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Smart fertilizer technologies: An environmental impact assessment for sustainable agriculture

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ABSTRACT

The global food supply heavily depends on utilizing fertilizers to meet production goals. The adverse impacts of traditional fertilization practices on the environment have necessitated the exploration of new alternatives in the form of smart fertilizer technologies (SFTs). This review seeks to categorize SFTs, which are slow and controlled-release Fertilizers (SCRFs), nano fertilizers, and biological fertilizers, and describes their operational principles. It examines the environmental implications of conventional fertilizers and outlines the attributes of SFTs that effectively address these concerns. The findings demonstrate a pronounced environmental advantage of SFTs, including enhanced crop yields, minimized nutrient loss, improved nutrient use efficiency, and reduced greenhouse gas (GHG) emissions. Nevertheless, amidst these benefits, the challenges and constraints associated with these technologies, such as production expenses and potential environmental impacts of specific components, are also discussed. A comparative assessment of these SFTs emphasizes the importance of a balanced approach, considering three crucial factors: efficiency, environmental safety, and cost-effectiveness. While no single SFT achieves optimal balance across these dimensions, integrating multiple fertilizer technologies may help mitigate individual drawbacks. Also, financial and cost-to-benefit analyses are essential to gauge their applicability across diverse cropping environments. Future perspectives shed light on emerging SFTs and innovative approaches to overcome prevailing challenges and cultivate a more impactful role in fostering sustainable agriculture.

1. Introduction

The global demand for food, driven by a rising population, presents a challenge for the agricultural sector to increase productivity while keeping agriculture's environmental footprint under control. Throughout history, both natural and synthetic fertilizers have been essential for improving food output, with a dramatic increment following the inception of nitrogen (N) based fertilizers [1]. About half the world's population relies on synthetic N fertilizers for sustenance [2]. However, this prevalent reliance on conventional fertilizers, including phosphorus (P) and potassium (K), is exerting significant strain on the environment, raising concerns about the long-term sustainability of these practices.

Environmental concerns about the use of fertilizers start even before they enter the growers' field. The manufacturing of N fertilizers is responsible for tremendous greenhouse gas emissions due to high energy requirements, and it has also been linked to increased levels of pollutants like ammonia and arsenic in the water and soil of the areas of operation [3]. Similarly, the mining and processing of phosphate rock, a vital component for P fertilizers, may harm the environment by discharging radioactive elements, heavy metals, and various other contaminants [4]. The production of another crucial component of fertilizers, potash, can potentially disrupt regional ecosystems and contaminate land, air, and water. This contamination can occur through mining or discharge of waste by-products.

The subsequent phase of environmental contamination begins with

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applying these fertilizers in agricultural settings. Despite ongoing initiatives, the management of applied fertilizers remains suboptimal. As a result, only a small portion of the fertilizers is utilized by plants, roughly 20–50% for the N fertilizers and a similar or lower proportion for P and K fertilizers. The remaining material is lost to the environment through leaching, emissions, fixation, runoff, or utilization by soil microorganisms, resulting in lower soil fertility and economic losses [5,6]. Furthermore, the increased levels of nitrates in the soil and water can harm livestock and humans, with studies showing negative health impacts on children, such as blue baby syndrome and methemoglobinemia [7]. Elevated P concentration in waterbodies can lead to excessive proliferation of algal blooms, leading to eutrophication and compromised water quality [8]. Similarly, the overuse of K can disrupt soil nutrient balance, causing environmental and economic losses. Food produced on soils exposed to excessive chemical fertilizers may result in adverse health effects for human beings [9].

Given the challenges, managing these nutrients well in the soil is important to minimize the losses. Various approaches are being employed to increase nutrient use efficiency (NUE), but one of the most promising is the introduction of smart fertilizer technologies (SFTs). A comprehensive evaluation of these technologies is imperative to explore their role in fostering sustainable agricultural practices [10]. Thus, the purpose of this review is to (i) outline the different types of smart fertilizer technologies, (ii) discuss the environmental benefits of these technologies, and (iii) explore the potential challenges linked to their use.

2. Criteria of the article selection

The primary aim of this review was to explore SFTs and their environmental impacts with a focus on sustainable agriculture. We examined biofertilizers, slow and controlled-release fertilizers, and nano fertilizers, highlighting their advantages in fostering eco-friendly agricultural practices, the environmental and regulatory challenges associated with their use, and future perspectives. We selected the literature for this review based on five key criteria: 1) Relevance: the papers had to be directly related to our topic and enhance our understanding of SFTs; 2) Timeliness: We focused on recent papers to provide the latest overview of the SFTs and their environmental impacts; 3) Quality: We chose high-quality studies with sound procedures and conclusions that were well backed up; 4) Representativeness: The chosen research had to be representative of the broader body of literature on the topic, outliers or extremely niche studies that failed to offer a wide viewpoint were not acceptable; 5) Evidence: The articles needed to provide empirical data to support their conclusions rather than theoretical justifications. We conducted our literature search using specific keywords across two major research engines: Google Scholar and Web of Science (Table 1).

Table 1
Summary of the total number of articles found using the following keywords.

Research engines	Relevant keywords	Number of studied articles
Google Scholar	[[[‘Smart Fertilizer technologies’ OR ‘environmentally friendly fertilizers’ OR ‘slow-release ecological fertilizers’] AND [‘Advantages’ OR ‘Limitations’ OR ‘Mechanisms’ OR ‘regulatory policy’ OR ‘future perspectives’] AND [‘biofertilizers’ OR ‘nano fertilizers’ OR ‘slow and controlled release fertilizers’] OR [‘nutrient use efficiency’]]	195
Web of Science	[[[‘Smart Fertilizer technologies’ OR ‘environmentally friendly fertilizers’ OR ‘slow-release ecological fertilizers’] AND [‘Advantages’ OR ‘Limitations’ OR ‘Mechanisms’ OR ‘regulatory policy’ OR ‘future perspectives’] AND [‘biofertilizers’ OR ‘nano fertilizers’ OR ‘slow and controlled release fertilizers’] OR [‘nutrient use efficiency’]]	77

After compiling and checking for duplicates, we finalized 272 unique articles. We excluded studies focusing on topics like the synthesis of various fertilizers, production technologies, modeling of release kinetics, or non-agricultural applications. These studies were not relevant to our area of focus, which was investigating the characteristics that make fertilizers "smart" for the environment, looking into novel advancements in slow-release, nano, and bio-fertilizers, and the advantages and challenges in their application.

3. Types of smart fertilizer technologies

A smart fertilizer is a substance that consists of one or more nutrients and comprises nanomaterials, multi-components, and bioformulations. It can modify the timing of the nutrient release in response to the plant's nutrient needs using physical, chemical, and/or biological processes. This adaptive characteristic improves crop yields and reduces environmental impact at reasonable expenses compared to traditional fertilizers [11]. Smart fertilizers, also referred to as environmentally friendly fertilizers [12], slow-release ecological fertilizers [13], or improved efficiency fertilizers [14] offer a way to increase food production while protecting the environment. They do this by utilizing a slow or controlled release mechanism that matches crop requirements with nutrient availability and by improving nutrient bioavailability. SFTs may result in substantial cost savings by preventing over-application and enhancing crop yields by improving NUE, ultimately adding to the farm profitability. Based on the composition, SFTs can be classified into the following three distinct classes: 1) *Slow and Controlled-Release Fertilizers* (*SCRFs*), 2) *Nano fertilizers*, and 3) *Biofertilizers.*

A comprehensive exploration of each classification, including their respective subtypes, will be meticulously detailed in the upcoming segments of the review paper.

4. Slow and controlled-release fertilizers (SCRFs)

The primary objective of slow and controlled-release fertilizers (SCRFs) is to prolong the release of a nutrient in the soil, which significantly extends the duration for which nutrients are available for plant uptake. The terminology surrounding slow-release fertilizers (SRFs) and controlled-release fertilizers (CRFs) has been progressively refined, reflecting the intricate mechanisms governing nutrient release and uptake within agricultural contexts. Initially, distinctions between SRFs and CRFs were ambiguous, with definitions varying across regulatory bodies and scientific literature. Nonetheless, recent efforts have aimed to clarify these classifications by emphasizing the predictability and regulation of nutrient release patterns [15].

SRFs are characterized by a gradual yet variable release rate influenced by environmental factors. In contrast, CRFs, encompassing fertilizers encapsulated with inorganic or organic coatings, offer greater control over release kinetics [16]. CRFs allow more precise delivery of nutrients customized to specific soil and crop demands, making them a smarter choice among the two. CRF formulations, whether polymer-coated granules or matrices, exhibit prolonged nutrient release, improving fertilizer use efficiency and minimizing environmental impacts [17]. As per existing scholarly sources, SCRFs can be categorized based on the method of nutrient delivery into the following three classifications:1) *chemically modified slow-release fertilizers*, 2) *controlled-release fertilizers with a physical barrier, and* 3) *slow-release fertilizers with the biochemical barrier*, as illustrated in Fig. 4.1 detailed description of each type will be explored in the subsequent sections.

