening plant cell walls and improving water retention, as reported by Lateef *et al.*<sup>65</sup>

### 6.5. Long-term soil fertility and sustainability

Nano-biofertilizers have the potential to sustain long-term soil fertility through several mechanisms:

- (i) Maintaining soil pH at an equilibrium level by gradually releasing nutrients into the soil solution.
- (ii) Reducing salinization, thereby preventing the rapid buildup of chemical residues.

- (iii) Enhancing carbon sequestration, which contributes to mitigating the impacts of climate change.<sup>19</sup>

Nano-biofertilizers help conserve soil biodiversity, promoting the sustainable management of soil fertility. They support the development of a balanced soil ecosystem and ensure that soils remain productive and viable as a resource for future generations.

## 7. Role of nano-biofertilizers in environmental protection and sustainability

Agricultural productivity and sustainability are becoming increasingly important in light of rising global food demand and growing environmental degradation. While conventional chemical fertilizers have been effective in boosting crop productivity, they pose significant environmental risks, including land degradation, water pollution, and greenhouse gas emissions.<sup>66</sup> In response, nano-biofertilizers have emerged as sustainable alternatives that enhance plant growth while minimizing ecological harm.<sup>67</sup> This section discusses the role of nano-biofertilizers in promoting environmental protection and long-term sustainability.

### 7.1. Integration with precision agriculture: Remote sensing and artificial intelligence (AI)

The integration of nano-biofertilizers with precision agriculture technologies – such as remote sensing, drones, and AI—represents a forward-looking approach to sustainable farming. Remote sensing tools (e.g., satellites, drones, and field sensors) can detect spatial variations in nutrient deficiencies, allowing targeted application of nano-biofertilizers only where needed. This minimizes waste and maximizes efficiency. For example, Normalized Difference Vegetation Index maps generated by drones can guide site-specific applications via smart sprayers, reducing both input cost and environmental impact. Additionally, sensors based on the Internet of Things and AI systems can optimize nutrient application timing and dosage by predicting crop nutrient demands or stress conditions. Nanosensors embedded in the soil can monitor nitrate levels in real time, transmitting data to AI models that trigger precise foliar applications. Because nano-formulations are typically in liquid or fine particle form, they are well-suited for modern variable-rate applicators and drone-based spraying systems. Countries such as India have already piloted drone-based nano-urea applications with promising outcomes. This integration supports the “4R” nutrient stewardship strategy (right source, right

rate, right time, and right place), thereby enhancing productivity and resource-use efficiency. As such, nano-biofertilizers are well-aligned with the evolving framework of data-driven, smart agriculture.<sup>68,69</sup>

### 7.2. Balanced perspective: Agronomic benefits versus environmental risks

Nano-biofertilizers offer clear agronomic benefits, but a balanced analysis must also acknowledge their potential drawbacks. On the benefits side, nano-biofertilizers can significantly improve nutrient use efficiency and crop productivity. Studies indicate that nano-formulations can increase plant nutrient uptake and yields by up to 30% compared to conventional fertilizers.<sup>70</sup> For example, controlled nano-nutrient delivery has been shown to boost chlorophyll content and root growth, translating into higher biomass and grain yield.<sup>71</sup> These fertilizers also enhance stress tolerance (e.g., drought and salinity) and stimulate beneficial soil microbes, contributing to long-term soil fertility. In summary, nano-biofertilizers can maintain high yields with smaller doses, potentially reducing nutrient leaching and environmental pollution.

On the limitations and environmental risks side, it is important to recognize that engineered nanoparticles may pose ecological challenges. Unlike conventional fertilizers, which typically dissolve or biodegrade, some nanoparticles are persistent and may accumulate in soil with repeated applications.<sup>70</sup> Persistent nanoparticles could affect soil health and ecosystem dynamics if they accumulate faster than they degrade. For instance, excessive or improper use of nano-fertilizers can result in nanoparticle pollution, which may adversely impact plant growth and soil biota. Moreover, research shows that nano-fertilizer applications can alter the composition of soil microbial communities, with both beneficial and deleterious effects.<sup>72</sup> Certain nanoparticles (e.g., ZnO, copper [II] oxide) at high concentrations have been found to reduce microbial diversity and activity.<sup>73</sup> A recent meta-analysis reported that nanomaterials reduced soil microbial biomass by ~14% on average and slightly decreased microbial diversity, highlighting this concern. Disruption of beneficial microbes (such as nitrogen-fixers or decomposers) could negatively affect nutrient cycling and soil health. Nanoparticles may also harm non-target organisms (e.g., earthworms and insects) and can enter water bodies through surface runoff. Laboratory studies have noted phytotoxic effects at high nanoparticle doses, including inhibited seed germination and chlorosis in plants exposed to certain metal oxide nanoparticles. Given these uncertainties, researchers emphasize the need for thorough, long-term

