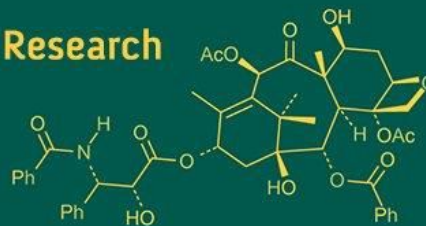


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Technological innovations in organic fertilizers advances, applications, and future prospects: A review

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Abstract

In addition to the numerous benefits to crop quality and productivity, organic fertilizers contribute to sustainable agriculture through their effects on soil health, nutrient availability, soil biodiversity, and decreased reliance on chemical fertilizers. New biotechnologies, such as bio-based fertilizers (microbial inoculants, biochar and vermicompost), precision agriculture techniques (soil sensors, drone mapping and data analytics) and controlled-release organic fertilizers (CROFs) with bio-polymer coatings and hydrogel based systems, have contributed to improving nutrient-use efficiency, reducing environmental impact and enhancing crop productivity. Worldwide pilot studies reveal that these technologies hold promise in increasing yield, reducing nutrient losses and improving economic and environmental viability of organic farming systems. Although there are challenges, such as the heterogeneous nutrient content, slow release of nutrients, expensive transportation, and insufficient knowledge among farmers, these solutions bring promising options to maximize organic fertilization in both smallholder and large-scale farming. This review delineates the recent progress, applications, and future perspectives of the innovation technologies in organic fertilizers, focusing on their importance to sustainable, productive, and environment-friendly agriculture.

Keywords: Organic fertilizers, bio-based fertilizers, controlled-release fertilizers, nutrient-use efficiency, hydrogel, biochar, vermicompost

Introduction

Organic fertilizers are derived from plant or animal matter and contain nutrients that are beneficial to both soil and crops (Barker and Pilbeam, 2007; Verma *et al.*, 2024) [7, 82]. They may be minerals in the raw state or slightly processed. When they are added to the soil, they enhance its texture, more efficient water retention, and growth of beneficial microorganisms (Khan *et al.*, 2024) [33]. Because they nutrients are released gradually, they maintain the health and fertility of the soil for a long period of time. Such as compost, manure and mineral based products too.

Panday *et al.*, (2024) [54] also stated that these fertilizers provide a solution to pollution and at the same time promote the health of the soil. Plant Based, Animal Based, Mineral Based They Categorize Them In Three Broad Classifications. Nutrients in each leverage the soil and feed biodiversity. "They (nutrients) are not immediately available, but you use such fertilizers consistently, and over time your soil becomes strong and fertile (Boru, 2025) [10]."

Role of organic fertilizers in sustainable agriculture:

Organic fertilizers contribute to improved soil quality, higher crop yields, and better environmental outcomes, and are thus critical for sustainable agriculture. Organic fertilisers serve the following functions in environment-friendly farming systems:

1. Soil Health Improvement

Organic fertilizers like compost, manure and cover crops promote natural fertility of the soil and enhance the soil structure, texture and water retention. They also enhance microbial activity which have significant role in nutrient cycling and degradation of organic matter.

Organic fertilizers improve the long-term soil sustainability by slow build-up of soil organic carbon (Kumar *et al.*, 2021) [36, 37].

2. Nutrient Supply

Plant essential nutrients like nitrogen (N), phosphorus (P), potassium (K), and many others micronutrients are required for plants to build healthy and strong tissues to have a productive yield. Organic fertilizers gradually provide nutrients, allowing plants to have a consistent source of nourishment. This slow release of nutrients contributes to reduce leaching of nutrients, which is a big environmental concern in synthetic fertilizers (Kibaret *et al.*, 2018; Priya *et al.*, 2024) [35, 58].

3. Reduction in Environmental Pollution

The application of organic fertilizer enables the farmers to prevent contamination of surrounding environment (Assefa and Tadesse, 2019) [3]. Synthetic fertilizers, on the other hand, have the potential to leak nitrogen and phosphorus into the environment and cause algae and other problems to flourish in water bodies, a process called eutrophication, which can compete with the plants (Liu *et al.*, 2021) [47].