4.1. Chemically modified slow-release fertilizers

This category of fertilizers can be categorized into organic and inorganic types. Organic slow-release fertilizers consist of a diverse

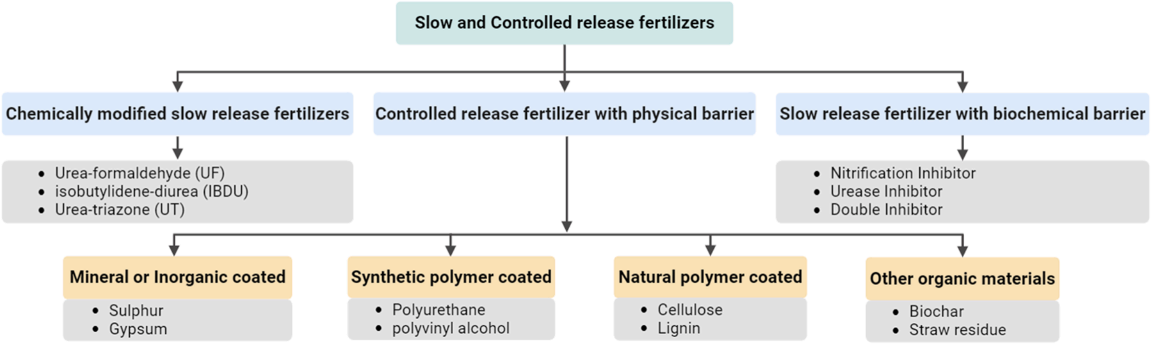

Fig. 4.1. Classification of slow and controlled-release fertilizers.

range of substances, such as urea-formaldehyde (UF), urea-triazone (UT), isobutylidene-diurea (IBDU), and crotonylidene diurea (CDU) [18]. These compounds undergo chemical transformations to form marginally soluble or water-insoluble compounds, thereby releasing nutrients in a gradual manner over an extended period. Inorganic slow-release fertilizers, while less prevalent, encompass magnesium ammonium phosphates ($MgNH_4PO_4$) and partially acidulated phosphate rocks (PAPR). These compounds are derived through chemical modification processes and exhibit low solubility in water. $MgNH_4PO_4$ and PAPR offer a gradual release of phosphorus, proving advantageous, especially in soils characterized by light texture or mild acidity [19,18]. Though less frequently employed in crop production due to their inconsistent nutrient release, these compounds still provide advantages over conventional fertilizers, like minimizing scorching and promoting longer nutrient availability [20].

4.2. Controlled-release fertilizers with a physical barrier

As the name suggests, this class of fertilizers employs specialized coatings, encapsulation techniques, or matrices to regulate the release of nutrients over an extended period. Based on the composition of the physical barrier, these can be further categorized into four classes: 1) *mineral or inorganic coatings*, 2) *synthetic polymer coatings*, 3) *natural polymer coatings* and 4) *other organic materials*

4.2.1. Mineral or inorganic coatings

This category of CRFs employs inorganic substances like sulfur, gypsum, and other mineral compounds. They serve a pivotal function in coating fertilizer granules, providing advantages in accessibility, cost-efficiency, and application convenience [21]. Early advancements by the Tennessee Valley Authority (TVA) introduced sulfur-coated Urea (SCU), enhancing nutrient longevity in soil [20]. However, challenges such as the "burst effect" resulting in sudden nutrient release, prompted innovations in hybrid coatings of sulfur and polymers to regulate the release pattern. Similarly, gypsum-based coatings exhibit controlled release properties and improve soil structure [22]. Mineral coatings like hydroxyapatite and bentonite also enhance nutrient retention and slow-release rates [23].

4.2.2. Synthetic polymer coatings

CRFs featuring synthetic polymer coatings provide superior regulation of nutrient release, making them among the most widely utilized smart fertilizer technologies. Various synthetic polymers, including polyurethane (PU), polylactic acid (PLA), and polyvinyl alcohol (PVA), have been employed to develop this class of CRFs. PU coatings derived from waste palm oil exhibit longevity and improved hydrophobicity [13]. Similarly, PLA coatings, known for their biodegradability, extend the release period of urea. Innovations such as hydrophobic gradient layers in polyurethane - hydroxypropyl-terminated polydimethylsiloxane copolymer coatings offer prolonged release periods, reducing coating thickness and production costs [24]. Multilayer coatings can be synthesized using two or more polymers with tailored compositions and thicknesses. This may allow for even more precise nutrient release dynamics, which leads to better optimization of crop nutrition as compared to only a single polymer coating [25].

In addition to conventional polymer coating techniques, an increasing interest lies in the utilization of hydrogels. Notably, synthetic hydrogels, renowned for their remarkable superabsorbent characteristics, have garnered significant attention across various fields, including agriculture [26,27]. These three-dimensional networks of cross-linked polymers exhibit the ability to absorb water multiple times with their own mass, therefore serving as effective materials for water management, particularly in regions suffering from water scarcity. Studies have indicated the efficacy of various synthetic hydrogel formulations in facilitating the slow release of nutrients such as urea and NPK fertilizers, showcasing their potential for enhancing agricultural practices [28].

4.2.3. Natural polymer coatings

Natural polymers offer a sustainable, eco-friendly coating solution for controlled-release fertilizers (CRFs). Polymers such as starch, cellulose, alginate, lignin, and chitosan are derived from natural sources and exhibit biodegradability and biocompatibility, making them ideal for coating materials [12]. Starch, sourced from various plants, is widely used due to its availability and low cost, with studies demonstrating its efficacy in delaying nutrient release [29]. Similarly, cellulose-based coatings, such as cellulose acetate, have shown promise in controlling nutrient release and improving water retention in arid environments [30]. Lignin itself may be used as a coating material or its dispersion and dissolution within a solution, resulting in a coating solution's formation. Furthermore, when employing lignin as a chemically modified form, the controlled release of nutrients can be achieved through the chemical reactions between lignin and the nutrients themselves [31]. Alginate and chitosan, derived from marine algae and crustacean shells, respectively, exhibit excellent water retention properties and antimicrobial effects, further enhancing the performance of CRFs [32].

Additionally, combining natural polymers with synthetic counterparts, such as polyurethane or polyvinyl alcohol, has been explored to improve biodegradability and mechanical integrity. Biodegradation studies have highlighted the potential of these natural polymer-coated CRFs to break down into harmless components, contributing to soil health and reducing environmental pollution [33].

4.2.4. Other organic materials

Organic materials, apart from polymers, present promising avenues for enhancing soil properties and augmenting nutrient release in CRFs [34]. Research indicates that the inclusion of biochar into CRFs, either independently or in conjunction with super absorbent polymers and mineral binders, can notably improve water retention and slow nutrient release, with as much as 70% of nutrients being released over one month [23]. Furthermore, using lignocellulosic straw as a carrier and coating material has demonstrated promise in developing slow-release fertilizers, leveraging its mechanical strength properties and reactivity [35]. Biochar, derived from the pyrolysis of organic biomass, has emerged as a versatile nutrient carrier, capable of retaining nutrients up to five times its weight, and can be supplemented with various fertilizers to promote plant growth and enhance soil health. While biochar-based CRFs show the potential to reduce GHG emissions and boost crop yield, further investigation is required to optimize nutrient sorption and desorption mechanisms and decrease production costs [36].

4.3. Slow-release fertilizers with a biochemical barrier

Incorporating substances to inhibit the degradation of fertilizers is a cost-effective method to enhance efficiency, especially in soils with high cation exchange capability [18]. Nitrification inhibitors (NIs), such as dicyandiamide (DCD), function by retarding the oxidation process of ammonium ions into nitrate ions through the suppression of Nitrosomonas bacteria activity. Conversely, urease inhibitors (UIs) like N-(n-butyl) thiophosphoric triamide (NBPT) operate by preventing the action of the urease enzyme, responsible for the conversion of urea into ammonium hydroxide and subsequently ammonium ions [15]. Coating or homogenizing these inhibitors within N fertilizers modifies the nitrogen release kinetics, resulting in a delayed release pattern that results in optimum nitrogen utilization. Additionally, substances such as neem oil, which are economically accessible, as well as synthetic NIs like nitrapyrin and DMPP, have also demonstrated promising outcomes in the retardation of ammonium oxidation processes [37].

