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REGENERATIVE AGRICULTURE: AN EMERGING SOLUTION AMIDST SYNTHETIC CHEMICALS

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ABSTRACT

In recent times, the agricultural sector has faced a significant challenge characterized by the shortage and escalating costs of synthetic fertilizers. These fertilizers, which have traditionally underpinned modern agricultural practices, have become increasingly difficult to obtain and afford due to supply chain disruptions, geopolitical tensions, and rising production costs. As a consequence, a paradigm shift towards organic fertilizers has emerged as a viable solution to mitigate the impacts of this crisis. The reliance on synthetic fertilizers has been a cornerstone of high-yield agriculture, enabling farmers to enhance soil fertility and increase crop productivity. However, this dependency has culminated in a systemic vulnerability. The recent crisis has prompted agricultural stakeholders to reevaluate their practices, leading to a burgeoning interest in organic alternatives. Organic fertilizers, derived from natural sources such as compost, manure, and cover crops, offer a sustainable approach to soil health that not only replenishes nutrients but also enhances biodiversity and soil structure.

Transitioning to organic fertilizers presents both challenges and opportunities for farmers. While there may be initial barriers, such as the need for education on organic practices and potential reductions in immediate crop yields, the long-term benefits are noteworthy. Organic fertilizers contribute to sustainable agriculture by reducing reliance on chemical inputs, promoting environmental health, and addressing consumer demand for organic produce. Furthermore, as the market for organic products continues to expand, farmers leveraging organic fertilizers can potentially benefit from premium pricing and increased market access. This paper offers a comprehensive overview of the key ongoing debates surrounding the performance of conventional and organic farming in terms of yields, especially under current and future climate conditions. With a primary focus on cropland, the impact of agricultural management on soil and plant microbiomes is examined. Furthermore, the benefits of integrating microbiome-based strategies into existing farming practices to maintain agricultural productivity while minimizing negative environmental effects are emphasized. To boost crop production in organic farming without significant land-use changes or farmland expansion, a microbial-based approach can be employed to achieve greater productivity, particularly in the face of a rapidly changing climate.

This review highlights a thorough overview of the key ongoing debates regarding the performance of conventional and organic farming in terms of yields, particularly under current and future climate conditions. With a primary focus on cropland, the influence of agricultural management on soil and plant microbiomes is explored. Additionally, the advantages of incorporating microbiome-based strategies into existing farming practices to sustain agricultural productivity while reducing negative environmental impacts are highlighted. To enhance crop production in organic farming without significant land-use changes or farmland expansion, a microbial-based approach can be utilized to achieve higher productivity, especially in the context of a rapidly changing climate.

Keywords: Fertilizers, Transition, Conventional Farming, Organic Farming, Plant Microbiome.

I. INTRODUCTION

Fertilizers are essential for agriculture, serving as the key providers of nutrients necessary for the establishment and proliferation of crops. In India, the fertilizer industry plays a pivotal role not only in enhancing agricultural output but also in addressing food security challenges and generating employment in rural areas. The sector's consistent growth reflects its fundamental importance in the country’s economy and agricultural landscape.

India boasts one of the largest fertilizer industries globally, driven by increasing agricultural demands. Fertilizers in India are generally categorized into nitrogenous, phosphatic, potassium, and organic types, each designed to meet the unique needs of different soils and crops. In 2023, the Indian fertilizer market reached a valuation of USD 41.2 billion, and it is anticipated to grow to USD 70.2 billion by 2032, reflecting a steady annual growth rate of 6.1%.

Government initiatives, such as the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), have significantly encouraged the use of fertilizers and enhanced agricultural productivity. Additionally, innovative practices like precision farming and the introduction of bio-fertilizers are driving market growth by improving efficiency and sustainability. With a stable yearly growth rate of 6.1%, the Indian fertiliser industry is expected to reach a worth of $ 70.2 billion by 2032, up from $ 41.2 billion in 2023.The Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) is one of the government initiatives that has greatly increased agricultural output and promoted fertilizer use. Innovative techniques that increase sustainability and efficiency, such as precision farming and the use of biofertilizers, are also propelling industry expansion.

The push towards eco-friendly practices has led to a rising demand for organic fertilizers. Collaborations among companies are further stimulating the market, expanding the availability of specialized fertilizers to meet diverse agricultural needs. In addition, the nation's accomplishments as the world's second-largest producer of veggies and fruits highlight how important the fertilizer sector has been for agricultural development. As the primary suppliers of nutrients required for crop growth and development, fertilizers are vital to agriculture. Recent government initiatives have aimed to lessen reliance on imports, which is an informed choice given a changing geopolitical environment. Notably, in the end of fiscal year urea imports dropped by seven per cent, DAP by twenty-two percent, and NPKs by twenty-one percent, demonstrating progress toward fertilizer production self-sufficiency. Programs like the entirely Neem overlay on subsidized agricultural-grade urea are designed to maintain soil health while increasing crop output and nutrient efficiency.

Moreover, the government is investing in innovative solutions, including the expansion of nano liquid urea production plants, poised to enhance India's fertilizer capabilities while promoting environmental sustainability. “According to projections, the Indian fertilizer market is expected to develop at a 4.2 percent CAGR from 2024 to 2032, reaching a size of Rs 1.38 lakh crore. This growth underscores the sector's vital contribution to enhancing agricultural productivity and ensuring food security in India, making fertilizers indispensable in the journey toward sustainable agricultural practices. The ambitious goal of attaining urea production self-reliance by 2025–2026 has been set by the Indian government.

This objective is largely hinged on the increased local production of nano urea, which is expected to enhance both crop yield and soil health. Nano urea, known for its efficiency in delivering nutrients to plants, could play a significant role in reducing dependence on imported fertilizers Alongside this endeavor, organic farming is being extensively promoted nationwide by the Paramparagat Krishi Vikas Yojana (PKVY). This program provides farmers with three years of financial assistance at a rate of Rs 50,000 per acre, with Rs 31,000 going directly toward organic inputs. As awareness of health and environmental issues grows, the market for organic and bio-fertilizers is poised for considerable expansion.

Nonetheless, there are difficulties in the agricultural environment. Food security is seriously threatened by climate change, as estimates suggest that wheat yields could drop by 19.3 percent by 2050 and by as much as 40 percent by 2080.The National Mission for Sustainable Agriculture (NMSA) is putting plans into action to strengthen Indian agriculture's resilience in order to address these issues. This includes not just the promotion of sustainable practices but also the revival of previously closed fertilizer plants in key locations such as Talcher, Ramagundam, Gorakhpur, Sindri, and Barauni. Furthermore, boosting agricultural output, educating farmers on the appropriate use of fertilizers, and offering them access to affordable discounted fertilizers continue to be the primary goals. This effort, which focuses on creating new fertilizer categories and enhancing current organic products, requires constant study and innovation.

In conclusion, India's multifaceted approach to increasing urea production, promoting organic farming, and addressing climate challenges showcases its commitment to a sustainable agricultural future. As these initiatives unfold, the potential for growth and resilience in Indian agriculture looks promising. (Economic times Industry, 2024)

In this review, we will explore how the cost of inputs used in farming has skyrocketed. Since 2020, the World Bank estimates that fertilizer prices have increased by 80%. This has left farmers strapped for cash and decreased yields, with effects surging through every part of the food chain. However, many farmers are turning this challenge into an opportunity. Through regenerative agriculture, they can dramatically reduce input costs and reliance on synthetic fertilizers while rebuilding the soil. We’ll examine how rising prices are impacting farmers, the role of regenerative agriculture in cutting costs, and the results of farmer’s transitioning.