4. Enhancing Soil Biodiversity

Organic fertilizers contribute to the development of an active and diverse soil ecosystem by promoting proliferation of beneficial organisms, including earthworms (Cai *et al.*, 2025) [12], bacteria, fungi, and insects. These organisms are

essential soil health, nutrient cycling and even in natural pest management and contribute soil fertility and resilience (Singh *et al.*, 2022) [74].

5. Carbon Sequestration

Studies show that the soil is more carbon rich on organic fertilizer farms than on conventional farms. Also, the organic waste introduced by these capacity fertilizers sequesters more that it ordinary would into the soil, which in turn offsets climate change by enhancing the soil’s carbon sequestering capacity (Baker *et al.*, 2007; Avasiloaiei *et al.*, 2023) [6, 5].

6. Reduced Dependency on Chemical Inputs

The use of organic fertilizers reduces the reliance of farmers on expensive and energy-intensive chemical fertilizers, therefore increasing the economic sustainability of their agriculture (Gomiero *et al.*, 2011) [24]. In addition, they help to keep the soil healthy and prevent the damage that can result from the use of chemical fertilizers for long periods.

7. Promotion of Integrated Farming Systems

Farmers are likely to apply organic manure in holistic systems, such as agroecology or IFS (integrated farming system), where crop and livestock production are combined. These practices promote recycling of farm waste and reduced dependency on imported sources of chemicals, enabling more sustainable and environment-friendly agriculture (Parr *et al.*, 2020; Sheikh *et al.*, 2021) [55, 69].

Table 1: Role of Organic Fertilizers in Sustainable Agriculture

Aspect	Key Contributions	References
Soil Health Improvement	Enhances soil structure and texture and its capacity to hold water; elevates soil microbial activity and soil organic carbon (SOC) content	Kumar <i>et al.</i> (2021) [36, 37]
Nutrient Supply	Contains balanced macro and micronutrients; slow release of nutrients ensures a constant supply to the plants and minimizes leaching	Kibaret <i>et al.</i> (2018) [35]
Reduction in Environmental Pollution	Reduces nutrient loss in runoff and leaching and bicarbonate contamination of soil water; reduces threat of eutrophication of surface waters	Liu <i>et al.</i> (2021) [47]
Enhancing Soil Biodiversity	Encourages the activity of helpful soil organisms (earthworms, fungi, bacteria) that contribute to nutrient cycling and pest suppression	Singh <i>et al.</i> (2022) [74]
Carbon Sequestration	Enhances soil organic matter and carbon sequestration, reducing greenhouse gases emissions	Baker <i>et al.</i> (2007) [6]
Reduced Dependency on Chemical Inputs	Reduce the cost and energy associated with synthetic fertilizers; avoid the acidification of the soil	Gomiero <i>et al.</i> (2011) [24]
Promotion of Integrated Farming Systems	Promotes recycling of on-farm waste and recirculation between livestock and crops to reuse resources	Parr <i>et al.</i> (2020) [55]

Table 2: Comparative Benefits of Organic vs. Synthetic Fertilizers

Parameter	Organic Fertilizers	Synthetic Fertilizers
Nutrient Release	Slow release; appropriate for rates of plant growth	Fast; may cause leaching of nutrients
Soil Structure	Enhances consolidation and porosity	Can lead to material fatigue
Microbial Activity	Increases microbial biodiversity and enzyme activities	It commonly suppresses microbial ecology
Environmental Impact	Mitigates pollution and enhances carbon sequestration	Induces water contamination and greenhouse gas emission
Long-term Soil Health	Builds soil organic matter and fertility	May result in acidification of soil and imbalance of nutrients
Economic Sustainability	Uses farm waste and lowers the cost of external inputs	Strong reliance on manufacturing output
Compatibility with IFS	Well-adapted to agroecological and integrated system	Less suitable for diversification with crop production