4.4. Mechanism of release of SCRFs

SCRFs aim to synchronize nutrient release with plant demand, optimizing agronomic yields while minimizing environmental impact. These fertilizers primarily rely on mechanisms such as coating dissolution influenced by moisture, temperature, pH, and microbial activity for nutrient release [34]. The release rate from SRFs is determined by water solubility, chemical hydrolysis, and microbiological decay. Smaller particle sizes and higher temperatures accelerate the rate of degradation in SRFs [38]. CRFs are characterized by a sigmoidal release pattern in three stages: lag, steady release, and decay. The release process is influenced by soil temperature and moisture content in CRFs [22]. Initially, soil moisture penetrates the granule core through the coating cracks, allowing a fraction of nutrient to dissolve in the core without releasing fertilizer. Subsequently, as water infiltrates, more solid fertilizer dissolves, increasing osmotic pressure and allowing slow release through cracks. If pressure exceeds a threshold, the coating ruptures, causing immediate fertilizer release or burst effect. In the decay stage, most fertilizer is released, reducing the concentration gradient and release rate. The release rate of coated fertilizers depends on membrane properties such as thickness, solubility, and density. Biochemical-based SRFs, such as urease and nitrification inhibitors, modulate nitrogen availability by inhibiting enzymatic reactions in the soil [18].

4.5. Advantages of slow and controlled release fertilizers

SCRFs offer various advantages over conventional fertilizers. They are a multifaceted solution to agricultural challenges as they enhance NUE and plant uptake, thereby increasing crop yield with comparable or reduced fertilizer input. SCRFs also help reduce environmental pollution, especially nitrate leaching and the volatilization of ammonia and nitrous oxides. The application of SCRF allows for a reduction of up to 30% in conventional fertilizer application rates while maintaining yield, leading to significant labor, time, and energy savings. By gradually releasing nutrients, CRFs minimize toxicity to plants, particularly seedlings, caused by the sudden release of high ion concentrations from conventional fertilizers, thus improving agronomic safety [15]. Studies also suggest that CRFs might improve soil aggregate characteristics [39]. Some studies which utilized SCRFs are summarized in Table 4.1.

5. Nano fertilizers

Nano fertilizers are described as fertilizers derived from traditional fertilizers, bulk materials, or plant extracts through various chemical, physical, mechanical, or biological processes facilitated by nanotechnology to enhance soil fertility, increase agricultural productivity, and improve the quality of crop yields [54]. It is a class of fertilizers which possess a tiny-size (below 100 nm) with better penetration, large surface area, better use efficiency, and environmentally friendliness due to the reduction in residues. The large surface area of nano fertilizers allows them to hold abundant nutrients and facilitates nutrient uptake in plants by steadily releasing them [55].

Nanotechnology facilitates nano fertilizers to operate at the molecular level for better target-specific delivery of nutrients to increase NUE and reduce the volume required for application [56]. Dapkekar et al. [57] reported that zinc complexed chitosan nanoparticles increased the zinc content and protein content in wheat (*Triticum aestivum*) grain at the rate of 40 mg/L (foliar application) as compared to a conventional source of zinc, i.e., zinc sulfate applied at a rate of 400 mg/L. In addition, reducing the particles in nano form also alters their properties and reactivity. The increased reactivity allows fertilizers to interact better with their surroundings, such as plant roots and soils, which leads to better nutrient absorption by plants, hence optimizing plant growth [58]. Abdel-Aziz et al. [59] reported that increased reactivity of nano NPK increased absorption in wheat (*Triticum aestivum*) and increased wheat performance regarding growth parameters and yield per plant. Nanotechnology allows the design of nanoparticles in such a way that they can be used create nano fertilizers for target specific applications, such as foliar spray or soil applications, thus reducing the use of agrochemicals for crop production [56]. These unique properties of nano fertilizers prove them to be cost-effective and ecologically beneficial.

5.1. Classification of nano fertilizers

Different studies have classified nano-fertilizers based on their purpose and mode of action ([60]; Mikkleson, 2018). Based on the purpose, nano fertilizers are classified into three major classes described in Table 5.1.

Based on the mode of action, Yadav et al. [60] have classified nano fertilizers into four classes: Control release, targeted delivery, plant growth stimulation, and water- and nutrient-loss-controlling nano fertilizers. The description, advantages, and examples of these nano fertilizers are described in Table 5.2.

5.2. Advantages of nano fertilizers

When compared to traditional fertilizers, nano fertilizers provide several benefits. Due to their nanoscale size gives them a larger surface area, enabling greater interaction with plant roots and more effective nutrient uptake [66]. Due to this increased efficiency, fertilizer may be applied at lower rates, which lowers the total amount required and, in turn, reduces the possibility of nutrient runoff into water bodies, which is a serious environmental concern. Nanotechnology allows us to develop fertilizers for controlled release, which minimizes losses from leaching and volatilization and ensure that nutrients are available to plants for a greater duration of time [62]. The case studies summarized in the Table 5.3 highlight the positive impacts observed through the utilization of nano fertilizers

6. Biological fertilizers

Biofertilizer is a specialized substance comprising living cells of different beneficial microorganisms (bacteria and fungi) that colonize the rhizosphere when applied to the soil or seed [77]. This colonization

Table 4.1
Summary of recent research utilizing slow and controlled release fertilizers (SCRFs) and their observed positive influences on various environmental aspects of crop production.

Controlled Release Fertilizer	Conventional Fertilizer	Crop	Location	Treatments	Main environmental takeaways	Refs.
Resin-coated urea (CRU)	Urea	Double-cropping rice	Hunan Province, China	Control (0 kg N ha^{-1}), 100% Urea (150 kg N ha^{-1} for ESR, 180 kg N ha^{-1} for LSR), 100% CRU (150 kg N ha^{-1} for ESR, 180 kg N ha^{-1} for LSR), 90% CRU (for ESR and LSR), 80% CRU (for ESR and LSR), 70% CRU (for ESR and LSR)	CRU significantly reduced NH3 volatilization losses by 20-43% for ESR and 20-32% for LSR compared with conventional urea application. Higher grain yield and apparent nitrogen recovery efficiency (ANRE) were achieved with 80% CRU compared to 100% conventional urea.	[40]
Polymer-coated complex fertilizer (PCCF), Polymer coated urea (PCU), Sulfur-coated urea (SCU)	Urea	Rice	Sichuan Province, China	No nitrogen (CK), Farmer Fertilizer Practice (FFP: 180 kg N ha^{-1} conventional urea), PCCF (180 kg N ha^{-1}), PCU (180 kg N ha^{-1}), SCU (180 kg N ha^{-1})	CRFs significantly increased biomass, N uptake, and yield. PCU was the most effective, enhancing photosynthetic potential, biomass, and N uptake. All CRFs improved nitrogen use efficiency and grain yield compared to conventional urea.	[41]
Blended controlled-release urea fertilizer (CRF) of PSCU, PCU, and conv. urea	Conventional urea fertilizer (CUF)	Field maize	Shandong, China	CUF1, CUF2, CUF3, CRF1, CRF2, CRF3, and control (no N fertilizer). N application rates: 0, 150, 300, 450 kg ha^{-1}	CRF treatments significantly improved soil aggregate stability, increased HA and FA content, enhanced soil N content, sap bleeding rate, and N delivery rate compared to CUF. CRF treatments also increased maize yield and nitrogen use efficiency.	[39]
Blended urea and slow-release nitrogen fertilizer (UNS)	Urea	Dryland maize	Shaanxi, China	CK (control), U (urea), S (slow-release nitrogen fertilizer), UNS1 (U:S=2:8), UNS2 (U:S=3:7), UNS3 (U:S=4:6) under two N rates: N1 (180 kg N ha^{-1}) and N2 (240 kg N ha^{-1})	UNS significantly reduced NH3 volatilization compared to urea, primarily due to lower soil pH and EC and higher SOM. The blending ratio of U and S at 3:7 (UNS2) significantly increased dry matter, N uptake, and NUE of maize while reducing NH3 volatilization and residual soil NO3-N.	[42]
Controlled-release potassium chloride (CRK)	Conv. KCl	Maize	Taian, China	Control (no K fertilizer), K1 (KCl at 113 kg K2O ha^{-1}), CRK1 (113 kg K2O ha^{-1}), CRK2 (75 kg K2O ha^{-1}), BBF1 (mixed CRK and KCl at 113 kg K2O ha^{-1}), BBF2 (mixed CRK and KCl at 75 kg K2O ha^{-1})	High-dose mixed CRK and KCl increased grain yields by 14.0% and 7.2% compared to traditional KCl. Low-dose mixed CRK and KCl achieved similar yields to traditional KCl. CRK treatments improved K use efficiency and soil available K levels, enhancing plant nutrient absorption and reducing K fixation.	[43]
Polymer-coated urea (PCU)	Urea, Ammonium sulfate	Second-season maize	Maringá, Paraná, Brazil	Two conventional N sources: Urea and ammonium sulfate. Three brands of PCU: Agrocote®, FortBlen®, Kimcoat®	FortBlen® reduced N-NH3 losses by 36.4% compared to uncoated urea. Agrocote® and FortBlen® promoted gradual N release and reduced N-NH3 volatilization.	[44]
Controlled-release urea (CRU) mixed with biochar (MBCB)	Bare urea (BU)	Rice	China	CK (control, no N fertilizer), BU (bare urea), CRU (controlled-release urea), MBC (50% BU + 50% CRU), MBCB (50% BU + 50% CRU + biochar)	MBCB treatment increased rice yield by 10.2%, NUE by 16.5%, and NAE by 4.0 kg kg−1 compared to MBC. CRU treatment increased yield by 12.2%, NUE by 33.9%, and NAE by 4.3 kg kg−1 compared to BU. MBCB and CRU treatments reduced soil residual N and N surplus, improving N use efficiency and reducing N losses.	[45]
A blend of urea and controlled-release urea (BU)	Conventional urea (CU)	Maize	Southwest China	N0 (control, no N fertilizer), N90 (90 kg N ha^{-1}), N180 (180 kg N ha^{-1}), N270 (270 kg N ha^{-1}), N360 (360 kg N ha^{-1}) with CU and BU	BU reduced reactive nitrogen losses: nitrous oxide emission (– 27%), ammonia volatilization (– 18%), and N leaching (– 24%). BU decreased global warming potential (8-13%), acidification potential (4-9%), and eutrophication potential (8-22%). BU increased economic benefits and ecosystem economic benefits (EEB) by 68%, 39%, 29%, and 25% at N rates of 90, 180, 270, and 360 kg N ha− 1, respectively.	[46]
Water-soluble, slow-release nitrogen fertilizer	Urea	Rapeseed	Shandong, China	Control (no fertilizer), UREA 100%, UREA 80%,	SSNF and BBW treatments significantly increased yields and nitrogen use efficiencies in rape	[47]