What is fertilizer?

Fertilizers are substances, either synthetic or natural, that are added to soils or plant tissues in order to treat nutrient deficiencies or provide vital nutrients for plant growth. They can be categorized as either inorganic (mineral) or organic, and they contain at least 5% of one or more primary nutrients, such as either potassium (K), phosphorous (P), or nitrogen (N).

Industrially produced fertilizers are often referred to as "mineral" fertilizers. In addition to the major nutrients, fertilizers may include minor elements like zinc (Zn), manganese (Mn), and iron (Fe), along with impurities and non-essential elements. Soil conditioners, such as lime and gypsum, are also considered fertilizers as they enhance nutrient availability and improve soil structure, thereby promoting plant growth.

Fertilizers Classification

In an amendment to Act No. 156/1998 Coll., the term "fertilizer" is defined. In order to restore the vitamins and minerals that have been depleted from the soil by crop harvesting, fertilizers are needed and are applied to increase crop output (Sharma & Chetani, 2017). In order to produce nutritious products for the world's growing population, plant nutrients are necessary. As a result, plant nutrients are essential to agricultural sustainability. According to Usman and Madu Alkali (2015), the type of fertilizers used to replenish the required plant nutrients have a significant impact on increased crop yield.

Nutrients from inorganic, organic, and biofertilizers have different roles and benefits for crop growth and soil fertility. Effective fertilizer management is essential for enhancing yields while protecting the environment. A balanced strategy that incorporates chemical, organic, and biofertilizers should be developed and evaluated. (Trenkel Martin E,2010)

Three Main Macronutrients

- Nitrogen (N) is essential for chlorophyll, promoting leaf growth.
- Phosphorus (P) supports energy transfer and the development of roots, flowers, seeds, and fruit.
- Potassium (K) activates enzymes in photosynthesis and respiration, aids stem growth, and encourages flowering and fruiting..

Three Secondary Macronutrient

1. Calcium (Ca) helps transport nutrients into the plant, activates enzymes, and is vital for photosynthesis and plant structure.
2. Magnesium (Mg) is a key part of chlorophyll and acts as a carrier in various enzyme reactions.
3. Sulfur (S) is essential for amino acids and vitamins, chloroplast function, and is involved in nitrogen fixation in legumes and the conversion of nitrate to amino acids.

Why does Organic farming overtake Conventional farming?

Conventional farming increases greenhouse gas emissions, soil erosion, water pollution, and poses health risks. In contrast, organic farming has a smaller carbon footprint, enhances soil health, and restores ecosystems without toxic pesticide residues. While conventional farming has a greater impact on ecotoxicity, acidification, and eutrophication when measured per hectare, organic farming performs worse in these areas when assessed per kilogram of wheat grain (Van Stappen *et al.,* 2015). A European meta-analysis found that organic farming has about 31% lower nitrogen (N) leaching losses per unit of area due to lower N rates (Tuomisto *et al.,* 2012). However, N leaching losses can be about 49% higher in organic farming when measured per unit of product.

Limited nitrogen (N) availability affects plant growth (Aronsson *et al.,* 2007). Organic farming uses about 50% less non-renewable energy than conventional farming, similar to grasslands, due to lower reliance on external inputs (Haas *et al.,* 2001). Organic farming reduces non-renewable energy use by 60% for barley per hectare (Tricase *et al.,* 2018). Producing 1 kg of urea requires 35.1 MJ of energy (Zegada-Lizarazu *et al.,* 2010). However, conventional farming has only 33% of the ecological impacts of organic farming (Tricase *et al.,* 2018). This is mainly due to the higher yields in conventional methods.

How can Organic Farming (OF) address significant threats to global agriculture and meet rising food demand?

Organic Farming faces challenges but shows potential for securing food production. A study by Purnhagen *et al*. (2021) suggests that integrating innovative plant breeding technologies like CRISPR/Cas9 with organic practices could foster more sustainable agriculture. Microorganisms in soil and plants produce bioactive compounds that enhance crop stress tolerance. Understanding their responses to management practices and climate change is vital for maintaining nutrient turnover and crop yields in agroecosystems. This article examines how interactions between agricultural practices and climate change affect these microorganisms, providing insights into the role of organic farming in addressing global agricultural challenges while ensuring sustainable food production.

The Need for Transition

Crisis in Synthetic Fertilizer Inputs

Farming input costs have skyrocketed, with fertilizer prices rising by 80% since 2020, according to the World Bank. This has strained farmers financially and reduced yields, affecting the entire food supply chain. However, many are seizing the opportunity to adopt regenerative agriculture, which helps reduce reliance on synthetic fertilizers and lower costs while improving soil health. We will explore the impact of rising prices on farmers and the benefits of transitioning to regenerative practices.

Environmental impact of chemical fertilizers

Farmers use fertilizers to enhance soil fertility and provide essential nutrients for crops. For centuries, mineral and organic fertilizers, such as manure, have been utilized.In the last century, synthetic fertilizers have significantly increased crop yields, allowing more food to be produced on less land. However, this increased use contributes to greenhouse gas emissions, making agriculture the second-largest source of climate change pollution(Emissions by Sector." Our World in Data. Using data from the CAIT Climate Data Explorer) (Fig.1).

Nitrogen is a critical nutrient for plants, but they cannot absorb it directly from the air. In the early 1900s, scientists developed a method to mass-produce ammonia, a nitrogen-rich compound that plants can utilize. Today, ammonia is the second-most produced chemical globally and is extensively used as fertilizer. This innovation has transformed farming, enabling one acre of land to feed twice as many people (Erisman, Jan Willem, 2008). However, producing ammonia requires a lot of energy, mainly from fossil fuels like coal and methane, which release carbon dioxide—a key factor in climate change. Ammonia production accounts for 1% to 2% of global carbon dioxide emissions (Ammonia, 2011).

