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Integrated Fertilization to Support Crop Productivity in Saline Soils

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INCREASING global population and climate change represent serious challenges to food, water, energy, and soil security for all people. It is thought that climate change will accelerate the harmful impacts of soil salinization and increase the spread of salinity related problems to new areas in the near future. Thus, soil salinity management should be considered a crucial challenge for the future of humanity. This future does not depend only on crop production, but also on other ecosystem services such as the supply of clean water, bioenergy, and related soil products that make modern civilization possible. Soil salinization can reduce crop productivity and other ecosystem services, but proper management, including integrated fertilization, may support crops under such conditions. Integration means utilization of multiple types of fertilizers, including bio-, chemical, and nano fertilizers. Integrated fertilization can mitigate salinity stress by enhancing the biochemical, physiological, and molecular attributes of cultivated plants under salt stress while improving soil properties and conditions. The right combination of fertilizers and cropping systems is still an open question that needs to be answered.

Keywords: Mineral fertilizer, Organic fertilizer, Biofertilizers, Nanofertilizers, Oxidative stress.

1. Introduction

Crop production depends on many factors, including soil and nutrient conditions. Fertilization can not only boost crop nutrition but also ensure nutrient carryover to future crops (Farias et al. 2025). There are many kinds of fertilizers, including biofertilizers, chemical fertilizers, nano fertilizers, and organic fertilizers. While these fertilizer types can be used independently, they can also be used in combinations designed to take advantage of the best attributes of each, an approach known as integrated fertilization systems (IFS). This approach is also known as integrated nutrient management. Integrated fertilization has many benefits for the soil, crops (including food and forage), and animal production (Simões et al. 2025). Studies confirm that IFS can increase crop productivity and resource use efficiency, along with improving soil quality due to improved soil properties (Wang et al. 2025). Improved soil properties in turn lead to improved soil security and ecosystem services, which supports food, water, and energy security (McBratney et al., 2014; Brevik et al., 2018). Optimizing nutrient and water management is a crucial role of IFS, especially under stressful conditions (Liu et al. 2025). Integrated fertilization can also help address global climate change, as greenhouse gas (GHG) emissions are reduced by ~46% under IFS compared to traditional agriculture (Chen et al. 2025).

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Soil salinization represents one of the largest global challenges under global climate change. Soil salinization hinders food security and environmental sustainability, and climate change is accelerating the spread of soil salinization into currently unaffected regions (Mukhopadhyay et al. 2021). Soil salinity threatens around 10% of

the world's total arable land, with soil salinization due to human activities affecting around 76 million ha (Mishra et al. 2023). The reduced crop yields and nutrient imbalances introduced by soil salinity also represent a threat to human health (Brevik, 2010). Therefore, approaches are needed to mitigate and manage soil salinity including (1) soil mapping (Chi et al. 2025), (2) physical management such as sub-soiling (Su et al. 2025), deep ploughing (Li et al. 2025), leveling (El-Ramady et al. 2022), sand mixing (Xu et al. 2025), leaching (El-Ramady et al. 2024), and mulching (Song et al. 2025), (3) chemical methods such as gypsum application (Liu Y et al. 2025), mineral fertilization (Duan et al. 2025), organic fertilization (Hou et al. 2025), bio-fertilizers (Dai et al. 2025), and nano-fertilizers (Shoukat et al. 2024, 2025); (4) remediation through bioremediation (Wang T et al. 2025), phytoremediation, and microbial remediation (Zhou et al. 2025).

While many papers have been published regarding ways to address soil salinity and crop production, and progress has been made, saline soils still represent a serious challenge to agricultural production. Therefore, this review discusses crop production in saline soils, highlighting the potential role of IFS in mitigating salinity stress.

2. Crop production in saline soils

Soil salinity represents a major restriction to global agricultural productivity by imposing a range of physiological, biochemical, and environmental stresses on crops (**Table 1; Figure 1**). Elevated salt concentrations in the soil lead to osmotic stress, which hinders water uptake and creates drought-like conditions even under normal irrigation regime (Majeed and Muhammad, 2019). In addition to water stress, salinity disrupts nutrient homeostasis by interfering with the uptake of essential ions, particularly through sodium-induced inhibition of potassium and calcium absorption (Faisal et al., 2024). This ionic imbalance is further impaired by the generation of reactive oxygen species (ROS), which cause oxidative damage to cellular structures, harm the photosynthetic efficiency, and disrupt key metabolic pathways (Kaviyazhagan and Prakash, 2023). These combined effects led to significant yield reductions, especially in arid and semi-arid regions, thereby increasing food and energy insecurity and increasing the economic burden on farmers through declining crop productivity and rising reclamation costs (Ashford, 2023; Baig et al., 2023). Moreover, the environmental implications of soil salinization contribute to secondary salinization, degradation of soil structure, and loss of microbial and plant biodiversity (Ashford, 2023).

Integrated mitigation strategies have been explored in response to these challenges, including the development of salt-tolerant crop varieties and the implementation of precision irrigation systems (Tarolli et al. 2024). However, the success of these strategies depends heavily on a supportive fertilization system designed to address the unique conditions in saline soils. Fertilization plays a pivotal role not only in compensating for nutrient imbalances but also in improving soil physical and biological properties. For example, the use of fertilizers enriched with organic amendments—such as alfalfa residues or pig manure—can enhance soil structure, increase cation exchange capacity, and improve nutrient availability (Liu et al. 2024). Additionally, microbial-enriched fertilizers have been shown to stimulate enzyme activity in the soil and promote root development, both of which are critical for enhancing nutrient uptake under salt stress (Wei et al. 2024). Nano fertilizers have also been shown to have beneficial effects in salt affected soils (El-Ramady et al., 2024). Innovative systems that integrate nutrient application with salt removal techniques can significantly improve the root zone environment, leading to better crop performance (Wang et al. 2024). Equally important is water management, particularly the use of irrigation and drainage systems that facilitate salt leaching and help maintain soil fertility over time (Tarolli et al. 2024). It is also important to recognize that plant responses to fertilization under saline conditions are highly variable across species where different crops exhibit unique physiological and biochemical responses due to the complex interactions between salts and nutrients in the rhizosphere (Sheoran 2023).