Table 3: Major Challenges in the Use of Organic Fertilizers

S. No.	Challenge	Description	References
1.	Variable Nutrient Content and Slow Nutrient Release	Composition and release rate of nutrients in organic fertilizers depends on the sources and processing, and is often variable. This couples with the inability to calculate exact rates of application and can lead to deficiencies at early stages of development of fast growing plants	Pradhan <i>et al.</i> (2021) ^[57] ; Lal (2021) ^[41]
2.	Bulkiness and High Transportation Costs	Moisture content is high and bulky, so transportation and handling costs are high. This restricts access, particularly for smallholder farmers in rural locations or where production facilities are dispersed	Sharma and Singh (2020) ^[67] ; Tonfack <i>et al.</i> (2019) ^[79]
3.	Risk of Pathogens and Contaminants	Animal-derived organic fertilizers have the potential to contain pathogenic (e.g., <i>E. coli</i> , <i>Salmonella</i>). If not properly processed, fertilizers made from waste materials can contain heavy metals or industrial waste.	Goss <i>et al.</i> (2020) ^[25] ; Kumar <i>et al.</i> (2022) ^[38]
4.	Labor-Intensive Application Process	Spreading, turning and composting manure is labor intensive, adding to the cost and the time, particularly for small farms or those with a limited labor pool	Singh and Prasad (2021) ^[73] ; Rahman <i>et al.</i> (2021) ^[60]
5.	Nutrient Imbalance and Limited Nutrient Availability	Some organic fertilizers can contain high levels of nitrogen but insufficient amounts of phosphorus or potassium. Deficiency of micronutrients such as Zn, B and Fe is common and causes imbalance in plant nutrients in crops	Gupta and Ramasamy (2020) ^[26] ; Yadav <i>et al.</i> (2021) ^[84]
6.	Lack of Standardization and Quality Control	Variations in quality of raw material and processes result in non-homogenous products. Lack of quality control or certification diminishes the trust of the farmers and their profits	Sharma and Singh (2020) ^[67]
7.	Lower Immediate Crop Yields	Organic fertilizers such as manures and composts release nutrients more slowly and result in lower initial yields than synthetic fertilizers. The benefits of the long term are a matter of years	Liu <i>et al.</i> (2018) ^[48] ; Muller <i>et al.</i> (2019) ^[52]
8.	Knowledge and Skill Gaps	Ignorance, training, and technical directives constitute major bottlenecks to its proper application. Extension services were limited and education of farmers still more so	Saravanan <i>et al.</i> (2021) ^[63] ; Bharadwaj and Singh (2021) ^[8]

Technological Innovations in Organic Fertilizers

A. Bio-based Fertilizer Development

Studies are being conducted on bio-fertilizers for these and related reasons, such as they contribute to keeping the soil healthy, giving nutrients to plants, and fostering eco-friendly farming. Novel bio-fertilizers such as microbial inoculants, biochar and vermicompost can enhance soil and crop productivity. Here is a brief rundown of these fertilizers and what they do:

1. Microbial Inoculants

Microbial inoculants are made up of a beneficial population of microorganisms such as nitrogen-fixing bacteria, phosphate-solubilizing bacteria, and mycorrhizal fungi (Das and Sengupta, 2024) ^[15]. These entered into symbiotic relationships with plants and enhance nutrient and water availability to plants.

Availability of Nutrient and Soil Health: Nitrogen-fixing bacteria (NFB) (e.g., *Rhizobium*, *Azospirillum*), which are involved in the conversion of atmospheric nitrogen to plant-available form, have also been a key factor in reducing the reliance on nitrogen fertilizer derived from chemicals and administered in bulk. Phosphate solubilizing bacteria (*Bacillus*, *Pseudomonas* and *Rhizobium* species) were also reported to enhance the availability of phosphate to the plant by solubilizing phosphate ions from the insoluble soil phosphorus complexes.

Targeted nutrient feeding: Microbial inoculants provide a controlled release of nutrients and operate as during plant management a slowly-releasing fertilizer. This balances the soil around the roots, so when chemical nutrients are minimal, organic farmers apply microbial inoculants to reduce their dependence on chemical fertilizers (Schutz *et al.*, 2018; dos Reis *et al.*, 2024) ^[65, 19].