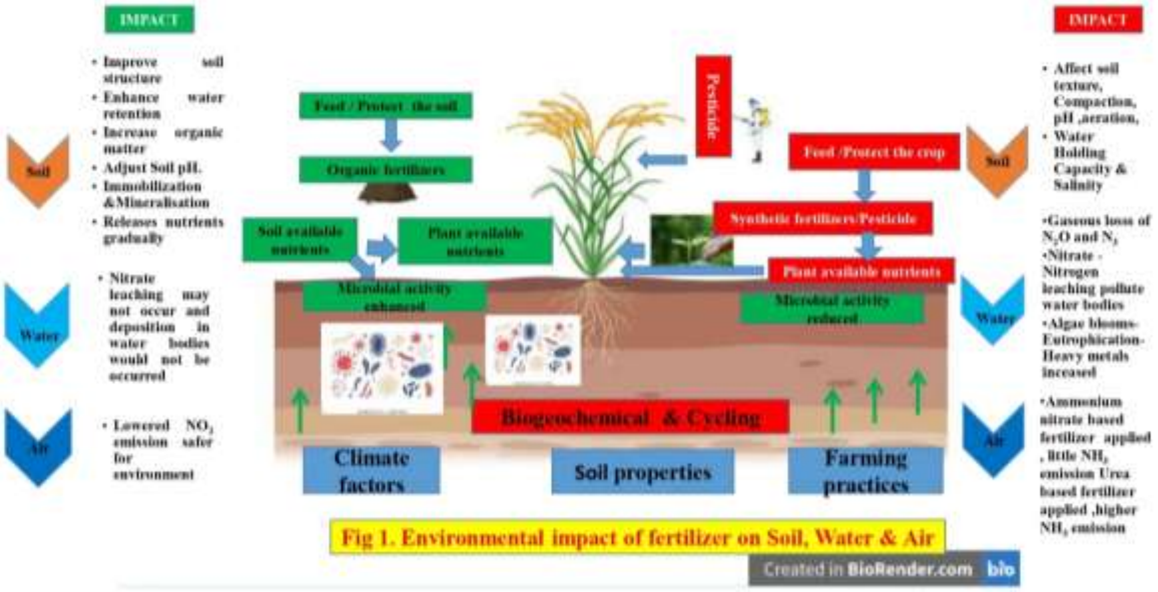

Fig 1. Environmental impact of fertilizer on Soil, Water & Air

Fertilizers also contribute to greenhouse gas emissions. On average, crops absorb only about half of the nitrogen supplied by fertilizers (Royal Society, 2020). The rest either breaks down or washes off into streams, releasing nitrous oxide into the atmosphere. Nitrous oxide is significantly more potent than carbon dioxide, warming the Earth 300 times more per pound (Canfield & Donald, 2010), yet it makes up a small fraction of total greenhouse gas emissions (USEPA, 2016).

The use of urea fertilizer and the burning of agricultural residues contribute about 5% of greenhouse gas (GHG) emissions in agriculture. Flooding rice fields during growth creates anaerobic conditions, leading to significant methane emissions (Thanawong *et al.,* 2014). Moreover, GHGs from rice fields can deplete stratospheric ozone by interacting with hydroxyl radicals (Akiyama *et al.,* 2005; Bayer *et al.,* 2015).

While chemical fertilizers boost crop yields, their excessive use harms ecosystem health and sustainability. This overuse leads to soil degradation, water pollution, and disruption of nutrient cycles. Runoff containing nitrates and phosphates can cause harmful algal blooms, threatening aquatic biodiversity. Additionally, synthetic fertilizers contribute to greenhouse gas emissions and climate change. Thus, adopting sustainable agricultural practices is crucial for promoting soil health and environmental integrity.

Fertilizer efficiency is crucial because excessive use and adverse climatic conditions can pollute soils, surface water, and groundwater. Runoff from fertilizers can lead to eutrophication in rivers and coastal areas, prompting restrictions on their use in regions like Europe. The 4R principle using the right fertilizer in the correct dosage, at the appropriate location, and at the optimal time maximizes plant growth (Heffer and Prud'homme, 2009). Proper fertilization enhances global food security and offers economic benefits by reducing operational costs, ultimately benefiting society, the environment, and financial returns. To restore soil fertility sustainably, research into controlled and slow-release fertilizers is vital. This includes exploring techniques and mechanisms related to smart fertilizers and their future potential, including smart Nano-fertilizers.

Impact of chemical fertilizers on human health

Agrochemicals are seen as essential for boosting agricultural productivity in developing nations (Bhandari, 2014). However, continuous use of chemical fertilizers can lead to pest resistance and environmental issues (Fig 2.). Nitrates and phosphates from these fertilizers can run off into water bodies, causing eutrophication. High nitrate levels in drinking water can lead to blood disorders and have been linked to testicular and stomach cancer.

Fig 2. Impact of fertilizer/pesticide on Human health

Harmful compounds in fertilizers enter the food chain through plants, causing health issues, including neurological disorders and cancer, as well as containing heavy metals like mercury and lead (WHO, 1990). Long-term use also disrupts microbial activity and soil pH, while certain ingredients can harm the dermal and respiratory systems. Ultimately, excessive use of chemical fertilizers damages vegetation and reduces soil fertility.

Ammonium nitrate can cause health issues like eye and skin irritation, breathing problems, headaches, anxiety, nausea, and fainting. In infants, excessive nitrogen in plants can lead to methemoglobinemia, and amines from nitrogen fertilizers are linked to cancer. Potassium chloride affects nerve and heart function, causing symptoms such as nausea, vomiting, convulsions, and eyelid irritation. Cadmium accumulates in tissues, leading to serious conditions like pneumonia and renal failure. High aluminum levels are associated with birth defects and Alzheimer's disease. Calcium toxicity can result in developmental issues and damage to the kidneys, nerves, and immune system

High concentrations of cobalt can cause lung injury, while boron impairs sperm production and irritates the eyes, nose, and throat. Manganese is believed to affect the respiratory, reproductive, and gastrointestinal systems. Lindane is a neurotoxin linked to breast cancer and reproductive system damage. Chlorpyrifos can lead to respiratory failure and malnutrition in fetuses, and malathion can harm the nervous system.

DDT, a common insecticide, is associated with various cancers, neurological injuries, lung damage, and birth defects (Thuy, 2015). Women with breast cancer are six to nine times more likely to have DDT or hexachlorobenzene in their blood compared to those without breast cancer, showing a strong correlation with pesticide exposure (Anitha K *et al.,* 2014). Additionally, organophosphate pesticides used on vegetables can accumulate in the body and are linked to cancer.

Impact on Soil and Water Pollution

Nitrate and Nitrite Toxicities and Risks to Human Health

Nitrate and nitrite ions are naturally present in soils and waters as part of the Earth's nitrogen cycle. They can also be released into the environment from fertilizers. Nitrite has two oxygen atoms and one nitrogen atom, while nitrate has one additional oxygen atom. Nitrates, the final product of nitrogen fertilizers, can seep into waterways if not absorbed by plant roots, with the highest concentrations found in green leafy vegetables like lettuce (Liu *et al.,* 2014).

In many countries, people consume groundwater, which often has elevated nitrate levels due to agricultural runoff. Consuming nitrate-contaminated groundwater and high-nitrate vegetables can lead to serious health issues, including thyroid problems, cancer, and blue baby syndrome (methemoglobinemia). A tolerable daily nitrate intake is set at 0-3.7 mg per kg of body weight (Santamaria, 2006), with a reference rate of 7.0 mg/kg and a Maximum Contaminant Level (MCL) of 10 mg/L for public water (Mensinga *et al.,* 2003).

Nitrate reductase activity (NRA) is influenced by light conditions, affecting the conversion of nitrate to amino acids (Tamme *et al.,* 2009). Exposure to nitrogen fertilizers can also lead to the formation of harmful N-nitroso compounds, which may be exacerbated by the consumption of preserved foods, fish, beer, and certain medications (Catsburg *et al.,* 2014).

Several studies indicate that 45-75% of human exposure to N-nitroso compounds results from in vivo conditions (Tricker, 1997). Certain occupations and cosmetics also contribute to this exposure. In the acidic environment of the stomach, nitrites and nitro-stable amides or amines from fish and meat can lead to the formation of these compounds, which may adversely affect infants and children. Antioxidants in fruits and vegetables can inhibit their formation and are linked to reduced cancer risk (Ferrucci *et al.,* 2010).

Nitrate in drinking water affects health at concentrations of 100 to 200 mg/L nitrate nitrogen (nitrate-N), influenced by additional sources in food. Some nitrate converts to nitrite in the body, which can react with amines to produce carcinogenic nitrosamines. Current research focuses on high nitrate concentrations (100-200 mg/L) linked to cancer (Mary, 2009).