Table 1. The response of different crops to soil salinity with and without fertilization programs.

Plant species	Soil salinity level	Fertilizer program	Major study findings	References
Wheat-maize cropping system	EC, 3.1-7.8 dS m^{-1} during period from 2015 to 2023	Base fertilizers: 150 kg N /ha, 75 kg P /ha and 50 kg K /ha	Salinity of irrigation water and soil control salt accumulation in the soil and crop yield	Liu et al. 2024
Wheat-maize cropping system	Coastal saline-alkali soil (EC 8.17 dS m^{-1}, pH 8.30)	N, P_2O_5, K_2O: 225, 180 and 100 kg ha^{-1}	Sodium carboxy-methyl cellulose increased soil water storage and reduced soil salinity	Li et al. 2024
Sweet sorghum	Saline -alkali coastal soil (EC 5.9 dS m^{-1}, pH 8.41)	Total nutrient content (N + P_2O_5 + K_2O) was 3, 5 and 2 %, resp.	Microbial fertilizers boost soil microbial community diversity and network complexity	Wu et al. 2024
Paddy rice production	Soil salinity 2-6 dS m^{-1}, pH 9.91	Applied N, P_2O_5, and K_2O at 120, 60 and 96 kg·ha^{-1}, respectively	Applied biochar increased rice yield by 14.2 %; enhanced N-content in leaves by 28.6 %	Zhao and Grossart (2024)
Sunflower in pots for 4 months	Saline-alkali soil (pH 8.77; EC 5.3 dS m^{-1})	Without fertilization program	Rhamnolipids increased crop growth by 117%, nutrient availability, and improved soil microbial communities	Zhang et al. 2024
Alfalfa cropping for 3 years	EC, 12 dS m^{-1} top-soil and pH, 10.12	Without fertilization program	Cropping alfalfa improves saline soils and soil fertility for sustainable use.	Zhu et al. 2025
Cotton in a long-term study (25 years)	EC, 3.12 – 34.37 dS m^{-1}	N, P_2O_5 and K_2O were 374, 235 and 103 kg·ha^{-1}, respectively.	Soil bacteria helped increase cotton growth; the combination reduced soil salinity	Jia et al. 2025
Several crops all over the world	Saline-alkali soils (EC > 4 dS m^{-1} or pH > 8.5)	Biochar, farmyard manure, and compost on a global level	Soil EC, pH, and salt content decreased by 23.6, 2.3 and 20.9 % %, compared to without organic amendments	Li T et al. 2025
Tomato plants under greenhouse conditions	Salt stress (60 and 120 mM NaCl; 6-12 dS m^{-1})	Applied commercial nutritive solution (Soluponics Universal, Inverfarms, Mexico)	SiO_2/TiO_2 nano-composites (up to 500 mg L^{-1}) enhanced salt tolerance by stimulate osmolytes production in tomato plants exposed to salinity	Rolón-Cárdenas & Rodríguez-González 2025
Euhalophyte *Suaeda salsa* L.	Experimental soil columns (pH 8.48-9.65; EC 0.18 to 70 dS m^{-1})	Basal fertilizers applied: 10.4 g urea and 7.5 g KH_2PO_4 to the 0–20 cm soil depth interval	Plants reduced soil salinity via phyto-desalination; improved soil quality via root-soil interactions	Wang et al. 2025
Paddy and cotton farm lands	Reclaimed saline-alkali soils for 25 years (EC 11 dS m^{-1})	Without fertilization program	Bacterial communities important in reclaimed saline-alkaline soil and influenced by pH, SOC, and soil moisture content	Yin et al. 2025