(continued on next page)

Table 4.1 (*continued*)

Controlled Release Fertilizer	Conventional Fertilizer	Crop	Location	Treatments	Main environmental takeaways	Refs.
(SSNF), Mixture bulk blend fertilizer (BBW)				SSNF 100%, SSNF 80%, BBW 100% (70% SSNF + 30% urea), BBW 80% (80% of BBW100%)	plants compared to urea. SSNF80% and BBW80% treatments produced nearly the same yields as UREA100% with reduced nitrogen application rate. Nitrogen use efficiencies for SSNF and BBW treatments were significantly higher than UREA by 37–52% and 42–43%, respectively.	
Urea-loaded cellulose hydrogel (CRF)	Recommended dose of urea fertilizer (RDF) in splits	Upland rice	Sarawak, Malaysia	T1: 0 N (control), T2H: 30 kg N ha^{-1}, (CRF) T3H: 60 kg N ha^{-1}, (CRF) T4H: 90 kg N ha^{-1}, (CRF) T5H: 120 kg N ha^{-1}, (CRF) T6U: 120 kg N ha^{-1} (RDF)	CRF treatment T4H resulted in maximum grain yield, increasing by 71% compared to control. Higher grain N uptake, harvest index (HI), and nitrogen use efficiency (NUE) were observed in T4H CRF. CRF with moderate N application (T4H) improved grain yield and N efficiencies compared to conventional urea with 100% N RDF.	[28]
Controlled-release urea fertilizer (CRUF) with biodegradable superabsorbent composite	Urea	Rice (greenhouse pot experiment)	Tanta, Egypt	CRUF doses: 10, 25, 50, 75, and 100 kg ha^{-1} under drought conditions (50% FC). Control: no fertilizer.	CRUF mitigated water stress and enhanced the growth, yield, and physio-biochemical traits of rice. Improved water and nutrient use efficiencies reduced osmotic and oxidative stress levels.	[48]
N-(n-butyl) thiophosphoric triamide (NBPT), Piadin, NZONE MAX	Urea, Urea ammonium nitrate (UAN)	No specific crop was mentioned (pot experiment)	Saxony, Germany	CK (control), U (urea), U + NZ (urea + NZONE MAX), U + P (urea + Piadin), U + NBPT (urea + NBPT), UAN (urea ammonium nitrate), UAN + NZ (UAN + NZONE MAX), UAN + P (UAN + Piadin)	NBPT effectively reduced NH3 volatilization by 50%. Piadin decreased N2O emissions by over 80% but increased NH3 emissions by 44%. NZONE MAX was ineffective in reducing NH3 and N2O emissions.	[49]
UREAStabil (slow-releasing N fertilizer)	Urea	Bread wheat	Ethiopia	0, 32, 64, and 96 kg N ha^{-1} UREAStabil. Control: split application of conventional urea at 64 kg N ha^{-1} (1/3 at planting, 2/3 at tillering)	The application of UREAStabil significantly influenced yield and yield components at both soil types. The highest grain yield and nitrogen uptake were recorded with 64 kg N ha−1 in the form of UREAStabil and prilled urea.	[50]
Biological nitrification inhibitor (MHPP), urease inhibitor (NBPT), and biochar (BC)	Conventional fertilization (CF)	Wheat	Chengdu, China	Control (no N), CF alone, CF + MHPP, CF + NBPT, CF + BC, CF + MHPP + NBPT, CF + NBPT + BC, CF + MHPP + BC	Individual and co-application of MHPP, NBPT, and BC decreased N leaching by 25.4% to 42.6%. MHPP, BC, MHPP_NBPT, and MHPP_BC increased N yield by 7.41%–10.3% and NUE by 9.94%–13.7% compared to CF.	[51]
Polymer-coated urea (PCU) combined with urease inhibitor (NBPT) and nitrification inhibitor (DMPP)	Urea	Winter wheat	China	CK (no N), U (urea), PCU (polymer-coated urea), PCU + NBPT, PCU + DMPP, PCU + NBPT + DMPP	PCU + NBPT + DMPP significantly reduced NH3 volatilization and NO3 leaching while improving soil N retention. This combination increased wheat yield and NUE compared to conventional urea application.	[52]
Biochar-based slow-release N-P-K fertilizer	Commercial N-P-K fertilizer	Maize and black gram	Sikkim and West Bengal, India	MSB-SRF (Maize Stalk Biochar), BGB-SRF (Black Gram Biochar), PNB-SRF (Pine Needle Biochar), LCB-SRF (Lantana Camara Biochar). Control: Commercial N-P-K fertilizer	Biochar-based SRFs significantly reduced nutrient leaching, enhanced soil health, and increased crop yield. MSB-SRF showed maximum reduction in nitrate leaching, while BGB-SRF resulted in the highest nitrogen use efficiency.	[53]

promotes plant growth by enhancing the supply or accessibility of essential nutrients to the host plant. The term "biofertilizer" is commonly associated with carefully selected strains of friendly soil microorganisms. These strains are cultured in laboratory settings and enclosed in suitable carriers. Essentially, biofertilizers, also called microbial inoculants, are artificially multiplied cultures of beneficial soil organisms that can improve soil fertility and crop productivity [78]. In the last few years, biofertilizers have become a vital component of integrated nutrient management, offering substantial promise for enhancing crop yields while ensuring environmentally sustainable nutrient provision.

While bio-fertilizers have been a part of traditional farming practices passed down through generations, the scientific documentation began in 1888 when a Dutch scientist first identified biofertilizers [79]. The commercial application gained momentum in 1895 with the introduction of "Nitragin" by scientists Nobe and Hiltner. Blue-green algae (BGA) and *Azotobacter* were later introduced and applied as additional biofertilizers. Over time, new biofertilizers such as *Azorhizobium*, Vesicular-Arbuscular *Mycorrhizae* (VAM), and *Azospirillum* have been incorporated [80]. Presently, various groups of microbes are employed through biofertilizers to enhance crop growth, as summarized in Table 6.1.

The successful utilization of beneficial microbes in biofertilizers relies heavily on the carrier material used to transport them from the laboratory to the soil. Singh et al. [81] emphasize that an ideal carrier

Table 5.1
Classification of nano fertilizers based on mode of purpose.