The limit for nitrate in drinking water is 10 mg/L nitrate-N (45 mg/L NO3), and short-term exposure poses risks, especially for children. The U.S. maximum contamination limit is set at this level, while the WHO recommends 50 mg/L NO_3, primarily to prevent infant hemoglobinemia, without considering other health impacts, like cancer [USEPA, 2017].

Most foods contain nitrates, particularly green leafy and root vegetables, with average daily intake ranging from 30 to 130 mg (7 to 29 mg/day NO_3-N) [IARC, 2010]. However, dietary nitrate may not significantly contribute to NOC synthesis due to the presence of ascorbic acid and polyphenols, which inhibit their development [IARC, 2010; Mirvish, 1995].

Children consume larger amounts of water relative to their body weight, especially when water is used to mix powdered or concentrated formulas or juices. Their immature gastrointestinal systems are also more likely to convert nitrate to nitrite compared to adult digestive tracts. The presence of nitrite in the gastrointestinal tract of infants can lead to methemoglobinemia, which is the most significant health issue associated with nitrate in drinking water.

Blood contains hemoglobin, an iron-based compound that carries oxygen. When nitrite is present, hemoglobin can be converted into methemoglobin, which cannot transport oxygen. In adults, enzymes continuously convert methemoglobin back to hemoglobin, and typically, methemoglobin levels do not exceed 1%. However, infants have lower levels of these enzymes, and their methemoglobin levels can be between 1% and 2%. Once diagnosed, methemoglobinemia can be effectively treated, although prolonged oxygen deprivation may cause lasting damage (Feig, 1981).

Another significant adverse consequence of heavy fertilizer use is water eutrophication, primarily driven by phosphorus. Surface waters should have less than 50 µg/L of phosphorus. Increased biomass growth can also lead to eutrophication from nitrogen contributions. Eutrophication results in a body of water being covered with aquatic plants and algae, which reduces the oxygen supply and can cause the extinction of other aquatic life, including fish. According to Sonmez Kaplan M & Sonmez S; Rivers CN *et al*. (1996), the consequences of eutrophication include oxygen-depleted environments unfit for drinking water and a decline in aquatic species, alongside the growth of undesirable species. This creates conditions unsuitable for recreation due to foul odors and contaminated water.

Impact on Air pollution

Air is essential for agricultural production, influencing crop quality and yield. However, fertilizer application must be managed carefully; both insufficient and excessive use can harm plants and the environment.

Agriculture is responsible for 60% of anthropogenic nitrous oxide (N_2O) emissions, primarily from agricultural soils (Shoji S *et al*., 2001). The production of nitrogenous fertilizers releases greenhouse gases like carbon dioxide (CO_2) and methane (CH_4), while excess nitrogen fertilizers generate nitrogen oxides (NO, N_2O, NO_2), causing significant air pollution(Cooper J *et al*., 2017).High application rates of chemical fertilizers to boost crop production are leading to harmful greenhouse gas emissions and ozone layer depletion, exposing humans to harmful ultraviolet rays (Chen & Jen-Hshuan (2006)).

Inadequate fertilizer leads to poor crop yield and quality, while excessive nitrogen-rich fertilizers contribute to air pollution through nitrogen oxides (NO, N_2O, NO_2), which degrade air quality and increase global warming.

Nitrous oxide levels are rising at 0.2 to 0.3% annually(Mani, 2002), raising health concerns from accumulation in leafy vegetables.

Calcareous and alkaline soils pose additional challenges. When ammonium fertilizers or urea are used, ammonia (NH_3) can evaporate, influenced by various soil and environmental factors. These emissions contribute to air pollution and can result in acid rain, harming both terrestrial and aquatic ecosystems (Sharma and Chetani,2017).

Nitrous oxide is now the third most important greenhouse gas, with a global warming potential 310 times greater than that of carbon dioxide. Its emissions contribute to global warming and ozone destruction, leading to increased ultraviolet radiation exposure for humans and animals Rütting *et al.*, 2018). Ammonia from fertilized lands can lead to the formation of acid rain, which damages vegetation, buildings, and aquatic life (Sharma & Chetani, 2017). Additionally, methane emissions from paddy fields increase with ammonium-based fertilizers, further contributing to global climate change (Chen & Jen-Hshuan, 2006).

In summary, balancing fertilizer application is crucial for sustainable agriculture. By managing air quality and understanding environmental impacts, we can protect crops and the health of our ecosystems. Addressing these challenges through informed practices is vital for the future of agriculture.

Impact of Fertilizer on Food Crops

Copper accumulation in food crops varied significantly based on crop type and growing site, with an average concentration ranging from 1.23 to 5.20 mg/kg. Zea mays (corn) from site 3 had the highest copper levels when treated with superphosphate and other fertilizers, while Triticum aestivum (wheat) from site 1 had the lowest. All values were below the WHO (World Health Organization) permissible limit of 10 mg/kg (WHO ,1996).

Nitrate intake primarily comes from raw vegetables (80%), drinking water (15%), animal products, and grains (5%) (Colla *et al.,* 2018). Although nitrates are generally not harmful, their conversion into nitrites and nitrosamines can be detrimental, contributing to gastric and bladder cancers (Colla *et al.,* 2018; Bivolarska & Gatseva, 2015).

Benefits of organic farming

Organic farming is experiencing significant global growth, with the area dedicated to it increasing from approximately 24 million hectares in 2006 to 71 million hectares in 2018 (Tu *et al.,* 2006; Willer *et al.,* 2020). Consumers are drawn to organic food primarily because it lacks chemical inputs, such as synthetic fertilizers and pesticides. Although organic farming uses more machinery than conventional agriculture, it is generally considered more environmentally sustainable. It has a positive impact on pollution levels, biodiversity, soil erosion, and energy use, which benefits both soil and water quality (Tuomisto *et al.,* 2012). However, the actual effects of organic farming on global warming and climate change mitigation remain widely debated (Tuomisto *et al.,* 2012; Chiriacò *et al.,* 2017; Giampieri *et al.,* 2022).

On one hand, organic farming prioritizes the maintenance of natural soil fertility while reducing reliance on external inputs. On the other hand, its lower yields per hectare require more land to meet food demand, presenting a challenge for this farming system. Recently, extensive literature reviews have been conducted to assess the true environmental impacts of both organic and conventional farming practices (Tuomisto *et al.,* 2012; Meier *et al.,* 2015; Chiriacò *et al.,* 2017).

Recent findings suggest that organic farming may not be a sustainable strategy for optimizing land use efficiency (Giampieri *et al.,* 2022). This aligns with earlier observations (Tuomisto *et al.,* 2012) indicating that organic farming requires approximately 84% more land compared to conventional methods. The lower yields (both for crops and livestock) in organic farming, which are about 20% to 34% less than those in conventional farming (De Ponti *et al.,* 2012; Seufert *et al.,* 2012), contribute to this issue. Generally, these reduced yields arise from nutrient deficiencies, as well as challenges related to weeds, pests, and diseases (Korsaeth *et al.,* 2008). However, some studies have noted that organic farming can result in a higher level of soil organic matter (SOM) due to the continuous addition of compost, manure, and crop residues (Santos *et al.,* 2012).