2. Biochar

Biochar is a solid material rich in carbon that is produced

during the thermal decomposition of organic wastes in an oxygen-limited environment. Upon soil application, biochar functions as a soil conditioner that improves water holding capacity, cation exchange capacity, and microbial activity (Singh *et al.*, 2022; Ferreira *et al.*, 2024) ^[74, 20].

Soil Fertility and Nutrient Availability: Because of its porous structure, biochar can hold nutrients and water, which (i) decreases nutrient leaching (Laird *et al.*, 2010) ^[39] and (ii) enhances soil fertility. Biochar also promotes beneficial soil microbes, potentially leading to enhanced nutrient cycling and soil health (Lehmann and Joseph, 2019) ^[45].

Focused Nutrient Delivery: Because of the biochar's structure, and high surface area, it can hold on to nutrients and release them slowly, so it can also be used as a carrier for the focused nutrient delivery. By taking up and releasing fertilizers or nutrients gradually, biochar makes the nutrient availability in organic agriculture (which are naturally slower to release nutrient sources) more stable (Brassard *et al.*, 2016; Yao *et al.*, 2012) ^[11, 86].

3. Vermicompost

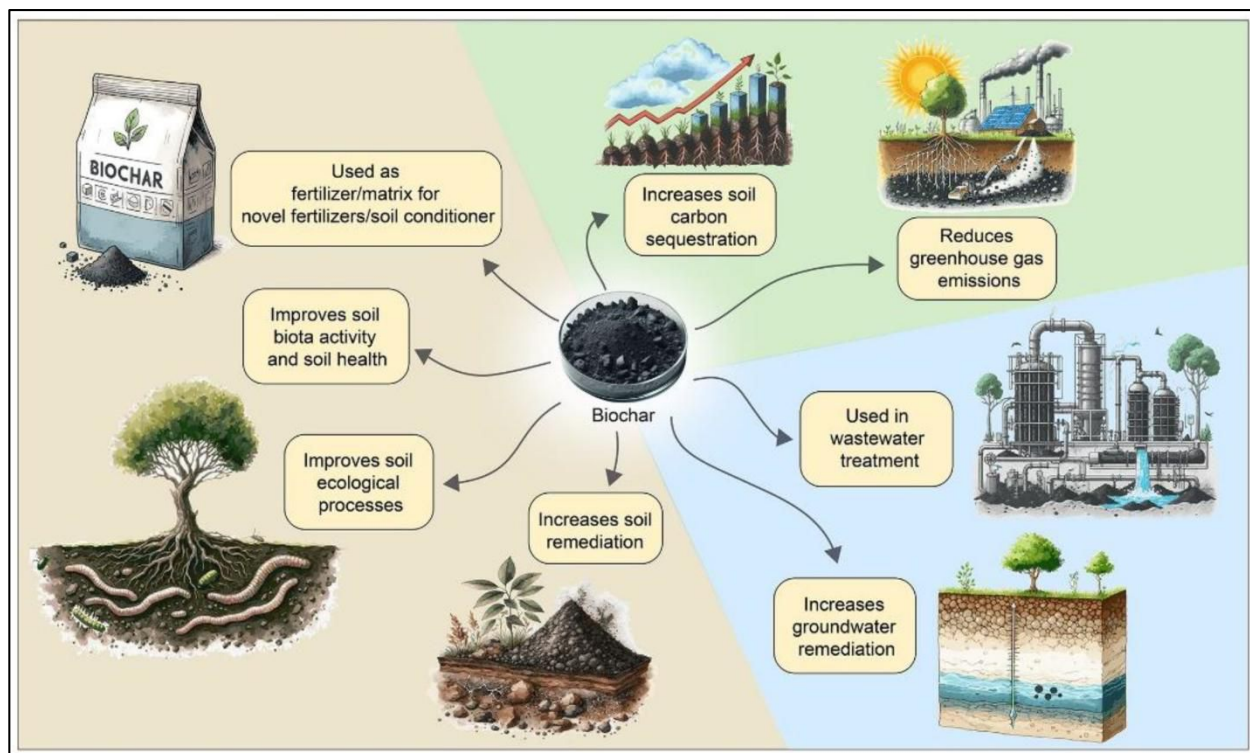
Vermicompost is the result of the digestion and decomposition of organic materials by the action of earthworms (Atiyeh *et al.*, 2000) ^[4]. Vermicompost contains a balanced spectrum of macro-and micro-nutrients and is an excellent source of nutrients available to the plants, enzymes and beneficial microbes (Sinha *et al.*, 2010) ^[75].