Class	Description
Nano-Fertilizers	Particles or emulsions with a nanoscale range that can be used as an alternative for conventional fertilizers and can be applied as foliar or soil applications fall into this category. Nano-fertilizers have better use efficiency than conventional fertilizers and are less prone to losses [57].
Nanoscale additives	Nanoscale additives are added to conventional fertilizers to improve efficacy. The additive may enhance plant growth by providing micronutrients or may provide resistance against biotic or abiotic stresses. The additive may also improve the overall properties of the fertilizers to which it is added ([61]; Mikkleson, 2018).
Nanoscale coating	Nanoscale coating refers to the coating of nanoparticles on macromolecules of fertilizers. The nanoscale coating is a porous nanomembrane that reduces the solubility of fertilizers in the soil and helps slow the period's release.

material should have high water-holding and retention capacities, ensuring a consistent moisture supply for the microorganisms. It should also maintain a nearly sterile, chemically, physically uniform, and non-toxic composition. Using carrier materials that are readily biodegradable and nonpolluting helps minimize potential environmental impact. Carrier materials include sawdust, vermiculite, talcum dust, peat, manure, and earthworm castings [82]. Each of these materials serves as a medium to support the viability and effectiveness of microbial inoculants during their application to the soil.

The term "organic fertilizer" should not be confused with biofertilizers. Previously, organic fertilizer was known as the term biofertilizer, though there is an immense variance among organic fertilizer and bio-fertilizer [78]. Biofertilizers encompass living microorganisms such as fungi, algae, and bacteria, either alone or in combination, with the potential to enhance crop production. On the other hand, organic fertilizer is derived from plant or animal sources, such as animal manure and green manure [83].

6.1. *Mechanism of action of bio-fertilizers*

The growth-promoting characteristics of biofertilizers can be understood through two distinct modes of action, influenced by the biochemical and genetic composition of the microorganisms used. There are two modes of action: Direct action and Indirect action (Fig. 6.1). In the direct mode of action, microbes in biofertilizers directly contribute to plant growth by supplying essential nutrients or growth-promoting substances [81]. Examples of direct modes of action include nitrogen fixation, phosphate solubilization, potassium release, and secretion of plant growth-promoting substances. This direct provision enhances the overall growth and development of the plant.

Nitrogen-fixing microbial inoculants in bio-fertilizers enhance soil nitrogen by fixing atmospheric nitrogen [84]. Nitrogen fixation stands as one of the most crucial biological processes. It serves as a vital mechanism for recycling nitrogen, pivotal in nitrogen homeostasis within the biosphere. This essential process is carried out by a diverse array of diazotrophic soil microbes, including *Azotobacter, Anabaena, Azosprillium, Beijerinckia,* and many more species [84,85,80] (Table 6.1).

Phosphate-solubilizing microorganisms in bio-fertilizers, such as fungi and bacteria, play a crucial role in solubilizing inorganic phosphatic compounds. These microorganisms absorb phosphorus for their needs and release it into the soil, making it available for plant uptake (Soumare et al., 2020). The mechanism behind the solubilization of insoluble phosphorus by PGPRs also involves the secretion of metabolites, notably gluconic and 2-keto gluconic acids [81]. Phosphate solubilizing microorganisms encompass various bacterial genera, including *Bacillus, Pseudomonas, Flavobacterium*, and *Micrococcus*, as well as fungi such as *Sclerotium, Fusarium, Aspergillus*, and *Penicillium* (Soumare et al., 2020; [86]). On the other hand, potassium-solubilizing microorganisms (KSM) consist of bacteria and fungi capable of converting insoluble potassium (K) into a soluble form that plants can efficiently absorb [87].

The rhizosphere microorganisms involved in biofertilizers also generate growth-promoting substances in significant quantities. Plant hormones, or growth substances, represent natural compounds produced by both microorganisms and plants. These hormones are important in regulating plant growth, development, and nutrient distribution. Many species, such as *Azotobacter, Bacillus*, and others, synthesize auxins, cytokinins, and gibberellins [88,89]. These substances, directly or indirectly, influence crops' overall morphology and physiology and increase plant growth and productivity.

Indirect mode of action: This involves the ability of microbes of biofertilizers to inhibit or eliminate unfavorable conditions that impede plant growth. Many beneficial microbes are known to prevent abiotic and biotic stress in the plant by secreting antibiotics and activating the defense mechanisms of the plant [90,91,92].

6.2. *Advantages of biofertilizers*

Nutrient-rich biofertilizers offer numerous advantages over chemical fertilizers, demonstrating their eco-friendly, cost-effective, and food safety-ensuring nature. Their application contributes to increased soil biodiversity, microbial populations, soil porosity, fertility, and NUE, ultimately enhancing the quality of agricultural produce [93]. These biofertilizers play a crucial role in augmenting soil organic matter content, releasing nutrients gradually, adding to the residual pool of organic

Table 5.2
Classification of nano fertilizers based on mode of action.

Class	Description	Advantage	Examples	Source
Control Release Nano fertilizers	Encapsulate nutrients with nanoscale carrier material composed of polymers, lipids, or inorganic substances. The release of nutrients is influenced by temperature, pH, moisture, or enzymes.	Improved NUE, better nutrient uptake, targeted and sustained delivery by plant requirements, reduced application rates, low fertilizer losses, and enhanced crop productivity	Carbon-Based, Nano Capsule-Based, and Polyurethane-Based.	Liu & Lal. [62]; Kah et al. [63]
Targeted Delivery Nano Fertilizers	Tiny molecules that target specific molecules in soils and deliver nutrients or other molecules directly to plants. These molecules are made of oligonucleotides and peptides to modify the nano fertilizers in such a way that activates the nutrient release once activated by a signal from the rhizosphere.	Precise delivery of nutrients from soil molecules to plant roots increases plant nutrient uptake.	Nano aptamers, Nano-hydroxyapatite.	Rameshaiah et al. [64]
Plant Growth-Stimulating Nano Fertilizers	Stimulate plant growth by interacting with plant root systems and boosting hormone synthesis. In seeds, it serves as a protective layer against pests and enhances its ability to absorb water and nutrients.	Improve soil structure, water retention, plant growth, and soil nutrient retention.	Carbon Nanotubes	Yadav et al. [60]
Water and Nutrient Loss-Controlling Nano Fertilizers	Release nutrients over time to reduce the nutrient loss and may have a hydrophilic surface to increase water holding capacity and reduce water losses through evaporation.	Increase water retention and nutrient retention.	Nano Emulsion Based Fertilizers; Nanobeads	Jakhar et al. [65].

Table 5.3
Summary of recent research utilizing nano fertilizers and their observed positive influences on various aspects of crop production.