An analysis of cumulative greenhouse gas (GHG) emissions revealed that olives, beef, and certain crops produce fewer emissions under organic farming (Casey and Holden, 2006; Tuomisto *et al.,* 2012). In contrast, higher GHG emissions were noted in specific sectors of organic farming, such as milk production, which is attributed to lower yields and increased emissions of CH_4 and N_2O (Thomassen *et al.,* 2008). Similarly, cereal and pig production also exhibited elevated N_2O emissions. However, Tuomisto *et al.* (2012) observed that emissions of N_2O and NH_3 can vary significantly depending on the calculation method used. They reported that organic farming generated approximately 31% lower emissions of N_2O and 18% lower emissions of NH3 per unit area compared to conventional farming. Conversely, when calculations were based on units of product, organic farming resulted in 8% higher emissions of N_2O and 11% higher emissions of NH_3. Additionally, lower yields have a considerable impact on the water footprint.

Interaction between plant and soil microbiomes in response to abiotic stress

From an ecological perspective, one of the fundamental characteristics of soil microbiomes is their capacity to withstand (resistance) and recover (resilience) from environmental stresses (Azarbad *et al.,* 2016). This concept is often referred to as "microbial stability" (see Philippot *et al.,* 2021 for recent discussions on resistance, resilience, and stability concepts). Previous studies have indicated that the stability Various management methods have a notable influence on the variety and makeup of soil microbiomes, which in turn affects the crucial roles they play. Nevertheless, the impact of these methods on plant microbiomes in different agroecosystems has not been thoroughly explored. Studies have proven that helpful microorganisms linked to various areas of the plant - like plant growth-enhancing bacteria (PGPB) - function as expanded plant traits. These tiny organisms are essential for helping plants absorb nutrients, fighting off harmful pathogens, and of soil microbial functions (such as process rates or functional genes) or community structures (the species present in the community and their abundance) under rapidly changing climates may depend on the management histories of agricultural fields (de Vries *et al.,* 2012; Fuchslueger *et al.,* 2019; Piton *et al.,* 2021).

Moreover, a recent survey summarizing the impacts of global environmental changes (e.g., drought, temperature fluctuations, nitrogen deposition, and salinity) on soil biota found that soil ecologists have generally considered only one stress factor (in 80% of cases) or two stress factors (in 19% of cases) in their experiments (Rillig *et al.,* 2019). This highlights the importance of addressing multiple stress factors to better understand the impacts of global environmental change on soil biota.

It is crucial to identify which soil microbial groups are selected within the microbial community under the selective pressures of different agricultural management practices and climate conditions, and to understand how this selection influences the resistance and resilience of the soil microbiome when faced with additional environmental stressors. However, the interactive effects of climate change-related stressors (such as drought and global warming) and agricultural management on soil microbial stability in the face of global change stressors are still poorly studied and understood.

Plant Microbiomes for sustainable production of agri output

Various management methods have a notable influence on the variety and makeup of soil microbiomes, which in turn affects the crucial roles they play. Nevertheless, the impact of these methods on plant microbiomes in different agroecosystems has not been thoroughly explored. Studies have proven that helpful microorganisms linked to various areas of the plant - like plant growth-enhancing bacteria (PGPB) - function as expanded plant traits. These tiny organisms are essential for helping plants absorb nutrients, fighting off harmful pathogens, and defending against environmental challenges (Li *et al*., 2019).

Changes in soil microbiomes caused by management practices can have various effects on the environment, such as releasing greenhouse gases and influencing soil organic carbon levels. Additionally, alterations in soil and plant-related microbiomes have the potential to influence agricultural output directly (Schmidt *et al*.,2019). Plants, in reaction to their immediate surroundings, modify the amount and type of carbon they release below the ground through either rhizo deposition or root exudation. This process entails the release of diverse organic substances into the nearby root environment. The microorganisms in the rhizosphere (the soil attached to the roots) play a key role in providing vital nutrients for plant growth and development by converting nutrients from organic matter (Richardson *et al*.,2009 ;Berendsenetal.,2012).

Root exudates contain various primary metabolites (like amino acids and organic acids) as well as secondary metabolites (such as terpenoids, flavonoids, and phenolics). Additionally, because microbes use root exudates for carbon, plants might change their microbial communities to support helpful microbes. This helps plants meet their nutritional requirements and deal with challenges such as drought (Marasco *et al*., 2012). Nevertheless, traditional farming methods frequently ignore the intricate synergistic relationships between plants and their microbiomes. Instead, they depend greatly on external inputs, like inorganic nutrients, to supply necessary elements for plant development (Hartmann *et al*., n.d.)

A study in 2015 examined the soil and root-associated microbiomes of winter wheat in a field experiment. The experiment included different management practices such as conventional and organic methods, along with various tillage intensities (no-tillage, reduced-tillage, and intensive tillage). Their research found that the variety of bacteria and fungi was greatest in the organic farming system with intensive tillage for both soil and root communities.

Recent studies conducted by Longley *et al*. (2020) is one of the initial studies that investigates the impacts of more than 30 years of traditional, no-till, and organic farming methods on soil and soybean-related microbiomes (such as roots, stems, and leaves) at different plant growth stages. Unexpectedly, their research shows that Organic Farming (OF) leads to decreased microbial Shannon diversity in both fungal and bacterial populations. They additionally stated that employing no-till methods led to a higher presence of helpful organisms like *Bradyrhizobium* and Glomeromycotina in the plant roots. In a separate research, Schmidt and colleagues suggested that the six paired tomato farms in northern California were analyzed in 2019, comparing conventional and organic practices.

Researchers discovered that the variety of bacteria and fungi was greater in the soil surrounding plants grown organically compared to plants grown using conventional methods. Furthermore, a variety of plant-growth-promoting bacteria, such as *Pseudomonas*, exhibited higher relative abundance in organic farms. A thorough investigation conducted by Ricono *et al.* in 2022, a study explored the lasting impacts of organic and conventional farming on the root-associated bacterial and fungal communities in 40 agricultural fields. Their findings showed that organic farming (OF) increased the Shannon diversity of root microbiomes when compared to conventional farming (CF). This involved a rise in the abundance of mutually beneficial fungi (like Glomeromycota) and disease-fighting bacteria, such as Pseudomonadaceae, Burkholderiaceae, Xanthomonadales and Gammaproteobacteria.

The key question remains: Will organic or conventional management strategies be more vulnerable to plant diseases in the face of global climate change?

Conditions:

Plants and the microbes they interact with can quickly adjust to challenging environmental conditions through various important mechanisms:

1. Obtaining fresh microbial companions from outside sources.
2. Promoting or decreasing the current microbes in the plant's surroundings.
3. Transferring genes horizontally from external microbes to resident microbes can impact the characteristics and overall health of plant hosts.

This process can be achieved through various strategies employed by plant-associated microbes. Nonetheless, altering and adjusting microbial communities within the plant environment to boost host characteristics and productivity is still a difficult task.

The practice of introducing soil or plant parts to one or a few beneficial microbial isolates is commonly done to enhance plant reactions to unfavorable environmental conditions.

Regrettably, numerous studies have produced inadequate outcomes because of issues like low survival rates of microbial isolates or strong competition with native soil and plant microbes (Agoussar and Yergeau, 2021; Wang and Song, 2022).

Although these research studies have offered valuable insights into the interactions between plants and microbes, it is crucial to shift focus towards studying more intricate microbiomes instead of solely examining single-isolate applications in order to enhance agricultural productivity (Raaijmakers and Mazzola, 2016).