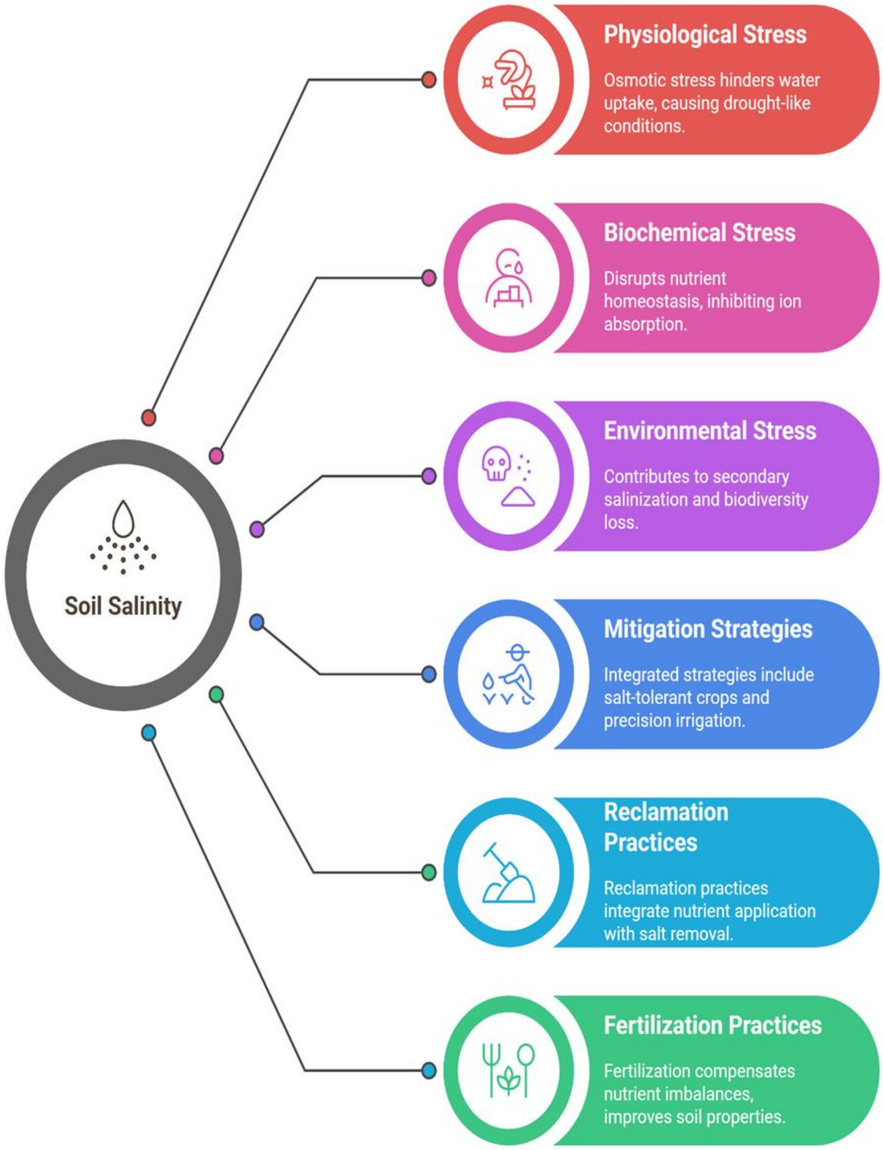

Fig. 1. The stresses soil salinity exerts on crops and suggested methods to address them.

3. Integrated fertilization and saline soils

Integrated fertilization is a strategy that combines multiple types of fertilizers (e.g., biofertilizers, chemical fertilizers, nano fertilizers, and organic fertilizers) (**Figure 2**). The IFS approach has proven effective at improving nutrient use efficiency, enhancing soil properties, and mitigating the harmful impacts of soil salinity on crops. This integrated approach supports sustainable crop production under salt-affected soil conditions (Wag *et al.* 2025). Fertilization *via* industrial chemical fertilizers supplies essential nutrients (*e.g*., N, P, and K), however, the efficiency of these fertilizers is reduced in salt affected soils due to leaching losses and ion antagonism (Liu *et al.* 2023). Bio-fertilizers such as compost improve the properties of salt-affected soils by increasing soil aggregates and improving water movement through the soil; thus, the salts leach away. Additionally, it supplies the soil and plants with nutrients as the compost decomposes (Hou *et al.* 2025). Nano-fertilizers offer controlled nutrient release in addition to higher surface area per unit mass, enabling precise nutrient delivery and better absorption by higher plant roots (Shoukat *et al.* 2024). Bio-fertilization that includes salt-tolerant microbial strains enhances availability of nutrients in the soil and promotes higher plant stress tolerance. This effect of bio-fertilization improves root architecture and produces growth-promoting substances. Moreover, it leads to better osmotic adjustment (Alotaibi *et al.* 2024). The synergistic influence of combining these different types of fertilization (IFS) helps improve soil structure and nutrient retention as well as maintain soil microbial diversity. **Table 2** illustrates the effect of IFS applied in saline conditions.

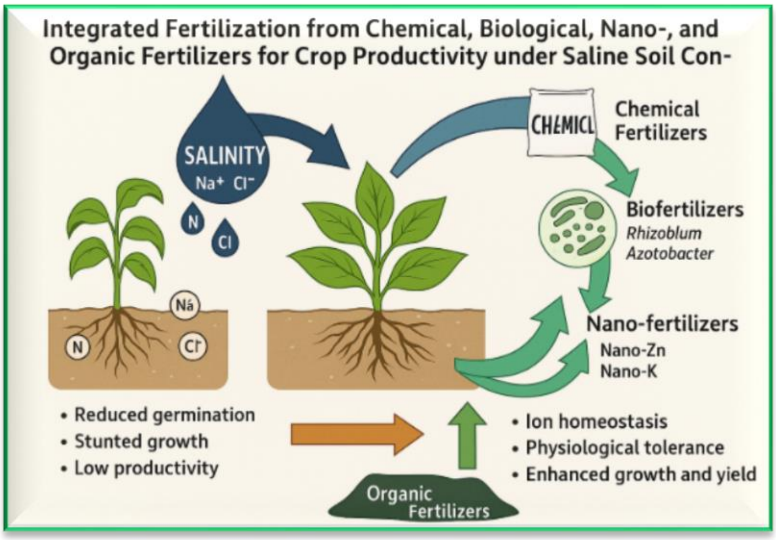

Fig. 2. Integrated fertilization against saline conditions.

Table 2. Integrated fertilization to address saline conditions as reported by some recent studies.