Nano fertilizer	Conventional Fertilizer	Crop	Location	Treatments	Main environmental takeaways	Refs.
Nano-N (nN), Nano-P (nP), Nano-K (nK), Nano-NPK (nNPK)	NPK	Rice	Iran	Control (without fertilizer), N, P, K, NPK, nN, nP, nK, nNPK, NPK+nNPK	Application of nano and conventional fertilizers increased grain yield and milled rice yield. Nano-fertilizers, particularly nN and nNPK, significantly enhanced grain yield and milled rice yield compared to conventional fertilizers.	[67]
Nano-biochar (BNC) derived from wheat straw	Conv. fertilizers	Wheat	Islamabad, Pakistan	Control (no fertilizer), Biochar (BC), Nano-biochar (BNC), BC + Conv. fertilizer, BNC + Conv. fertilizer	Nano-biochar (BNC) significantly improved soil fertility and water retention compared to conventional fertilizers. BNC treatments showed higher nutrient adsorption, water absorbance, and slow-release properties, enhancing crop yield and sustainability.	[68]
Super Micro Plus (SMP) nano-fertilizer containing N, P, K, and essential elements	Traditional fertilizer	Wheat	Al-Shafeieyah, Iraq	Control, Nano(N+P), Nano(N+K), Nano(P+K), Nano(N+P+K), Nano SMP, Traditional fertilizer	Foliar application of SMP nano-fertilizer significantly enhanced plant height, spike length, chlorophyll content, and nutrient concentrations (N, P, K) compared to control and traditional fertilizers. SMP treatment resulted in the highest grain yield (5.996 Mg ha-1) and protein content (13.69%) compared to control and traditional fertilizer.	[69]
Nano zinc oxide (ZnO), Nano iron oxide (Fe2O3), Nano nitrogen (N)	Traditional NPK fertilizers	Tomato	India	T1 - Farmers Practice (FP) (100% NPK + 100 % Zn), T2 - FP (50% N+100% PK+100% Zn), T3 – FP (100 % NPK + 50 % Zn), T4 – FP (100% NPK + 100% Zn), T5 - FP (50 % N + 100 % PK + 50 % Zn)	T5 treatment produced the maximum plant height (122.45 cm), number of branches per plant (12.4), fruit length (7.15 cm), fruit girth (5.32 cm), number of fruits per plant (64.03), individual fruit weight (66.48 g), and highest yield per ha (425.24 q/ha). Application of nano-fertilizers enhanced growth, yield, and economic return compared to traditional fertilizers.	[70]
Liquid nano NPK	Mineral NPK fertilizer	Cucumber	Giza, Egypt	Control (Mineral NPK), 3 ml nano NPK, 4.5 ml nano NPK, 6 ml nano NPK, 9 ml nano NPK, Untreated	Nanofertilizer treatments significantly improved the growth and yield of cucumber compared with the control. The treatment of 6 ml NPK increased the yield by 4.84% and 53.42% in the first and second seasons, respectively.	[71]
Nano-nitrogen fertilizer	Mineral urea fertilizer	Maize	Al-Jadiriya, Iraq	Control (T0: 300 kg N/ha), Nano-nitrogen (T1: 1 ml/L, T2: 2 ml/L), Humic acid (T3: 1 ml/L, T4: 2 ml/L)	Nano-nitrogen treatments (T2) showed significant improvements in yield indicators, including the number of rows per ear, number of grains per row, number of grains per ear, and 500-grain weight, compared to control and humic acid treatments. Nano-fertilizers enhanced nutrient absorption and utilization efficiency.	[72]
Nano urea, Nano zinc, Nano copper	Traditional NPK fertilizers	Various crops (maize, wheat, mustard, rice, etc.)	Multi-location trials across India	Different combinations and concentrations of nano and traditional NPK fertilizers for various crops and seasons exist.	Nano fertilizers significantly increased crop yields and nutrient use efficiency compared to traditional fertilizers. Foliar application of nano urea, nano zinc, and nano copper improved nutrient absorption, reduced environmental impact, and increased economic returns.	[73]
Nano-iron oxide (Fe3O4) nanoparticles	No conventional fertilizer is specified	Soybean (Glycine max)	Fars Province, Iran	Control (0 ppm Fe3O4), 100 ppm Fe3O4, 200 ppm Fe3O4 under drought (40% FC) and well-watered (80% FC) conditions	Nano-iron oxide at 200 ppm increased soybean seed yield by 40.12% under drought and 32.60% under well-watered conditions compared to control. Improved chlorophyll content, relative water content, and reduced water saturation deficit.	[74]
Nano-chelated nitrogen fertilizer	Urea	Wheat	Fars Province, Iran	Control (no fertilizer), Urea (0, 37, 74, 110 kg ha^{-1}), Nano chelated nitrogen (0, 14, 27, 41 kg ha^{-1})	The application of nano-chelated nitrogen fertilizer significantly improved physiological traits under drought-stress conditions. Nano-chelated nitrogen (41 kg ha^{-1}) led to increases in RWC (37%), protein (69%), phosphorus (80%), potassium (38%), remobilization (73%), and photosynthesis rate (55%) compared to control.	[75]
Nano-urea (nano-N), Nano-zinc (nano-Zn), Nano-copper (nano-Cu)	Traditional NPK fertilizers	Maize, Wheat, Pearl Millet, Mustard	New Delhi, India	Many combinations and concentrations of nano fertilizers and traditional NPK fertilizers	The application of nano-fertilizers in combination with traditional fertilizers significantly increased crop yields and nutrient uptake. Yield increases for maize (66.2–68.8%), wheat (62.6–61.9%), pearl millet (57.1–65.4%), and mustard	[76]

(*continued on next page*)

Table 5.3 (*continued*)

Nano fertilizer	Conventional Fertilizer	Crop	Location	Treatments	Main environmental takeaways	Refs.
					(47.2–69.0%) were observed over control plots. Nano-fertilizers also enhanced soil microbial biomass carbon and dehydrogenase activity, indicating improved soil health.	

Table 6.1
Classification of microbial inoculants used as biofertilizers.

Group	Species
Nitrogen fixer	Symbiotic Bacteria: *Rhizobium, Azorhizobium, Frankia, Bradyrhyzobium, Mesorhizobium,* and *Sinorhizobium* Non-symbiotic Bacteria: *Cyanobacteria, Azotobacter, Anabaena, Azospirillum, Clostridium, Diazotrophicus, Nostoc,* and *Gluconaacetobacter*
Phosphorus solubilizing	Bacteria: *Arthrobacter, Bacillus, Chryseobacterium, Gordonia, Pseudomonas, Rhodococcus, Serratia.* Fungi: *Aspergillus, Penicillium, Trichoderma strains,* and *strains of Rhizoctonia solani*
Phosphorus mobilizing biofertilizers	*Endo mycorrhizae, Rhizoctonia solan,* species of *Amanita, Boletus, Laccaria, Pisolithus Ectomycorrhiza,* and *Pezizella ericae*
Plant Growth-Promoting Rhizobacteria (PGPR)	*Bacillus* and *Pseudomonas*

nitrogen and phosphorus, and reducing the leaching of N and P. Studies [90,91,92] suggest that biofertilizers also contribute to the suppression of certain plant diseases, parasites, and soil-borne diseases. Some of the studies which utilized biofertilizers are summarized in Table 6.2.

7. Regulatory policies for SFTs in various countries

The global market for controlled-release fertilizers is projected to expand from USD 2.2 billion in 2023 to USD 2.9 billion by 2028, reflecting a compound annual growth rate (CAGR) of 5.9%. This growth trajectory is supported by the increasing demand for sustainable agricultural practices, with the Asia-Pacific region, particularly China, exhibiting a strong market demand [106]. The biofertilizer sector is anticipated to grow from USD 2.3 billion in 2023 to USD 4.5 billion by 2028, at a CAGR of 14.3%. This surge is predominantly driven by the rising consumer preference for organic food products and environmental consciousness, with North America and Europe at the forefront and significant growth in the Asia-Pacific and Latin American markets [107]. Moreover, the nano-fertilizer market is also experiencing a rapid expansion, projected to grow from USD 401.8 million in 2022 to USD 1, 675.61 million by 2032 at a CAGR of 15.4% (Precedence [108]).

The environmental benefits of SFTs are widely accepted and the increase in their popularity is evident from the rate of growth. These factors might be responsible for an increasingly favorable regulatory policy. The European Union (EU) leads in regulatory frameworks for SFTs, particularly SCRFs, as articulated through several directives to promote sustainable agriculture. Regulation (EU) 2023/2055 integrates specific provisions for incorporating biodegradable polymers in fertilizers to mitigate microplastic pollution. Additionally, the EU's emphasis on nutrient efficiency aligns with its broader legislative goals under the European Green Deal and the Farm to Fork Strategy, which collectively aim to reduce nutrient losses by at least 50% while ensuring soil fertility [109]. The EU also enforces comprehensive regulations for biofertilizers and bio stimulants under Regulation (EU) 2019/1009, emphasizing

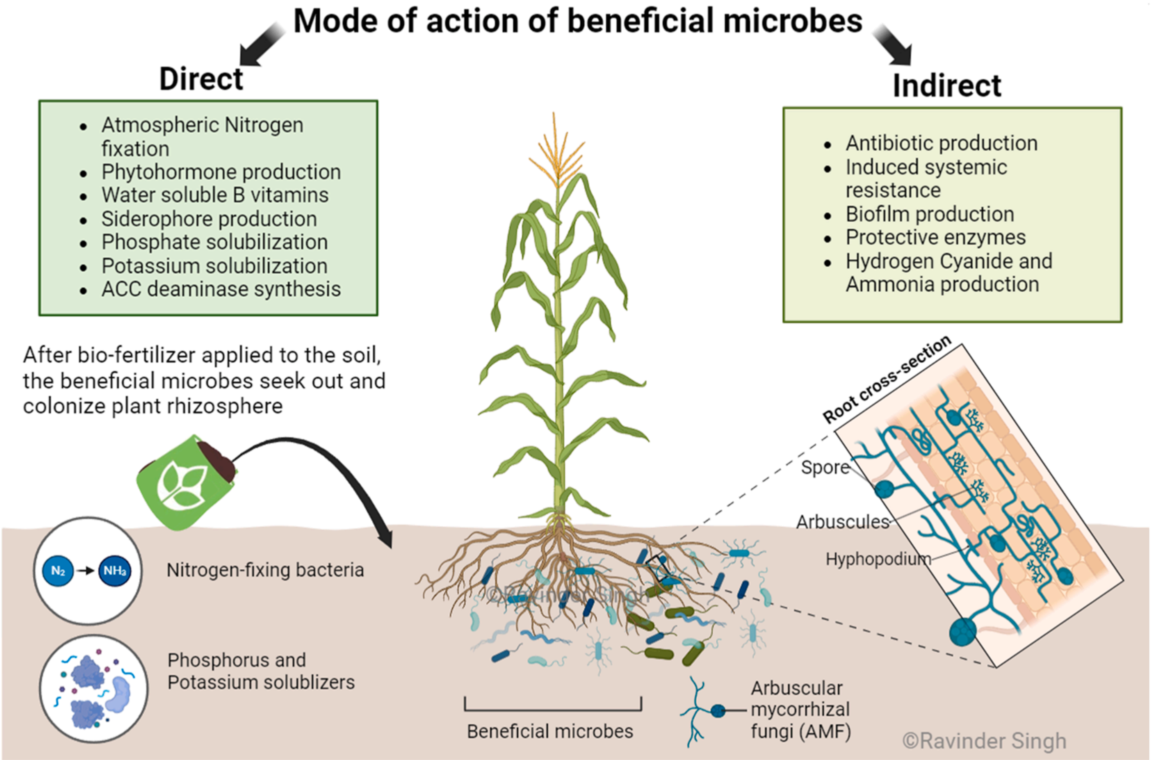

Fig. 6.1. Summary of the mechanism of action of bio-fertilizer inoculants.