Replacing chemical fertilizers with synthetic fertilizers

Overuse of chemical fertilizers on the same soil for long periods can result in soil degradation, depletion of beneficial microorganisms, and various adverse outcomes (Vitousek *et al*., 1997). In order to achieve improved and lasting agricultural production while also safeguarding the environment, it is recommended to take an integrated approach that involves using various nutrient supplements like chemical fertilizers, organic manures, biofertilizers, and slow- or controlled - release fertilizers (Pandiselvi *et al*., 2017). Research has shown that combining organic fertilizers with chemical fertilizers, rather than depending solely on organic fertilizers, has a more significant positive effect on microbial biomass and therefore enhances soil health (Usman and Madu Alkali, 2015).

Organic fertilizers release nutrients gradually over time, necessitating larger quantities to maintain a consistent nutrient supply. They also contribute to retaining soil moisture and improving its overall health and quality by boosting humus levels. Research shows that using a mix of organic and chemical fertilizers is better for soil health and microbial biomass than only using organic fertilizers (Popiha and Arunachalam, 2022; Ummyiah *et al*., 2022; Rizwan *et al*., 2022; Vijayalakshmi *et al*., 2022).

What is Biofertilizer?

Biofertilizers are materials containing living microorganisms that aid in boosting root growth and enhancing seed germination. An thriving plant usually grows well in soil containing many helpful microorganisms. In contrast to chemical and organic fertilizers, biofertilizers do not provide nutrients directly to crops. Instead, they are made up of cultures of particular bacteria and fungi. The technology for creating biofertilizers is quite simple, with lower installation costs compared to chemical fertilizer plants (Trenkel, 1997).

Slow-Release Fertilizers

Slow-release fertilizers have a coating made of biodegradable organic or inorganic polymers. This coating slows down the release of nutrients, leading to better crop yields per unit of fertilizer used. Therefore, utilizing slow-release fertilizers is regarded as a best management practice (BMP) for crop production. Scientists are currently working on creating affordable, effective slow-release fertilizers (SRFs) that deliver nutrients slowly over time to match the requirements of plants. SRFs decrease fertilization usage by preventing nutrient loss through leaching and runoff, thus reducing environmental harm and improving crop productivity (Alharbi *et al*., 2018). The initial SRFs were developed in the 1920s, with significant market expansion occurring in the 1960s. The industry of SRF experienced notable changes in the 21st century, with a yearly growth rate of 6.5% between 2014 and 2019 (Wang *et al*., 2021). As a result, there has been a growing interest among farmers in using SRFs instead of traditional fertilizers in recent years.

SRFs typically release nutrients at a slower pace compared to conventional fertilizers, but the exact control over the rate, pattern, and duration of this nutrient release is not always precise. In comparison, controlled-release fertilizers have clearly defined parameters according to Shaviv (2000).

Different types of slow or controlled-release fertilizers include:

Organic-N Low-Solubility Compounds: Examples include urea-formaldehyde (UF) and isobutylene-diurea (IBDU). Fertilizers with a Physical Barrier

Coated fertilizers use organic polymers (such as thermoplastic or resin-based) or inorganic materials like sulfur or mineral-based coatings. Inorganic Compounds with Low Solubility: Examples include metal ammonium phosphates and partially acidulated phosphate rock (PAPR).

After being applied, the nutrients in a Slow-Release Fertilizer (SRF) are not readily accessible to plants. However, the availability of these nutrients in fertilizers lasts much longer than quick-release fertilizers (QRFs) such as potassium chloride, ammonium phosphate, urea, or ammonium nitrate. Inorganic SRF fertilizers contain nitroform, also called trinitromethane, with the chemical formula HC[NO2]3 (Loper and Shober, 2012). Organic slow-release fertilizers (SRFs) consist of urea-formaldehyde (UF), urea-isobutyraldehyde/ isobutylidene diurea (IBDU), and urea-acetaldehyde/Cyclodiurea (CDU) (Trenkel, 2010).

Natural and Synthetic SRF Fertilizers

SRFs can be classified as either natural or synthetic, depending on where they come from. As stated by Shukla and colleagues. In 2013, common sources of natural soil fertility replenishers (SRFs) consist of compost, various animal manures (like chicken, cow, and poultry), and plant manures like green manure or cover crops. These substances need to go through microbial breakdown in order for their nutrients to be released to plants. Typically, organic fertilizers release nutrients slowly, which can lead to plants being unable to absorb them when necessary. Elements such as temperature and soil moisture impact microbial activity, which in turn affects the rate at which nutrients are released from organic fertilizers. Both micronutrients (such as iron, manganese, copper) and macronutrients (such as nitrogen, phosphorus, potassium) are found in organic SRFs. However, in comparison to synthetic SRF fertilizers, organic SRFs generally contain lower levels of nutrients. The water solubility of synthetic SRFs is frequently restricted. Their availability is also affected by temperature and soil moisture, and they typically appear as pellets or spikes. As per Trenkel (2010), nutrients are released from these fertilizers over different time frames.

Difference between Slow-Release and Controlled-Release Fertilizers

There is a difference between "controlled-release fertilizer" (CRF) and "slow-release fertilizer" (SRF). Alternative names for controlled-release fertilizer are coated fertilizer (Oertli and Lunt, 1962), controlled-availability fertilizer, delayed-release fertilizer, metered-release fertilizer, and slow-acting fertilizer (Gregorich *et al*., 2001).

Key Contrasts

Nutrient Release: Slow-release fertilizers release nutrients more slowly than traditional water-soluble fertilizers. Yet, they rely on microbial organisms, whose efficiency is affected by soil temperature and moisture levels. This leads to an unpredictable pace, structure, and length of nutrient discharge (Trenkel, 2010).

Leaching Dangers: SRFs could heighten the risk of harmful leaching as they depend on microbial breakdown to release nutrients. This is particularly true when the conditions are conducive to microbial activity following the agricultural cycle.

Benefits of Utilizing CRFs and SRFs:

Nutrient Efficiency: Slow-release fertilizers (SRFs) and controlled-release fertilizers (CRFs) can both help minimize nutrient wastage and enhance nutrient utilization efficiency. Utilizing Controlled-Release Fertilizers (CRFs) and Slow-Release Fertilizers (SRFs) could reduce fertilizer usage by 20-30% in comparison to the standard rate for conventional fertilizers (Trenkel, 2010). Environmental Advantages: These fertilizers aid in reducing risks associated with overuse of fertilizers, such as eutrophication (the accumulation of excess nutrients in water bodies), leaf scorching, and water pollution. They reduce runoff and leaching losses by keeping nutrient levels in the soil solution low with a slow release of nutrients. Cost Reduction: Cost savings can result in lower labor expenses and reduced application costs. Based on discussions with local potato growers, commercial potato farmers in northeast Florida typically use three to four nitrogen fertilizer applications, whereas farmers in southwest Florida use two applications. Liu and colleagues According to a study from 2011, farmers have the potential to reduce costs by $5 to $7 per acre by reducing unnecessary fertilizer applications. Furthermore, crop damage can be prevented by refraining from applying fertilizers in the late growth stage.

Enhanced Comprehension: CRFs provide a more thorough insight into the speed and length of nutrient discharge, reducing their vulnerability to soil and climate factors (Trenkel, 2010). Improved understanding of optimal timing and appropriate quantities of fertilizer application improves the efficiency of nutrient management practices. This not only minimizes potential negative impacts on both crops and the surrounding environment, but also results in cost savings. Soil pH and Nutrient Availability: Lowering the pH of alkaline soils can increase the availability of specific nutrients. For example, when sulfur-coated urea is used, it can make the soil more acidic because both sulfur and urea help in reducing the pH level. As stated by Liu and Hanlon (2012), this process can enhance the availability of iron or phosphorus, which is beneficial for crops like sweet potatoes, blueberries, and potatoes that rely on sulfur as an essential nutrient. Production Expenses:

If SRF sources like manure are easily accessible, the cost of production will decrease. Using CRFs and SRFs, farmers can improve their fertilizer efficiency and support sustainability and cost-effectiveness.