Plant type	Salinity conditions	Fertilization type	Response	References
Rocket (*Eruca sativa*)	Irrigation by agro-drainage water	Nano-fertilizers (NPK), salicylic acid, and poultry wastes	The combined treatment of nano-compound fertilizer + poultry wastes + salicylic acid led to improvements in plants, as this approach help the plant resist the adverse effects of saline irrigation water.	Al-Taey and Al-Musawi, (2019)
Wheat (*Triticum aestivum*)	Salt affected soil (5.89 dS m^{-1})	chemical fertilization (NPK) with bio-fertilization on nanoparticles	This approach is effective as an integrated fertilization system in increasing the values of N, P, and K in grain and straw	Hasan and Saad (2020)
Wheat (*Triticum aestivum*)	Saline-alkali stress (pH 8.13; EC 13.2 dS m^{-1})	Organic amendments combined with bio-stimulants	The highest plant production of enzymatic and non-enzymatic antioxidants was realized when plants were treated with vermicompost and moringa extract	Awwad *et al.* (2022)
Wheat (*Triticum aestivum*)	Salt affected soil (EC=7.17dS m^{-1})	Molasses, compost tea, K-humate nano-selenium, nano-manganese, nano-silica	Organic amendment increased soil cation exchange capacity while nano micronutrients improved wheat grain yield. Co-application of organic amendments and nano-fertilization is an effective approach under salinity stress	Sorour *et al.* (2022)
Alfalfa (*Medicago sativa*)	Saline water (6 and 10 dS m^{-1})	Chemical and nano-fertilizers (K_2SO_4, ZnO and SiO_2)	The incorporation of nano-fertilizers with chemical fertilizers provide a promising strategy, especially in regions with low water quality	El-Shal *et al.* (2022)
Soybean (*Glycine max*)	Salt affected soil (10.48 dS m^{-1})	NPK nano-fertilizers, bio-fertilizers and humic acid	Integrated fertilization led to a slight decrease in soil pH, a significant decrease in EC values and significant increases in the availability of soil macro and micro-nutrients, as well as increases in the macro- and micronutrient contents in the grains.	Esmaeil *et al.* (2022)
Barley (*Hordeum vulgare*)	Salt-affected soil and water	Phosphate solubilizing bacteria, nano phosphozink	The integrated fertilization approach was effective in improving barley yield and enhancing soil physical and chemical properties.	Ibrahim and Hegab (2022)
Wheat (*Triticum aestivum*)	Salt affected soil (6.33 to 8.13 dS m^{-1})	Molasses, compost tea or K-humate combined with nano-silica	The co-application of organic substances and nano-silica was an effective approach to restore and conserve the soil and improve wheat productivity under salt-affected soil conditions	Rashed *et al.* (2022)
Cowpea (*Vigna unguiculata*)	Salt affected soil (8.85 dS m^{-1})	Nano-NPK, organic fertilizers, NPK fertilization	The combination of compost, chemical and nano-fertilizers improved soil nutrients' status and production of cowpea under saline soil conditions.	Shaban *et al.* (2025)

4. Crop production using integrated fertilizers in saline soils

4.1. Benefits of Integrated Fertilization

Integrated fertilization offers numerous benefits and some limitations (**Figure 3**). This approach combines various agricultural practices, enhancing productivity and sustainability while addressing environmental concerns (Akter et al. 2025). The following points outline the key benefits and limitations of IFS:

(1) Enhanced productivity: IFS promotes the synergistic integration of crops, livestock, and aquaculture, leading to increased overall productivity per unit area (Singh et al., 2024; Bahadur et al., 2024). It is worth to mention that, the integration of livestock and aquaculture, for example, is not a requirement of IFS. It may encourage farmers to be diverse in their production, but IFS can be done with only crops.

(2) Soil health management: The balanced use of bio-, chemical, and nano-fertilizers improves soil fertility and maintains soil organic matter, crucial for sustainable crop production (Goda 2019; Hanurawaty, 2022).

(3) Diversified income: By integrating multiple agricultural enterprises, farmers can generate diversified income streams throughout the year, reducing economic vulnerability (Singh et al., 2024).

(4) Environmental sustainability: Integrated practices reduce reliance on chemical fertilizers, thereby minimizing environmental degradation and greenhouse gas emissions (Hanurawaty, 2022).

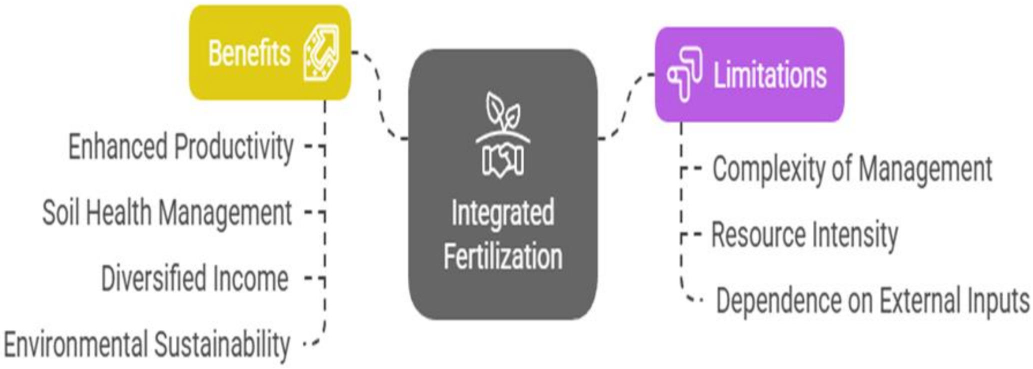

Fig. 3. An overview onf the integrated fertilization including benefits and limitations of integrated fertilization.

4.2. Limitations of Integrated Fertilization

Despite its limitations, integrated fertilization remains a promising strategy for enhancing agricultural sustainability and productivity. However, the complexity and resource demands may hinder its widespread adoption, particularly among smallholder farmers. The most important limits may include the following:

(1) Complexity of management: Implementing IFS requires knowledge and skills to manage diverse components effectively, which can be challenging for smallholder farmers (Bahadur et al., 2024).

(2) Resource intensity: Initial investments in infrastructure and training can be high, potentially limiting adoption among resource-poor farmers (Hashmi and Saleem, 2017).

(3) Dependence on external inputs: While integrated systems aim to reduce chemical use, they may still rely on external inputs, which can be economically burdensome (Goda, 2019).