Nutrient Availability and Soil Health: Vermicompost provides nutrients to the plant in an available form (nitrogen, phosphorus, potassium, calcium, and magnesium), as well as growth promoting hormones (Arancon and Edwards, 2019) ^[2], and the microbial activity of vermicompost also contributes to the enhancement of soil biodiversity and the formation of good soil structure.

Targeted Nutrient Supply: The gradual release of nutrients from vermicompost ensures the availability of nutrients to the plants all through the crop duration. In organic farming systems, the harmoniously matched and sustained nutrient supply empowers the plant and enhances soil organic matter that is responsible for holding nutrients and shielding plants from environmental stressors (Sinha *et al.*, 2018; Lim *et al.*, 2015) ^[76, 46].

Advantages of Bio-Based Fertilizers in Organic Systems

Improved Nutrient Use Efficiency: The biofertilizer products are formulated to mimic nutrient cycles in nature, sequestering nutrients in a natural form and timing as auster as attainable, which is said to facilitate plant systems in the absorption of nutrients and lowers the potential for loss (Singh *et al.*, 2020; Schutz *et al.*, 2018) ^[72, 65].



Soil Microbiome and Biodiversity Protection:

Application of biofertilizers has positive effect on soil health by increasing microbial biodiversity and play vital role in nutrient cycling, disease suppression and overall ecosystem resilience. This microbial stimulation is critical to organic systems that rely on natural nutrient sources and biological soil management (Rillig *et al.*, 2019) ^[62].

Enhanced Soil Structure and Water Holding Capacity:

Organic matter in the soil derived from bio-fertilizers sources such as vermicompost and biochar improves soil structure by improving the aggregation and water retention of soil (Abel *et al.*, 2013) ^[1]. This enhancement inhibits soil erosion and facilitates sustainable crop production, that is even more crucial in the organic system which disallows the use of chemical soil additives (Glaser and Birk, 2019) ^[23].

B. Precision Agriculture for Organic Fertilization

Precision agriculture technologies, until now predominantly used in conventional agriculture, are also being adapted to the management of organic manuring (Oliver *et al.*, 2013) ^[53]. With real-time information on soil and crop conditions, these technologies help farmers apply organic fertilizers more efficiently, resulting in increased nutrient management, healthier soil and less waste. Soil sensors, drone mapping, and data analytics are transforming how organic farms operate (Getahun *et al.*, 2024) ^[22].

1. Soil Sensors

A multitude of soil parameters, including moisture, temperature, pH, and nutrient concentration, can be measured by soil sensor directly in situ. As a result of gathering uninterrupted data, soil sensors provide farmers with real-time advises on when to conduct and how much of the organic fertilizer (Lee *et al.*, 2020; Soussi *et al.*, 2024) ^[44, 77].

Improved Efficiency and Less Waste: The release of nutrients from input sources such as compost or manure is slower and less predictable in organic production systems, and soil sensors can be used for refinement of timing and rate of application. Certain nutrient deficiencies or soil characteristics may be identified by sensors in real-time to apply nutrients in a site-specific manner that minimizes nutrient leaching and wastage (Mulla, 2013) ^[51].

Example in organic systems: Soil sensors allow the organic fertiliser to be applied in closer proximity to the root zone, because it senses nutrient demand on very small areas within a field, enabling avoidance of the potential over-application and run-off of that fertiliser into the environment. This level of precision is especially useful in organic farming where the flow of nutrients needs to be closely controlled in order to maintain soil health and meet organic requirements (Wheeler *et al.*, 2021) ^[83].