environmental assessments of nano-biofertilizers.<sup>1</sup> Overall, while nano-biofertilizers have the potential to reduce the environmental footprint of agriculture by lowering fertilizer requirements, a cautious approach is warranted. Potential risks—such as nanoparticle accumulation, impacts on the soil microbiome, and unknown long-term ecosystem effects—should be transparently acknowledged. This balanced perspective ensures that the review does not appear overly optimistic and aligns with current calls in the literature for comprehensive risk–benefit analyses of nanotechnology in agriculture.<sup>70</sup>

### 7.3. Environmental benefits of nano-biofertilizers

Nano-biofertilizers combine nanotechnology with bio-based nutrient sources to improve nutrient use efficiency while reducing environmental degradation. The release of nutrients is more slowly than conventional fertilizers, minimizing leaching into water bodies and reducing soil contamination.<sup>74</sup> The use of nanocarrier-encapsulated essential nutrients improves bioavailability, allowing for lower application rates while maintaining high crop yields.<sup>75</sup> In addition, nano-biofertilizers stimulate microbial diversity and soil health by promoting beneficial microbial interactions. For example, nitrogen-fixing bacteria in bio-nanocomposites enhance nitrogen availability and reduce dependence on synthetic nitrogen, a major contributor to nitrate pollution.<sup>76</sup> Such biological interventions help maintain long-term soil fertility and support environmental stability.

### 7.4. Contribution to sustainability

The application of nanotechnology in biofertilizers aligns closely with the principles of sustainable agriculture, aiming to lower chemical inputs and maximize resource efficiency.<sup>77</sup> Furthermore, nano-biofertilizers help reduce the carbon footprint, as their precision application reduces the need for energy-intensive manufacturing, transportation, and excessive usage.<sup>18</sup>

They also support plant climate resilience by mitigating the effects of abiotic stress factors like drought and salinity. Nanoparticles such as ZnO and silica, when incorporated into biofertilizers, have been shown to improve water retention and enable plant growth under adverse conditions.<sup>78</sup> These features position nano-biofertilizers as a strategic tool in addressing the effects of climate change on agriculture.

## 8. Challenges and future perspectives

Challenges in the large-scale adoption of nano-biofertilizers include concerns regarding nanoparticle

toxicity regulations and production costs.<sup>79</sup> Extensive research is needed to evaluate their long-term impacts on ecosystems and human health.<sup>80</sup> This should be a priority for governments and research institutions – to develop safe, cost-effective, and environmentally benign products that can be widely adopted. However, implementation in numerous regions remains hindered by high costs, difficulties in scaling up production, and regulatory approval hurdles.<sup>16</sup> Future research should focus on:

- (i) The development of biodegradable nano-carriers for microbial stabilization.
- (ii) The assessment of long-term impacts on soil health.
- (iii) The commercialization of low-cost nano-biofertilizers for global agriculture.

There is significant potential for nano-biofertilizers to revolutionize sustainable and precise food production systems in agriculture.<sup>19</sup> Key regulatory challenges include the absence of clear legal frameworks governing the use of nanoparticles in agriculture, which delays their commercial adoption. Economic challenges also persist, such as high initial production costs and limited government support in many developing countries. Barriers to farmer adoption include a lack of awareness, limited technical knowledge, and concerns about potential environmental impacts. As Rai *et al.*<sup>74</sup> emphasized, the limited availability of long-term studies and insufficient understanding of nanoparticle behavior in the environment remain major obstacles to the widespread application of this technology in agriculture.