4.3. Integrated fertilizers and plant growth under saline soil conditions

The synergistic effects of combining bio-, mineral, organicchemical, and nano- and bio-fertilizers on plant growth and nutrient uptake in saline soils have been extensively studied, revealing significant benefits for agricultural productivity. The integration of these fertilizers enhances soil properties, nutrient availability, and plant resilience against salinity, leading to improved crop yields, as follows:

(1) ***Enhanced Nutrient Availability***

The use of salt-tolerant plant growth-promoting bacteria (PGPB) like *Bacillus* species increases the availability of essential nutrients such as nitrogen, phosphorus, and potassium in saline soils (Mohaseb et al., 2019). Nano-fertilizers can improve nutrient solubility and uptake efficiency, allowing for controlled release and targeted delivery of nutrients, which is particularly beneficial in saline conditions (Tomar et al., 2024). At the same trend, applying manures and composts as fertilizers improves the soil ecological environment through enhancing the nutrient availability (Tuo et al. 2025). Regarding nanofertilizers, several reports confirmed the role of such fertilizers in promoting the soil nutrient availability (Rashid et al. 2023; Ansari et al. 2024).

(2) ***Improved Plant Growth***

Studies show that the combination of biofertilizers with chemical fertilizers, nanoparticles, and/or organic fertilizers significantly enhances plant growth parameters, including biomass yield and nutrient content in crops like rice and wheat (Mohaseb et al., 2019; Saleh et al., 2024). The interaction between nanoparticles and biofertilizers has been shown to promote better growth traits, such as increased chlorophyll content and reduced sodium accumulation in plant tissues (Karunakaran et al., 2024; Saleh et al., 2024). Different formulations of nano biofertilizers have been shown to be effective in enhancing plant growth (El-Bialy et al., 2023) and as bio-emerging strategies for sustainable agriculture (Garg et al. 2023; Sharma et al. 2023; Thirumurugan et al. 2024; Kumar et al. 2025).

(3) ***Soil Health and Salinity Mitigation***

The application of combined fertilizers leads to improved soil pH and reduced salinity levels, enhancing overall soil health and fertility (Saleh et al., 2024; Xing et al. 2025). Organic amendments, when combined with bio- and nano-fertilizers, promote salt leaching, further mitigating the adverse effects of salinity on plant growth (El-Sharkawy et al. 2024). While the synergistic effects of these fertilizers are promising, it is essential to consider the potential for over-reliance on such technologies, which may lead to unforeseen ecological impacts or nutrient imbalances if not managed properly.

(4) ***Mechanisms of synergistic interaction between nano-, bio-, organic and chemical fertilizers***

The synergistic interaction between nano, bio-, organic, and chemical fertilizers is facilitated by several underlying mechanisms that enhance nutrient efficiency and promote sustainable agricultural practices (**Figure 4**). This integration leverages the unique properties of nanoparticles, bioactive compounds, and traditional fertilizers to optimize plant growth and minimize environmental impact. This mechanism may include targeted delivery and controlled release of nutrients, enhanced nutrient bioavailability to cultivated plants, microbial synergy and physiological benefits (Yadav 2025). Nanofertilizers (NFs) enable precise nutrient delivery to plants, reducing nutrient losses and enhancing uptake efficiency through controlled release mechanisms (Fazelian and Morteza 2022; Padhan et al., 2023). The small size and high surface area of nanoparticles improve the solubility and bioavailability of nutrients, allowing for better absorption by plant roots (Padhan et al., 2023; Garg et al., 2023). Biofertilizers, when combined with NFs, promote beneficial microbial activity in the soil, enhancing nutrient cycling and plant health through mechanisms like rhizoremediation and disease resistance (Fazelian and Morteza 2022; Garg et al., 2023). The application of nano-biofertilizers can improve plant stress resistance and growth parameters, such as photosynthetic efficiency and leaf area, leading to increased crop yields (Kalenska et al., 2023; Rasool et al., 2024). While the integration of these fertilizers shows great promise for enhancing agricultural productivity, concerns regarding the long-term environmental impacts and potential toxicity of nanoparticles necessitate careful evaluation and regulation to ensure sustainable practices. The strong relationship between mineral and organic fertilizers for enriching the soil with fast and proper nutrients is considered by reaserchers several years ago. Thus, it is reported that the application of organo-mineral fertilizers can improve soil health and builds up a favorable environment for better plant growth, garanttee the release of nutrients slowly, reduce the nutrient leaching loss and greenhouse gas emissions than menieral fertilizers (Kafil Uddin et al. 2025). Organo-mineral fertilizers also able to enhance crop productivity by increasing the nutrient use efficiency over mineral fertilizer application (Oliveira et al. 2025).