Table 6.2
Summary of recent research utilizing bio fertilizers and their observed positive influences on various aspects of crop production.

Biofertilizer	Location	Crop	Treatments	Yield results	Main environmental takeaways	Refs.
Mesorhizobium, Azotobacter, Pseudomonas, and *Trichoderma*	India, Uttar Pradesh	Chickpea	Various combinations of microbial strains (single, dual, triple, and tetra-inoculations)	Significant yield increase in plots treated with combinations, especially tetra-inoculation.	Tetra-inoculation significantly enhanced the growth, yield, and disease suppression of chickpeas.	[94]
Bacillus subtilis	Chongqing, China	Tarocco blood orange	Control, 50% NPK + B. subtilis, 100% NPK + B. subtilis	Improved fruit size, weight, and quality metrics with biofertilizer treatments.	Biofertilizer application with reduced chemical fertilization improved fruit quality and reduced chemical input.	[95]
Blue green alga, Azolla	India	Paddy	Control, Chemical fertilizer (NPK), Bio-fertilizer (BGA, Azolla)	Bio-fertilizer treatments resulted in the highest yield, showing a 14.77% increase over the control.	Bio-fertilizers are more effective than chemical fertilizers in increasing yields and promoting growth.	[96]
Pseudomonas fluorescens	Cuba	Sweet Potato	Various biofertilizer and chemical fertilizer combinations	Highest yield with 100% NPK and P. fluorescence immersion for 15 mins.	P. fluorescence biofertilizer improves sweet potato yield and can reduce chemical fertilizer use.	[97]
Azotobacter chroococcum	Iraq	Cucumber	Control, Bio-fertilizer, Chemical fertilizer, Combination of bio-fertilizer and 1/2 chemical fertilizer	A combination of bio-fertilizer and half chemical fertilizer produced the highest yield.	Combination treatment significantly increased yield and growth traits, highlighting the effectiveness of integrating bio and chemical fertilizers.	[98]
Azotobacter chroococcum	Sudan	Maize	Zero, 6.25 L/Ha, 12.5 L/Ha, 18.75 L/Ha, 25 L/Ha	Highest grain yield with 18.75 L/Ha bio-fertilizer application.	Significant increase in plant height, stem diameter, leaf area, 100-grain weight, and grain number per cob.	[99]
Blue Green Algae	Tamil Nadu, India	Mustard	Control, BGA at varying concentrations	Enhanced plant growth and improved soil quality in treated pots compared to control.	Blue Green Algae improved soil fertility, increased nitrogen content, and promoted better plant growth and health.	[100]
Cyanobacteria	Iraq	Tomato	Control, Seeds inoculated with cyanobacteria, Cyanobacteria added to soil	The highest yield and fruit quality traits were achieved with the Marwa variety treated with seed inoculation.	Cyanobacteria significantly improved tomato's qualitative and quantitative characteristics, enhancing fruit quality and yield.	[101]
Mycorrhiza (*Glomus intraradices*)	Iraq	Eggplant	Control, 150 kg NPK ha^{-1}, 300 kg NPK ha^{-1}, 450 kg NPK ha^{-1}, With and without bread yeast emulsion 5 g L^{-1}	Control: 2.16 t ha^{-1}, 150 kg: 3.12 t ha^{-1}, 300 kg: 4.76 t ha^{-1}, 450 kg: 4.24 t ha^{-1}	The addition of Mycorrhiza, bread yeast emulsion, and NPK 300 kg ha-1 resulted in the highest yield increases.	[102]
Bacillus subtilis	Tajikistan	Cotton	Control with NPK, Only seed treatment with FZB 24, no NPK, Seed treatment with FZB 24 + NPK, Seed treatment with Extrasol 55, no NPK	FZB 24 alone increased yield up to 30% compared to NPK alone	FZB 24 significantly enhances cotton growth and yield, showing the potential to partially replace conventional fertilizers	[103]
Bradyrhizobium strains and *Streptomyces griseoflavus*	Myanmar	Mung bean, Cowpea, Soybean	Control, Biofertilizer	Significant increases in growth, nodulation, NPK uptake, and seed yield	Biofertilizer was effective in enhancing growth and yields regardless of N application.	[104]
Rhizophagus intraradices	Various locations in Brazil	Maize	Inoculated and non-inoculated seeds, three levels of phosphate fertilization (0, 50, 100% of the recommended P)	54% average increase in grain yield with inoculation	Inoculation with R. intraradices significantly increased biomass, P uptake, and grain yield, especially in soils with low or medium P	[105]

biosafety and effectiveness for human, animal, and environmental health [110]. The REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals) regulation is pivotal in overseeing nano fertilizers, necessitating detailed assessments of their safety and environmental impacts [111].

In the United States, the regulation of SFTs, including SCRFs, is overseen by the Association of American Plant Food Control Officials (AAPFCO) [15]. However, each state has its own legislation. For instance, in California and Texas, fertilizer labels cannot imply slow or controlled release unless the components are guaranteed at a minimum of 15% of the total nutrient guarantee. The Environmental Protection Agency (EPA) and the Food and Drug Administration (FDA) regulate nanomaterials under existing frameworks such as the Toxic Substances Control Act (TSCA) and the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), ensuring that nanomaterials do not pose unreasonable risks to health or the environment [111]. Additionally, nitrogen stabilizer products in the U.S. also require registration under FIFRA, confirming their safety and efficacy.

Japan's regulatory approach involves detailed standards for SCRFs established by the Ministry of Agriculture, Forestry, and Fisheries (MAFF), which include rigorous testing protocols for nutrient release rates and environmental impacts [15]. Moreover, the Ministry of the Environment and the Ministry of Economy, Trade, and Industry provide guidelines for safely handling and using nanomaterials, focusing on minimizing exposure and environmental risks [111].

In contrast, China and India, collectively home to more than a third of the global population, are making strides in regulating SFTs, albeit at a pace not comparable to the EU or US. China has developed a robust regulatory framework for fertilizer management to support sustainable productivity, with continued financial backing for innovative products that align with environmental goals [112]. India is encouraging its biofertilizer industry because of its cost and user-friendliness, while it prioritizes agricultural output to maintain food security. The regulation of biofertilizers in India, initiated under the Fertilizer (Control) Order of 1985 and amended in 2009, mandates product testing by authorized government laboratories before marketing, though the registration process can be slow [113]. Advances in nanotechnology are also evident, yet a robust regulatory framework for such technologies remains underdeveloped in both nations.

8. Challenges in the commercialization of SFTs

While SFTs offer promising solutions for sustainable agriculture, several challenges hinder their widespread adoption and economic viability. For instance, polymer coatings, integral to many CRFs, can alter soil properties over time, impacting soil health. The susceptibility of polymer coatings to environmental factors such as temperature and moisture poses challenges in maintaining consistent nutrient release patterns [21]. The reliable determination of nutrient release rates from CRFs remains unstandardized, with laboratory data often failing to correlate with field performance. Polymer-coated CRFs, commonly evaluated for 80% nutrient release at 25°C, may overlook potential release bursts, leading to agronomic and environmental consequences. Issues such as soil acidification from sulfur-coated urea application and slow degradation of synthetic coatings also pose challenges [114]. The tailing effect, where nutrients continue to be released even after the main release period complicates nutrient management [22]. Concerns also arise regarding the potential environmental impact of non-biodegradable coatings, leading to the accumulation of microplastics in agricultural soil, posing risks to terrestrial wildlife and food security [115,116].