Limitations of using SRF and CRF

Employing CRFs or SRFs can help protect the environment, reduce nutrient losses, and improve nutrient-use efficiency. Hence, a recommended method for improving agricultural production is the utilization of Controlled Release Fertilizers (CRFs) or Slow-Release Fertilizers (SRFs).

Nanofertilizers:

Nanofertilizers are created by altering traditional fertilizers or plant extracts. They are produced by utilizing different chemical, physical, mechanical, or biological techniques with nanotechnology to improve soil fertility, productivity, and the quality of agricultural products. Nanoparticles can be produced from large materials. For example, seeds treated with nano-TiO_2 led to plants with increased dry weight, higher photosynthetic rates, and elevated chlorophyll-a production compared to the control group.

The adoption of nanotechnology-based synthetic fertilizers in agriculture is gaining traction as a successful approach because of their beneficial effects on boosting crop productivity, enhancing nutrient use efficiency, and alleviating environmental limitations on crops (Beig *et al*., 2022). Different kinds of nanomaterials, such as inorganic, carbon, organic, and composite types, have been used in farming to grow crops.

Scientists have created specialized nano-fertilizers, herbicides, pesticides, fungicides, and insecticides for specific sites, known as nano-based agrochemicals (Bana *et al*., 2020; Qazi and Dar, 2020; Ahmed *et al*., 2021; Okey-Onyesolu *et al*., 2021). The precise use of nano-fertilizers improves nutrient utilization and reduces nutrient waste. Moreover, decreasing the excessive use of fertilizers can reduce toxicity, a method adopted by many farmers (Hofmann *et al*., 2020; Mejias *et al*., 2021). In addition to nano-fertilizers, nano- herbicides are employed for the purpose of controlling weeds. Weeds reduce farm output by battling main crops for nutrients and space.

Due to nanotechnology, improved nano-based herbicides have been created, providing superior results compared to traditional herbicides currently available (Abigail and Chidambaram, 2017; Balah and Pudake, 2019). Conventional weed killers remove only the top leaves of weeds, letting them grow back. Nano herbicides, on the other hand, focus on the roots. Once the roots haved, weed plants are unable to grow again. Applications of nano pesticides based on nanomaterials are also efficient at managing various pests that harm crops. Typically, conventional pesticide use results in higher farming expenses and adds to environmental contamination (Hajji-Hedfi and Chhipa, 2021). Nano-based pesticides provide numerous benefits compared to conventional pesticides. These advantages include enhanced retention capacity, increased efficacy, improved durability, better dispersion, and increased wettability. These characteristics increase their effectiveness, as their gradual release in small amounts improves efficiency and decreases environmental losses, soil damage, and toxicity (Kumar *et al*., 2019; Vignardi *et al*., 2020).

Utilizing beneficial microorganisms to enhance plant growth as biofertilizers and biopesticides is a sustainable method in agriculture. These advantageous microorganisms improve the favorable characteristics of host plants (Khan *et al*., 2019; Elnahal *et al*., 2022; Massa *et al*., 2022; Chaudhary *et al*., 2022c). Like probiotics for people, the concept of "plant probiotics" has become popular recently to refer to these tiny organisms essential for plant well-being (Carro and Nouioui, 2017; Menéndez and Paço, 2020; Sarbani and Yahaya, 2022). Plant probiotics and plant growth-promoting microorganisms, like bacteria and fungi, are mostly the same and are members of a complicated microbial group. They either inhabit the rhizosphere, referred to as the rhizomicrobiome (Ravichandran *et al*., 2022), or live inside plant tissues as endophytes (Pandey *et al*., 2022; Rai *et al*., 2023).

These living beings contribute to favorable functional characteristics that support plant development, such as enhanced productivity (Gavelienė *et al*., 2021), reduction of environmental and biological pressures (Santoyo *et al*., 2021), alleviation of climate change impacts (Fiodor *et al*., 2021), and enhancement of crop micronutrient levels through biofortification (Upadhayay *et al*., 2018, 2021, 2022a, b, c).

In order to be successful, plant probiotics need to demonstrate particular traits that enhance plant growth. These consist of dissolution of important nutrients (phosphorus, potassium, and zinc; Singh *et al*., 2022), nitrogen fixation (Pandey *et al*., 2022), synthesis of plant hormones (Kurniawan and Chuang, 2022), and the release of substances necessary for combating pathogens, like antibiotics and different enzymes (Duhan *et al*., 2022). Moreover, the generation of unstable substances (for example, HCN; Vaghela and Gohel, 2022) and the stimulation of overall immunity against diseases are important benefits of plant probiotics (Yin *et al*., 2022; Chaudhary *et al*., 2022a).

Additionally, plant probiotics have the ability to create exopolysaccharides and biofilms. These provide several advantages such as shielding against abiotic stress (Banerjee *et al*., 2019) and dehydration (Mandal *et al*., 2022), as well as promoting better root colonization (Naseem *et al*., 2018) and boosting soil aggregation and stability (Jhuma *et al*., 2021). Many different types of microbes have been found to have beneficial effects on plants, promoting growth and increasing crop productivity. These microbial strains can act as plant probiotics, improving eco-friendly farming practices. By serving as effective "elicitors" or "biofertilizers," plant probiotics can enhance important traits related to yield, such as shoot and root length, plant biomass, photosynthetic pigments, grain yield, and overall biological output. Noteworthy improvements in yield-related characteristics have been noted in rice, wheat, and maize following treatment with plant probiotics such as Bacillus (Abd El-Mageed *et al*., 2022), Azospirillum brasilense (Zaheer *et al*., 2019), and Pseudomonas stutzeri (Jiang *et al*.,2022).

Furthermore, plant probiotics like Burkholderia cepacia and Pantoea rodasii, recognized for their zinc-solubilizing capabilities, have enhanced rice plant growth and offered biofortification advantages by notably raising zinc concentration in grains (Upadhayay *et al*., 2022b). The probiotics aid in reducing the impact of abiotic stress on plants by increasing stress resilience. This is evident through the accumulation of osmolytes (Tahiri *et al*., 2022), activation of antioxidant enzymes (Shultana *et al*., 2022), lower malondialdehyde (MDA) levels, decreased electrolyte leakage, and enhanced photosynthetic pigment activity (Zarei, 2022).

Pseudomonas sp. (DN18) trapped in alginate beads along with salicylic acid and zinc oxide nanoparticles displayed antifungal properties against *Sclerotium rolfsii* and improved plant growth-promoting effects on *Oryza sativa* seedlings in comparison to the standalone bacterial strain (Panichikkal *et al*., 2021). Nanoencapsulation of *P. aeruginosa*, *P. fluorescens* (VUPF5) and *B. subtilis* (VRU1), by utilizing silica nanoparticles and carbon nanotubes, greatly enhanced the process of pistachio micropropagation through the enhancement of root length and proliferation (Pour *et al*., 2019). Moreover, nanoencapsulated *Bacillus subtilis* (VRU1) combined with sodium alginate, starch, and bentonite successfully managed the propagation of *Rhizoctonia solani* and improved the growth characteristics of bean plants (Saberi-Rise and Moradi-Pour, 2020). "Sodium alginate-gelatin microcapsules" loaded with nanomaterials (SiO_2 and carbon nanotubes) and plant probiotics, specifically *Bacillus velezensis*, showed combined ability to inhibit pathogens, especially *Phytophthora drechsleri* in *Pistacia vera* L. (Pistachio; Moradi Pour *et al*., 2022).