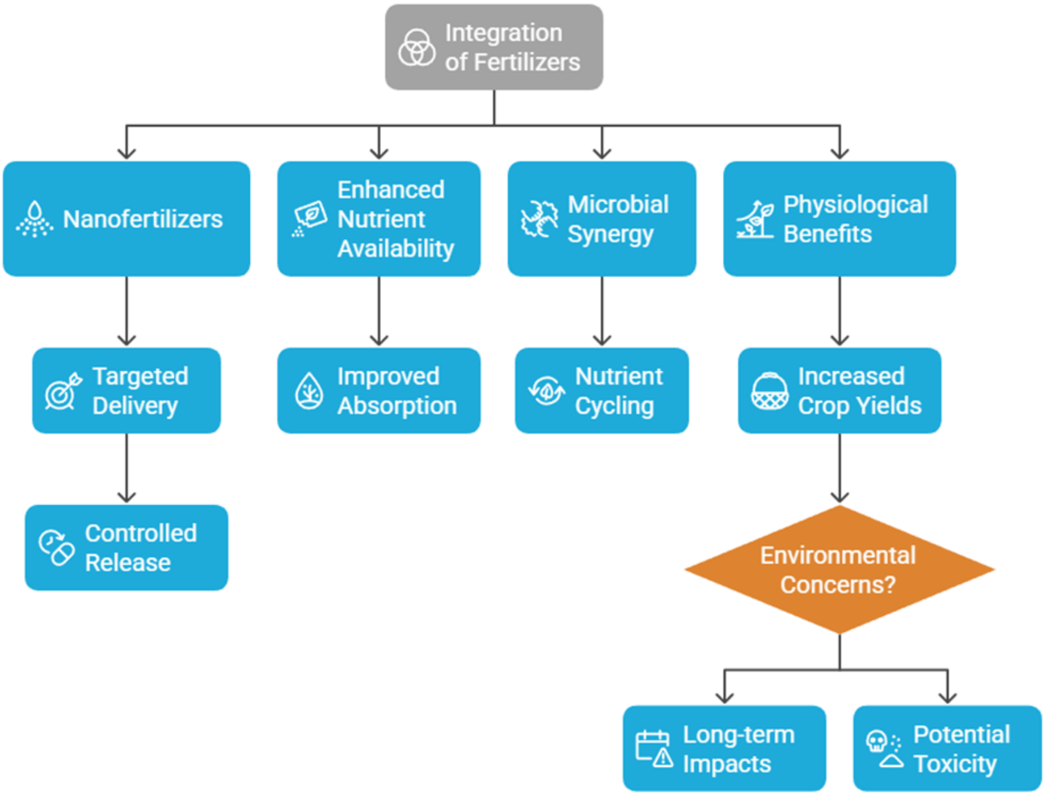

Fig. 4. The integration of applied fertilizers and environmental concern.

4.4. Comparison of fertilizers

The use of fertilizers in agriculture is essential for maintaining soil fertility and ensuring crop productivity. However, the environmental and health impacts of different types of fertilizers, including organic, nano, bio-, and chemical fertilizers, have been a subject of extensive research (**Figure 5**). This section provides a comparison of the environmental and health risks associated with these fertilizers, as well as the regulatory frameworks governing their use (**Table 3**).

4.4.1. Environmental risks of fertilizers

(1) Chemical fertilizers: Chemical fertilizers consist of synthetically formulated nutrient mixes and/or the transformation of mineral nutrient sources into forms that are more readily available to plants in the soil environment. Chemical fertilizers been widely used in agriculture, particularly since World War II (Havlin et al., 2013). However, their production and use have significant environmental and human health impacts. The production of chemical fertilizers is energy-intensive and contributes to greenhouse gas emissions (Santolin et al., 2024). Additionally, the excessive use of nitrogen-based fertilizers has been linked to environmental pollution, including nitrate contamination of water bodies, a human and environmental health hazard (Brevik, 2010), and the release of nitrous oxide, a potent greenhouse gas (Huzenko, 2024). The leaching of nutrients from traditional fertilizers into water bodies can lead to eutrophication, which can have devastating effects on aquatic ecosystems (Eldridge et al., 2024; Jithendar et al., 2024). Furthermore, the use of traditional fertilizers has been associated with soil degradation, including acidification and the depletion of organic matter (Upadhyay et al., 2023).

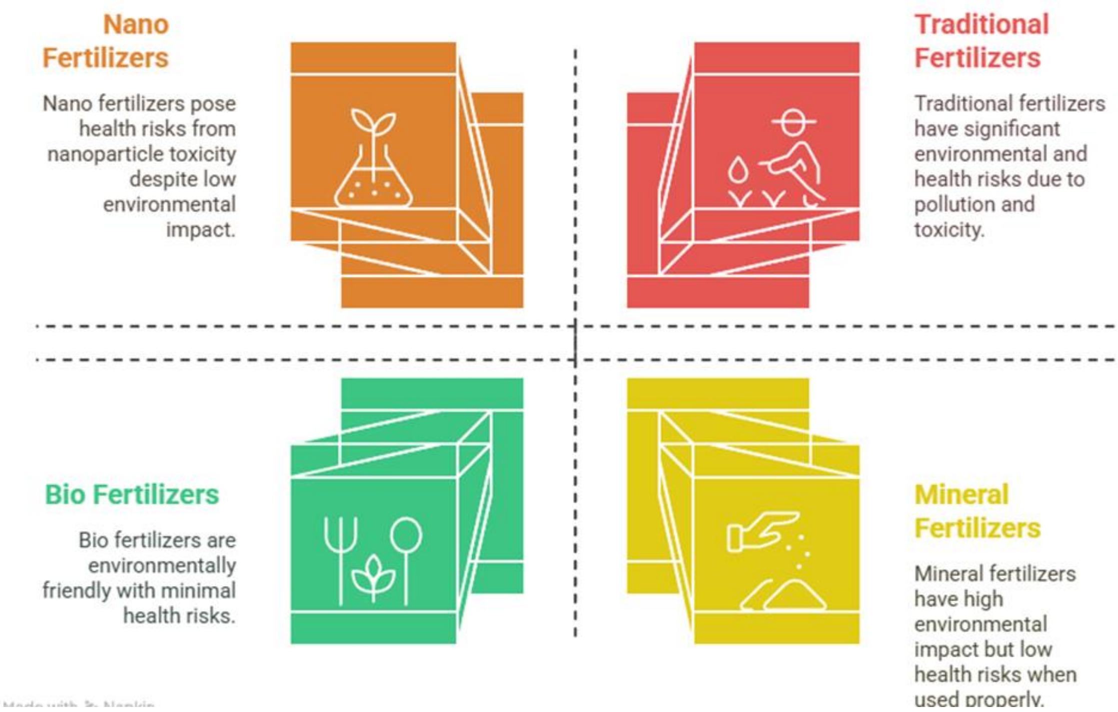

Fig. 5. Comparative risk Analysis of Fertilizer types.

Table 3. A comparison among different types of fertilizers.