### 8.1. Regulatory frameworks and global examples

The regulatory landscape for nano-biofertilizers is still developing, with approaches varying widely across countries. Globally, no unified regulatory framework exists for nanofertilizers. This regulatory gap means that approval processes, safety evaluations, and labeling requirements for nano-enabled fertilizers are handled differently depending on jurisdiction. Several illustrative examples can be provided: (i) India – proactive regulatory inclusion: India has been one of the early adopters of nanofertilizer regulation. In 2021, the Indian government amended its fertilizer control order (FCO) to officially include “nanofertilizers” as a distinct category. Specific guidelines and quality standards were issued – for instance, the FCO now defines and sets specifications for nano urea (liquid), including permissible nutrient content and particle size. Initially, the IFFCO was authorized to commercially produce nano-urea.<sup>81</sup> As a result, any nano-fertilizer in India must undergo a government approval process,

demonstrating efficacy and safety before entering the market. This move has facilitated the rollout of IFFCO's nano-urea to farmers under regulatory oversight; however, the approval is provisional—the inclusion of nano-urea was initially granted for 3 years, indicating that regulators are adopting a cautious approach while gathering performance and safety data. India's example illustrates a country developing a dedicated regulatory framework for nano-fertilizers, aiming to promote innovation (particularly by encouraging reduced urea consumption) while maintaining regulatory oversight;<sup>81</sup> (ii) European Union (EU) – existing chemical and fertilizer laws: In the EU, nanomaterials are regulated under broader chemical and product safety regulations. The EU fertilizing products regulation 2019/1009 does not explicitly create a separate category for nanofertilizers but requires labeling if a product contains intentionally manufactured nanomaterials, according to specific size thresholds. In practice, nano-biofertilizers in the EU are assessed under existing frameworks like Registration, Evaluation, Authorization, and Restriction of Chemicals for chemical safety, and under fertilizer regulations for efficacy. While the EU provides guidance on nanomaterials in food and feed, regulatory guidance for agricultural inputs is still evolving. Products containing nanoscale ingredients must be clearly indicated to end-users in the EU, and risk assessments are conducted on a case-by-case basis. However, there is currently no distinct approval pathway for nano-fertilizers, placing them in a regulatory gray area between fertilizer laws and general nanomaterial policies. This can hamper innovation, as manufacturers may face uncertainty regarding regulatory requirements, and regulators may lack specific protocols for assessing the behavior of nanoparticles in soil. The EU's approach reflects a cautious stance, treating nano-biofertilizers within existing frameworks while emphasizing the precautionary principle;<sup>82</sup> (iii) United States and other regions – lack of nano-specific fertilizer rules: In the United States, fertilizers (excluding pesticides) are primarily regulated at the state level, with some oversight from federal agencies like the United States Department of Agriculture and the environmental protection agency (EPA). Currently, there are no fertilizer laws specifically targeting nanoscale products; nano-biofertilizers are regulated similarly to conventional fertilizers in terms of nutrient claims. However, any novel materials, such as nanoparticle coatings, may be subjected to environmental and safety regulations (e.g., the Toxic Substances Control Act may apply if the nanoparticles are considered new chemical substances). Although the

EPA has started evaluating nanopesticides under specific guidelines, nano-fertilizers have received comparative regulatory attention. Many countries in Africa, Asia, and Latin America also lack explicit nano-specific regulations. Most rely on traditional fertilizer approval systems that do not address nanoscale issues. A recent review pointed out that many nations have yet to draft regulatory guidelines for nano-agricultural products. This absence of oversight means such products could reach markets without thorough safety evaluation. While this can accelerate innovation and market entry, it raises concerns about safety, consistency, and public trust. For instance, in countries without specific regulations, a company may sell a “nano-biofertilizer” containing engineered nanoparticles without any obligation to test or label it as such. This presents a risk of regulatory lag, where technological advancement outpaces policy development, which could lead to either environmental harm or diminished consumer confidence.<sup>83</sup>

## **8.2. Farmer awareness, training, and adoption in developing countries**

Regardless of how effective nano-biofertilizers may be, their real-world impact ultimately depends on farmer adoption. In many developing countries, farmer awareness and education regarding this emerging technology remain limited. Successful implementation therefore requires targeted outreach and training at the grassroots level.