The research conducted by De Gregorio *et al*. (2017) demonstrated the efficacy of rhizobacteria immobilized on nanofibers (*P. agglomerans and B. caribensis*) made using electrospinning as a seed bioinoculant. This method improved root length, dry weight of roots and shoots, leaf growth, and soybean harvest. Likewise, *Pseudomonas stutzeri* encapsulated in a layer of N-hydroxysuccinimide (NHS)-modified poly γ-PGA and calcium ions displayed strong resilience to tough conditions and exhibited improved plant growth capabilities (Yang *et al*., 2021).

Plant probiotics (PPs) have been recognized as promising biostimulants that have led to substantial increases in grain yields in different crops, including wheat (with growth enhancements ranging from 9.6% to 29.29%) by *Bacillus* sp. (Öksel *et al*., 2022) reported that rice yields reached 3.35 tons per hectare when treated with *B. subtilis* and *B. cereus* are both types of bacteria commonly found in soil and water. megatherium variety (Abd El-Mageed *et al*., 2022), and corn (5,880 kg/hectare) by P. putida (Mubeen *et al*., 2021) Recent studies show that using nanomaterials (NM) and plant probiotics (PPs) together has resulted in significant advancements in agriculture, specifically in boosting crop production (Akhtar *et al*., 2022).

Recent agricultural research suggests a promising approach to increasing crop yields by combining plant probiotics with nanomaterials. For instance, research carried out by Seyed Sharifi and colleagues. A study in 2020 showed that combining *Azotobacter*, a helpful soil bacteria, with nano-zinc-iron oxide led to a remarkable 88% growth in wheat grain production when water was limited. This showcases the promise of merging microbial solutions with cutting-edge nanotechnology to tackle issues brought about by climate change and scarcity of water resources.

Hafez *et al*. conducted research in 2021, examined how rhizobacteria and silicon nanoparticles (SiNPs) working together can impact maize yield. They discovered a notable rise in production, achieving a remarkable 6325.4 kg/ha. This blend not simply increased crop production but also improved the absorption of vital nutrients such as nitrogen, phosphorus, and potassium (NPK). This two-pronged approach showcases how beneficial microbes and nanomaterials working together can enhance plant health and productivity.

Using probiotics and nanomaterials provides an environmentally-friendly solution that decreases the need for conventional agrochemicals. This method reduces the environmental harm caused by chemical fertilizers and increases crop yield. In order to fully actualize this potential, multiple goals must be pursued. Initially, it is crucial to perform in vitro assessments of plant probiotics obtained from rhizospheric soils to pinpoint potent microbial contenders with various plant growth-enhancing characteristics. Next, researchers need to study how well chosen probiotic strains work with appropriate nanocompounds to make sure they work well together. Improving crop productivity means using both probiotics and nanomaterials to boost nutrient absorption and crop quality. Moreover, assessing nutrient content in various plant sections can showcase the advantages of these progressive farming techniques. Examining soil health and tracking bacterial population changes in field areas will yield valuable information on sustainability and microbial resistance.

In the end, this approach strives to lessen reliance on harmful agrochemicals, which have been extensively studied for their negative impacts, thereby promoting a more enduring agricultural outlook. The incorporation of plant probiotics with nanomaterials boosts crop production and supports soil health and environmental preservation, highlighting its significance in tackling worldwide food issues.

II. CONCLUSION

Based on projections, the global population is predicted to grow to 9.6 billion by 2050 (FAO, 2017) from the present 7.8 billion. Issues surrounding soil degradation and the food-energy-environment trilemma related to land use (Tilman *et al*., 2009) play a crucial role in this dilemma. An extra 2.2 billion individuals are projected to increase in the upcoming 30 years. This scenario emphasizes the urgent requirement for collaboration across different sectors to introduce creative agricultural enhancements on current land (Chabbi *et al*., 2017).

Improving plant fertilization techniques may be a successful approach to increase agricultural productivity. Phosphorus (P) and nitrogen (N) are now widely recognized as crucial minerals for plant growth, especially following the Green Revolution in the 1960s. This is because they have a significant influence on crop productivity (Haygarth *et al*., 2013). In order to sustain and enhance food production, it is essential to consistently use fertilizers. Yet, in efficient systems, plants generally take in few nutrients, posing a problem for mineral fertilizer application (International Fertilizer Industry Association, 1992).

Over-fertilization may result in nitrogen and phosphorus runoff, leading to poor water quality and higher levels of greenhouse gases in the air (Haygarth *et al*., 2013). Hence, it is crucial to sustainably manage biogeochemical cycles and improve fertilizer use efficiency in agricultural systems without delay. To supplement conventional fertilization techniques, it is necessary to investigate and utilize contemporary biotechnological strategies like diazotrophic N2-fixing bacteria and plant growth-promoting rhizobacteria (PGPR). At present, the agricultural sector heavily depends on pesticides, with 188.2 million tons of synthetic fertilizers manufactured globally in 2019, along with 4 million tons of pesticides applied in agricultural areas (Kah *et al*., 2019). The amount of agrochemicals needed to feed 9.6 billion people by 2050 is expected to significantly rise (FAO, 2017; Diatta *et al*., 2020; Seleiman *et al*., 2020).

While synthetic chemical fertilizers are used to improve crop growth and yields, current agricultural methods have been limited in their ability to enhance crop productivity, nutrient use efficiency (NUE), and plant nutrient uptake simultaneously (Seleiman *et al*., 2020; Adnan *et al*., 2020).

Overuse of synthetic fertilizers not only reduces farmers' profits but also raises production costs (Diatta *et al*., 2020; Seleiman *et al*., 2020). Persistent obstacles to attaining sustainability in agriculture encompass poor Nutrient Use Efficiency (NUE) levels and increasing environmental worries (Cymmek *et al*., 2020) associated with the application of extra synthetic fertilizers (Diatta *et al*., 2020; Preetha and Balakrishnan, 2017). Low NUE values are usually the result of alterations in nutrient forms that plants cannot readily use or excessive levels of synthetic fertilizers that exceed plant absorption capacity.

Innovative techniques outlined by Shang *et al*., 2019 can boost worldwide food output while reducing strain on natural resources and the environment, as noted by Arora, 2018, thus supporting sustainable agriculture. Recent studies show that nanotechnology can change the way agricultural systems are currently created (Prasad *et al*., 2017). It can enhance the performance of new agrochemicals (Kerry *et al*., 2017) and help with different challenges in agriculture and the environment (Usman *et al*., 2020).

To sum up, the lack of synthetic fertilizers and the high costs involved are driving significant changes in the agricultural industry. Moving to organic fertilizers solves supply issues and sets the stage for a sustainable farming system. Through the implementation of organic farming methods, farmers have the ability to address the prevailing crisis, support planetary well-being, and safeguard food security for upcoming generations.

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Author's contribution

RU collected the literature, wrote the article and compilation of the content. JP contributed by suggesting idea for writing the Revie. TS helped in revising the manuscript and summarized it. All authors read and approved the final manuscript.

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