The higher production costs of CRFs compared to conventional fertilizers limit their widespread use in agriculture. Additionally, growers lack clarity regarding the selection and applicability of various products available in the market, which is further exacerbated by the varied environmental conditions [116]. Addressing these limitations will be crucial in realizing the full potential of SCRFs in sustainable agricultural practices.

Nano fertilizers benefit several cereal crops in yield, quality, and NUE. However, nano fertilizers have also been proven to inhibit growth and yield and create toxicity in plants [117]. Reddy et al. [118] reported that nano zinc oxide can negatively affect plant growth in maize (*Zea mays*) at the rate of 2000 mg/L. Additionally, soil properties affect the toxicity of nano fertilizers. Pullagurala et al. [119] observed that nano zinc oxide shows greater toxicity in acidic soils than alkaline ones. The study also indicates that higher concentrations of nano zinc oxide (exceeding 500 mg/L) may be toxic. However, nanoparticles at low concentrations (10-40 mg/L) are proven to be beneficial and improve plant growth, yield, and NUE [59,57,118]. The long-term effect of nano fertilizers is still unknown, and the accumulation of nanoparticles in the soil might impact soil health [60]. Another key challenge in commercialization includes unclear regulatory definitions and a lack of comprehensive toxicological data, which hinder the establishment of safety standards and environmental exposure limits. The existing regulatory frameworks struggle to adapt to the unique properties of nanomaterials, often lacking specific legislation tailored to manage these new technologies. Additionally, there are economic concerns, including the high costs associated with developing and implementing nano-agrochemicals in an already price-sensitive market [111]. Albeit nano fertilizers are an attractive prospect in agriculture, they should be researched extensively to harness their potential eventually.

In the case of biofertilizers critical limitation revolves around the availability and quality of microbial strains. The vitality, efficiency, and adaptability of biofertilizers can be compromised when strains lack competitiveness and struggle to thrive in the soil [120]. The need for effective strains that outperform others and colonize better in the soil is crucial. Another concern is the potential heavy metal content in some biofertilizers, raising environmental concerns due to the adverse impact on soil health and crop safety [121]. The unavailability of suitable carrier materials is another challenge, affecting the survivability and efficacy of biofertilizer organisms in different soil conditions [81].

Adopting biofertilizers faces hurdles due to the strict and varying regulatory frameworks across countries, which can delay new biofertilizer products' approval and market entry. The lack of awareness and understanding about the benefits of biofertilizers among farmers, especially in developing regions, hampers adoption rates. Financial constraints also play a role, as developing and scaling biofertilizer production requires substantial investment, which can prohibit growth [122]. Addressing these drawbacks necessitates ongoing research and development efforts to enhance biofertilizers' formulation, stability, and adaptability, ensuring their compatibility with diverse soil types and crops while minimizing environmental concerns [78].

9. Future trends and innovations

A previous section of the article has identified the challenges regarding the adoption of SFTs. The critical question remains: How can the efficiency and ecological sustainability of these technologies be enhanced in the future? Significant efforts are being directed towards addressing these limitations. For instance, in the case of CRFs, there are ongoing initiatives to combat the issue of microplastics by integrating biodegradable polymers [27]. Polymer blends, especially when combined with natural polymers like cellulose, lignin, starch, and chitosan, potentially induce biodegradation [33]. These endeavors aim to balance optimizing slow-release characteristics and facilitating biodegradation of the coating material. Additionally, biochar and other organic coating-based slow-release fertilizers demonstrate promise, offering 2–4 times slower release of nutrients than traditional fertilizers, proving to be worthy alternatives to more expensive synthetic polymer coated CRFs [123].

Biofertilizers are known to have fewer adverse effects than S/CRFs and nano fertilizers. However, their efficacy remains subject to variability and environmental influence, leading to unpredictable performance outcomes. To optimize their effectiveness, strategies may entail the amalgamation of various strains of plant PGPRs possessing a spectrum of growth-promoting attributes, thereby ensuring thorough nutrient uptake and defense against pathogens. Maintaining anaerobic conditions is important to sustain nitrogenase enzyme activity, facilitating nitrogen fixation. This necessitates implementing innovative strategies to mitigate oxygen sensitivity and optimize nitrogen-fixing capabilities. The advancement of carrier materials, such as biochar integration, improves the root colonization and viability of PGPRs in soil [81]. Recent progress in genetic engineering and biotechnology holds promise for developing genetically modified PGPRs with enhanced abilities for nutrient acquisition and plant growth promotion [124].

Advancements in nanotechnology are catalyzing the development of innovative nanostructures and multifunctional materials intended for incorporation into fertilizers. Investigational efforts include a broad spectrum of nanostructures, including nanoparticles, nanotubes, and nanocomposites, to optimize nutrient delivery mechanisms [125]. In addition, incorporating sensing and feedback systems within nano fertilizers shows potential for accurately monitoring the nutrient needs of plants and enhancing the efficiency of fertilizer administration dynamically. Biodegradability is another crucial focus area for future nano fertilizers, with researchers striving to develop nanostructures that can break down benignly in the soil [124]. Stimuli-responsive nanomaterials represent an advanced strategy for targeted nutrient delivery in nano fertilizers, where nutrient release is triggered by specific stimuli present in the plant or soil environment. Hydrogels are frequently employed as a polymeric matrix for designing stimuli-responsive materials. These hydrogels can be tailored to undergo triggered responses, such as contraction or expansion, in reaction to variations in their surrounding conditions. These stimuli encompass alterations in pH, temperature, redox potential, or the presence of molecular species within the rhizosphere. By manipulating nano fertilizers to react to these stimuli, the release of nutrients can be fine-tuned to align with the fluctuating nutritional demands of plants during various stages of their growth cycle [126].

The combination of beneficial microorganisms and nanoparticles in nano-biofertilizers technology exhibits great potential. Nano-biofertilizers can improve the durability and efficiency of microbial inoculants, resulting in a more reliable and consistent provision of nutrients to plants [127]. To guarantee the secure and enduring utilization of nano fertilizers in agricultural settings, it is crucial to address a range of obstacles, such as phytotoxicity, environmental consequences, and regulatory policies.

Regulatory landscapes are eventually shifting in favor of SFTs, with policies like the European Union's European Green Deal and Farm to Fork Strategy leading the way, aiming to balance productivity and soil health. Federal and state regulations are evolving to integrate these novel technologies in the United States. Meanwhile, nations like China and India are gradually realizing the potential of SFTs, although their progress is slower than in the West. This global shift towards sustainable agriculture, reinforced by supportive regulatory frameworks, suggests that smart fertilizers will soon be able to better penetrate the markets and become an integral part of production practices.

10. Conclusion

Smart fertilizer technologies are advancing to transform agricultural practices by incorporating chemistry, biotechnology, nanotechnology, and agronomy. Biological fertilizers are advantageous because they have minimal side effects and are crucial for improving soil health and microbial biodiversity. Nevertheless, the efficacy of these fertilizers may differ depending on the specific soil and environmental circumstances. On the other hand, SCRF technologies have the potential to improve nutrient use efficiency, but they are less popular due to their high production expenses. The research efforts are dedicated towards enhancing the coating materials and methods of production to make them cost-effective. Furthermore, the advancement of stimuli-responsive CRFs shows potential by allowing for controlled nutrient release in response to environmental stimuli, thereby further improving their effectiveness. The utilization of biopolymers as a sustainable substitute for petroleum-based polymers fosters eco-conscious solutions by mitigating potential hazards of microplastics. Nano fertilizers provide precise nutrient delivery, but the concerns regarding their toxicity and long-lasting nature require thorough investigation to guarantee their environmental safety.

Lastly, the focus should be on developing environment-specific strategies by integrating multiple SFTs to best optimize the potential of these technologies to help minimize the negative environmental impact of agriculture at reasonable costs. An initiative is required to educate growers about the advantages and optimum methods of applying SFTs. To fully achieve the sustainability potential of SFTs, it is necessary to prioritize research, development, and extension efforts.

Ethics statement

Not applicable: This manuscript does not include human or animal research.

CRediT authorship contribution statement

Sukhdeep Singh: Writing – review & editing, Writing – original draft, Data curation. **Ravinder Singh:** Writing – review & editing, Writing – original draft. **Kulpreet Singh:** Writing – review & editing, Writing – original draft. **Karun Katoch:** Writing – review & editing, Writing – original draft. **Ahmed A. Zaeen:** Writing – review & editing, Writing – original draft. **Dereje A. Birhan:** Writing – review & editing, Data curation. **Atinderpal Singh:** Validation, Data curation. **Hardev S. Sandhu:** Validation, Data curation, Conceptualization. **Hardeep Singh:** Validation, Investigation, Conceptualization. **Lakesh K. Sahrma:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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