Fertilizer Type	Environmental Impact	Health Impact	Regulatory Framework
Chemical fertilizers	High risk of nutrient leaching, soil degradation, and greenhouse gas emissions [1,2]	Health risks from water and air pollution, and accumulation of toxic substances in food [2,3]	Established regulatory frameworks, but need for stricter controls [1,2]
Nano-fertilizers	Lower risk of nutrient leaching and runoff, but potential toxicity of nanoparticles [4,5]	Potential health risks from nanoparticle toxicity [5,6]	Regulatory frameworks in early stages of development, need for standardized testing protocols [5,6]
Bio-fertilizers	Lower environmental impact, improves soil health, but potential for pathogen contamination [7,8]	Generally safer for human health, but risks from untreated waste and antibiotic resistance [9]	Established regulatory frameworks, but need for further research and harmonization [8,9]
Organic fertilizers	High environmental impact from mining and soil degradation [1,3]	Health risks from toxic substances in soil and water [3]	Regulatory frameworks in place, but need for stricter controls on mining and use [1,3]

List of refs. [1] Santolin et al. (2024), [2] Huzenko (2024), [3] Upadhyay et al. (2023), [4] Jithendar et al. (2024), [5] Noor & Elgharbawy (2024), [6] Langangmeilu et al. (2024), [7] Hu et al. (2024), [8] SAD (2024), [9] Gupta et al. (2024)

(2) Nano fertilizers: Nano fertilizers, which are fertilizers coated or encapsulated in nanomaterials, offer several environmental benefits compared to traditional fertilizers. These fertilizers release nutrients slowly, reducing the risk of leaching and runoff, which can contribute to water pollution (Jithendar et al., 2024). The controlled release of nutrients also reduces the need for frequent applications, thereby decreasing the overall environmental impact (Singh et al., 2023). However, the use of nano fertilizers is not without risks. The potential toxicity of nanoparticles to plants and soil organisms has been a concern. Some studies have shown that nanoparticles can cause phytotoxicity if applied in excess (Jithendar et al., 2024). Additionally, the long-term environmental fate of nanoparticles in agroecosystems is not yet fully understood, raising concerns about their potential accumulation in the environment (Noor and Elgharbawy, 2024).

(3) Biofertilizers: Biofertilizers focus on enhancement of the soil microbiome to enhance nutrient uptake and plant growth. They are considered more environmentally friendly than traditional fertilizers. These fertilizers improve soil health by increasing the availability of nutrients and enhancing soil organic matter (Hu et al., 2024). Biofertilizers also reduce the need for synthetic fertilizers, thereby decreasing greenhouse gas emissions and minimizing the risk of nutrient leaching (SAD 2024). However, the use of bio fertilizers is not without challenges. The production of bio fertilizers can be resource-intensive, and their effectiveness can vary depending on the specific microbial strains used (SAD 2024). Additionally, the use of bio fertilizers may require additional management practices, such as proper storage and application, to ensure their effectiveness and safety (Gupta et al., 2024).

(4) Organic fertilizers: Organic fertilizers are derived from organic sources such as animal waste and plant residues. They differ from biofertilizers in that the focus of organic fertilizers is on the addition of organic material to the soil with the benefit of slow nutrient release over time as the organic material decomposes, along with building of soil aggregates and its associated benefits (Liu et al. 2024; Tuo et al. 2025). While organic fertilizers also enhance soil microbial activity, unlike biofertilizers, organic fertilization does not involve adding particular target microorganisms to the soil (**Table 4**). The benefits of oranic fertilizers include mitigation of greenhouse gas (GHG) emissions (He et al. 2023), imrpving soil health (Howe et al. 2024), sustainable remediation (Li et al. 2025), and can considered novel fertilizers for organic farming (Balkrishna et al. 2025). Recently, a new approach towards application of organo-mineral fertilizer for improving soil health and building up a favorable environment for better plant growth was established (Kafil Uddin et al. 2025; Oliveira et al. 2025).

Table 4. The fundamental differences between biofertilizers and organic fertilizers.

The comparison item	Organic fertilizers	Biofertilizers
Definition	Decayed organic matter from plants and/or animals that directly enriches soil	Live microbes that enhance nutrient availability in soil
Composition	Derived from decayed plant and/ or animal matter	Living microbes of bacteria, fungi, algae, solubilizing phosphorus or potassium
Examples	Farmyard manure, green manure, neem cake, poultry litter(compost, manure, bone meal, vermicompost, etc.)	Rhizobium, Azotobacter, Azospirillum, Mycorrhizae, and phosphate-solubilizing bacteria (PSB)
Mode of action	Enhancing SOM, improving water retention, soil structure, microbial diversity, releasing nutrients slowly through microbial breakdown.	By biological N-fixation, phosphate solubilization, or stimulating plant growth hormones (like IAA, cytokinins), and enhancing nutrient uptake efficiency
Nutrient supply	Directly supply macronutrients (N, P, K) and micronutrients as they decompose, and acting as a slow-release fertilizer.	Enhancing nutrient availability (e.g., N-fixing bacteria convert atmospheric N_2 into plant-usable forms). More targeted in function (e.g., Rhizobium for legumes).
Application method and efficiency	Applied to soil by broadcasting, mixing, decomposition though microbes, provide SOM in slower nutrient release	Applied via seed treatment, root dipping or soil application, for microbial survival specific conditions (i.e., moisture, pH, host compatibility) are required
Environmental dimension	Improving soil health but may introduce pathogens if not properly composted, excessive use can lead to nutrient leaching (e.g., nitrate pollution).	Eco-friendly, reduce dependency on synthetic fertilizers, do not cause pollution but may have limited shelf life.
Shelf life and storage	Longer shelf life if stored properly (no moisture)	Short shelf life (6–12 months) due to living microbes; require proper storage (cool, dry conditions).