### *8.2.1. Current awareness gap*

As nano-biofertilizers represent a relatively recent innovation, many farmers (especially smallholders) are unfamiliar with the term or may associate “nano” with something overly technical, risky, or expensive. Surveys and extension reports consistently indicate that a lack of knowledge is a major barrier to the adoption of improved agricultural inputs in developing regions. A recent analysis highlighted that economic, technological, and perceptual barriers limit farmers' willingness to adopt nano-agricultural products in the absence of adequate awareness and guidance.

### *8.2.2. Need for training programs*

To bridge this gap, targeted training and demonstration programs are essential. Farmers must understand how nano-biofertilizers work (e.g., their slow-release properties), the correct application methods, and the benefits they offer. Improper use could lead to reduced efficacy or wastage of products. For example, it is important that farmers learn that nano-formulations

require lower dosages than conventional fertilizers and that over-application can be harmful or counterproductive. Educational programs should also address safe handling practices, compatibility with other agrochemicals, and integration into existing fertilization schedules.

Governments and agricultural extension agencies in some countries have begun implementing such initiatives. In India, for example, field demonstrations and “farmer field days” for nano-urea have been organized, allowing growers to observe yield improvements with reduced fertilizer input. This participatory approach builds trust and understanding through firsthand observation and practical experience.

### 8.2.3. *Benefits of awareness*

When farmers understand the value of nano-biofertilizers – such as reduced input costs and improved productivity – they are more likely to adopt the technology. For smallholder and resource-poor farmers, special attention must be given to affordability, appropriate packaging sizes (e.g., small sachets), and clear labeling (preferably using pictorial instructions). Training modules should cover topics such as identifying deficiency symptoms, appropriate timing and dosage, safe storage practices, and long-term benefits for soil health.

### 8.2.4. *Challenges in developing countries*

Weak extension infrastructure and skepticism toward new technologies can hinder effective outreach. Farmers may ask: “Why switch from manure or urea to something unfamiliar?” To address this, the involvement of trusted local figures – such as lead farmers, agricultural officers, or cooperatives – is vital. Furthermore, training helps prevent misuse (e.g., over-application), ensuring responsible and efficient use of nano-biofertilizers.

The successful adoption of nano-biofertilizers depends significantly on farmer education and training. Without this foundation, innovations risk remaining limited to research trials and failing to reach millions of potential beneficiaries. This section introduces a socio-economic dimension to the review, by emphasizing that technological advancement must be accompanied by effective knowledge transfer, particularly in regions where yield gaps are wide and the need for sustainable agriculture is most pressing.

## 8.3. Antibiotic resistance gene transfer risk from microbial components

The potential risk of antibiotic resistance gene (ARG) transfer from the microbial components of

nano-biofertilizers is a significant biosafety concern. Many plant growth-promoting bacteria used in biofertilizers naturally harbor ARGs, sometimes located on mobile genetic elements such as plasmids. The large-scale application of such bacteria could introduce ARGs into the soil microbiome, where horizontal gene transfer to native microbes or even opportunistic pathogens may occur. Studies have shown that strains such as *Pseudomonas fluorescens* can carry resistance to antibiotics such as tetracycline, and repeated soil exposure may increase the abundance of resistant microbes. Although nano-components themselves do not cause resistance, nanoparticles may create stress conditions that potentially facilitate gene exchange. To mitigate this, researchers recommend rigorous screening of microbial strains using molecular diagnostics or genome sequencing to ensure they lack transferable ARGs. Regulatory agencies should consider incorporating ARG risk assessments into the biofertilizer approval process. While current guidelines often focus on pathogen exclusion, ARG monitoring remains largely unaddressed. Therefore, responsible development of nano-biofertilizers must include biosafety evaluations of microbial inputs to prevent unintended contributions to antimicrobial resistance.<sup>84,85</sup>

## 9. Effect of fertilizer type and concentration on soil health

Soil is one of the most important components of the agricultural environment. It serves as the medium in which plants grow and obtain nutrients and water. With the increasing demand for agricultural production, fertilizers have become essential to replenish nutrients lost from the soil. However, the type and concentration of fertilizer used play a significant role in determining the extent to which both soil and plants benefit, as well as the broader environmental impact. Healthy soil is the foundation of productive farming. It supports plant growth, regulates water, filters pollutants, and sustains biodiversity. However, maintaining soil health is a growing concern as modern agriculture relies heavily on fertilizers. While fertilizers help boost crop yields, their type and concentration can significantly influence soil vitality over time.

The impact of fertilizer type and concentration on soil health cannot be overlooked. Although fertilizers are intended to enhance agricultural productivity, their unplanned or excessive use can negatively affect both the environment and long-term soil fertility. Striking a balance in fertilizer application and choosing appropriate

types are keys to maintaining healthy and productive soil for future generations. Understanding the impact of fertilizer type and concentration on soil health is critical to achieving sustainable agriculture. While fertilizers contribute to increased productivity, their indiscriminate use can lead to soil degradation and environmental pollution. Therefore, adopting sustainable agricultural practices that balance productivity with the preservation of soil and environmental health is essential.

Organic fertilizers differ significantly from chemical fertilizers in their impact on soil health. Organic fertilizers, such as compost and manure, improve soil structure and increase its organic matter content, improving aeration as well as the soil's ability to retain moisture and nutrients. These fertilizers also enhance soil biological activity by creating a favorable environment for the growth of beneficial microorganisms that contribute to soil health and fertility. Although their effects are slower to manifest, they are long-lasting, sustainable, and environmentally friendly. In contrast, chemical fertilizers provide nutrients rapidly, accelerating plant growth and increasing yields in the short term. However, excessive use can negatively impact soil health in the long term. Overuse of chemical fertilizers leads to salt accumulation, degradation of soil structure, reduced microbial diversity, and an increased risk of groundwater contamination. Therefore, a balanced use of both fertilizer types, based on the specific needs of soil and plants, is recommended to ensure high productivity while preserving soil health and sustainability. Nutrient inputs such as chemical fertilizers and animal manure have positively influenced soil health characteristics. Fertilizers may enhance soil organic matter when applied appropriately. However, further research is needed to better understand the impact of these inputs on soil health and carbon storage.<sup>86</sup> A study by Pahalvi *et al.*<sup>87</sup> emphasizes the importance of maintaining soil health to ensure sustainable ecosystems and agricultural productivity. It highlights that the physical, chemical, and biological properties of soil are affected by the excessive use of chemical fertilizers. While these fertilizers contribute to increased crop yields, they also reduce microbial activity, degrade soil quality, and pollute the environment. The study concludes that continued reliance on chemical fertilizers threatens soil biodiversity and negatively impacts its long-term health.

Researchers<sup>88,89</sup> have also noted that soil is an essential natural resource for plant growth, and its health is significantly affected by human interventions such as tillage, irrigation, and fertilization. Nitrogen, a key nutrient in fertilization, influences soil organic

matter, microbial populations, and acidity. Studies have shown that applying nitrogen at optimal rates promotes plant growth and increases organic matter without compromising soil health.<sup>18</sup> However, excessive nitrogen application can lead to organic matter loss and increased acidity, which negatively impacts soil microorganisms. As such, balanced nutrient management and the incorporation of organic fertilizers are recommended to maintain and improve soil health.<sup>90</sup>

## 10. Conclusion

Nano-biofertilizers have demonstrated significant potential in enhancing soil fertility by improving nutrient absorption, boosting microbial activity, and reducing dependence on chemical fertilizers. While current findings affirm their positive role in sustainable agriculture, further research is essential to evaluate their long-term impacts under various soil and crop conditions. Future studies should also assess their cost-effectiveness, environmental safety, and compatibility with traditional fertilization practices to fully harness their potential.

Nano-biofertilizers are thus considered a promising innovation in sustainable agriculture. They enhance microbial activity, improve soil structure, reduce the need for chemical inputs, and support long-term sustainability. With continued research into environmentally friendly, relatively inexpensive, and efficient nano-biofertilizer formulations, this technology could revolutionize agricultural practices worldwide, contributing to the production of healthier and more secure food systems. Nano-biofertilizers have the potential to improve nutrient efficiency, enhance soil health, and minimize environmental pollution. Although challenges remain, further research and supportive policies can accelerate their integration into diverse and mainstream agricultural practices, paving the way for a greener and more sustainable future.

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The authors declare that they have no competing interests.

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