Sources: Lal (2025), El-Ghamry et al. (2018), Lio et al. (2025)

4.4.2. Health risks of fertilizers

(1) Chemical fertilizers: The excessive use of traditionalchemical fertilizers has been linked to several health risks (Steffan at al., 2018). The contamination of water bodies with nitrates from nitrogen-based fertilizers can lead to health problems, including methemoglobinemia in infants (Huzenko, 2024). Additionally, the release of ammonia from fertilizers can contribute to air pollution, which has been linked to respiratory and cardiovascular diseases (Huzenko, 2024). The use of traditionalchemical fertilizers has also been associated with the accumulation of toxic substances in food crops, which can pose health risks to consumers (Upadhyay et al., 2023). Furthermore, the use of chemical fertilizers has been linked to the development of antibiotic resistance in soil microorganisms, which can have broader implications for human health (Gupta et al., 2024). MineralChemical fertilizers are generally considered safe for human health when used properly. However, the excessive use of these fertilizers can lead to the accumulation of toxic substances in soil and water, which can pose health risks to humans, and animals, and the broader environment (Upadhyay et al., 2023). Additionally, the mining to obtain raw materials for the manufacture of mineralchemical fertilizers can lead to the release of heavy metals and other toxic substances into the environment, which can have long-term effects on human health (Steffan et al., 2018; Santolin et al., 2024).

(**2) Nanofertilizers**: The health risks associated with nano fertilizers are primarily related to the potential toxicity of nanoparticles. Some studies have shown that nanoparticles can cause oxidative stress and DNA damage in plants and soil organisms (Noor & Elgharbawy, 2024). Additionally, the inhalation of nanoparticles by humans can lead to respiratory and other health problems (Langangmeilu et al., 2024). However, the health risks associated with nano fertilizers are still not fully understood, and more research is needed to assess their long-term effects on human health and the environment (Noor and Elgharbawy, 2024). Regulatory frameworks governing the use of nano fertilizers are still in the early stages of development, and there is a need for standardized testing protocols to ensure their safe use (Langangmeilu et al., 2024).

(3) Bio-fertilizers: Bio-fertilizers are generally considered safer for human health and the environment compared to chemical fertilizers. These fertilizers are derived from natural sources and do not contain synthetic chemicals, which reduces the risk of toxic substances accumulating in food crops (SAD 2024). Additionally, biofertilizers can improve soil health, which can lead to the production of healthier food crops (Hu et al., 2024). However, the use of bio fertilizers can also pose some health risks if not managed properly. For example, the use of untreated animal waste as a bio fertilizer can lead to the contamination of soil and water with pathogens, which can pose health risks to humans and animals (Gupta et al., 2024). Additionally, the use of certain microbial inoculants in bio fertilizers can lead to the development of antibiotic resistance in soil microorganisms, which can have broader implications for human health (Gupta et al., 2024).

(4) Organic fertiliers: For example, the use of untreated animal waste as a bio fertilizer can lead to the contamination of soil and water with pathogens, which can pose health risks to humans and animals (Gupta et al., 2024). Additionally, the use of certain microbial inoculants in bio fertilizers can lead to the development of antibiotic resistance in soil microorganisms, which can have broader implications for human health (Gupta et al., 2024).

4.4.3. Regulatory frameworks governing fertilizer use

(1) Chemical fertilizers: The use of traditional fertilizers is governed by various regulatory frameworks aimed at minimizing their environmental and health impacts. For example, the European Union has implemented regulations to reduce the use of nitrogen-based fertilizers and to promote the use of organic fertilizers (Santolin et al., 2024). Additionally, many countries have established standards for the safe use of fertilizers, including guidelines for application rates and the management of fertilizer waste (Huzenko, 2024).

(2) Nanofertilizers: The regulatory frameworks governing the use of nano fertilizers are still in the early stages of development. There is a need for standardized testing protocols to assess the safety and efficacy of nano fertilizers, as well as their potential environmental and health impacts (Noor & Elgharbawy, 2024). Some countries have established regulatory frameworks for the use of nanotechnology in agriculture, but these frameworks are not yet harmonized at the international level (Langangmeilu et al., 2024).

(3) Bio- and organic fertilizers: The use of bio-and organic fertilizers is governed by regulatory frameworks aimed at ensuring their safety and efficacy. For example, the European Union has established regulations for the use of microbial inoculants in biofertilizers, including requirements for the safety of microorganisms and their potential impact on the environment (SAD 2024). Additionally, many countries have established standards for the production and use of bio fertilizers, including guidelines for quality control and labeling (Gupta et al., 2024). Regulation 2019/1009 is well-known and issued by European Union (EU)-Fertilising Products Regulation, which aimed to create a single market for the organic fertilizer products, ensuring safety, quality, and appropriate labeling while also addressing environmental and health concerns (EU 2022). This regulation included some rules to open a single market to organic and waste-based fertilizers, to establish limit values for toxic pollutants in fertilizing products, and to allow optional harmonization (EU 2022). A very wide range of fertilizing products within the EU including organo-mineral fertilizers, organic fertilizers, and biostimulants is reported (EU 2025).

5. Conclusions

As a result of climate change, soil salinization may be accelerated with increased pressure on the global food production. This needs continuous innovative solutions to mitigate and treatment such global problems. Soil salinity can be found in new places all over the world due to this change. The integrated fertilization is an important approach for mitigating the soil salinity, but to what extent can this agronomic strategy be followed? More studies are needed to emphasize the right combinations from of different kinds of fertilizers in various agroecological systems. The most important concern is to reduce the use of chemical fertilizers by replacing them with organic, nano, and biofertilizers when this is appropriate and effective, and in finding ways to maximize the contributions of all types of fertilizers through the use of IFS.

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