2. Drone Mapping and Remote Sensing

Multispectral and hyperspectral cameras attached to drones take aerial photos that display the condition of crops, available nutrients and soil conditions across the whole field. Along with the remote sensing data, the images are used to generate maps of in-field variability at a relatively high spatial resolution (Zhang and Kovacs, 2012) ^[87].

Greater Efficiency and Less Waste: Drones map farmers fields, enabling them to apply fertilizers selectively and not uniformly in areas where the nutrients are depleted. Precision application reduces the amount of applied fertilizer and increases nutrient uptake of crops, and therefore leading to the better utilization of organic input and less pollutant waste (Huang *et al.*, 2018) ^[31].

Sample in Organic Systems: In organic Systems, where crops are diversified and mixed cropping is common, drone mapping enables farmers to tailor fertilizer treatments to the needs of each crop, promoting uniform growth and reducing heat stress in the nutrient competition. They also aid in monitoring how crops react to fertilization, so farmers can adjust the regimens to produce the best results (Lamb *et al.*, 2021) ^[42].

3. Data Analytics and Machine Learning

Data analytics and machine learning on huge datasets gathered from sensors, drones, and historical field record to deliver insights and recommendations for efficient use of organic fertilizers. These insights may lead to predictions on the nutrient needs of crops, best application times, and likely responses of crops to fertilization (Shamshiri *et al.*, 2018) ^[66].

Better Efficiency and Less Wastage: Farmers are counseled by data science to make better decisions about when to apply organic fertilizers, which reduces guesswork and increase nutrient-use efficiency in one go. The nutrient release curves of organic fertilizers under environmental conditions can be predicted by using machine learning techniques, which allow farmers to adapt the application rates to the local conditions in order to prevent nutrient shortages or surpluses (Khanna and Harms, 2020) ^[34].

For instance in Organic: Organic farming systems reap the most benefits from such knowledge as organic fertilizers have a slower and more variable nutrient release rate than synthetic fertilizers. Conversely, ML algorithms can also be applied to model the mineralization rates of organic fertilizers to allow farmers to more closely match fertilizer application timing with crop nutrient demand (Cambouris *et al.*, 2019) ^[13].

Benefits of Precision Agriculture for Organic Fertilization

Environmental Footprint Reduced: Precision agriculture reduces the environmental impact of organic fertilizers because the nutrients are delivered very specifically where, when and in what amount needed. This also prevents nutrient leaching, reduces the emission of greenhouse gases related to over-fertilization, and prevents contamination of bodies of water near farmlands (Bongiovanni and Lowenberg-DeBoer, 2004) ^[9].

Increased Crop Yields and Soil Quality: Management for real-time nutrient application and resulting healthier plants and higher yields is especially important in organic production, where yields routinely fall below those of conventional production. Balanced nutrient management also improves soil health leading to greater sustainability and better pest and disease resistance over time.

Cost-Benefit and Energy Use Optimization: The precision technology use helps to increase the utilization efficiency of organic fertilizer and reduce the amount of input. This is good news for organic farmers, who generally face higher input costs and have less access to synthetic options (Dikshit and Lal, 2020) ^[18].

C. Controlled-Release Organic Fertilizers

The idea of controlled-release technology, which has been extensively applied in synthetic nitrogen fertilizers, is now being extended to organic materials with the introduction of controlled-release organic fertilizers (CROFs). CROFs The nutrient release from these fertilizers is a slow release and This slow nutrient release has the advantage of neutralize an important limitation in the organic agriculture: the uncertain

time when nutrients can be absorbed. Two major drawbacks of organic fertilizers are their short period of effectiveness and the unpredictability of their nutrients availability. Utilizing new materials such as bio-polymers, and new building-block encapsulation techniques, CROFs provide a more predictable nutrient release that more closely align with crop growth needs, improving nutrient-use efficiency and reducing impact on the environment.

1. Bio-Polymers for Controlled Nutrient Release

Bio-polymers are organic polymers scientifically derived from sustainable resources like starch, bio-polymers act as coatings for organic fertilizer pellets. They are environment friendly and can undergo bio-degradation, i.e., they get broken down naturally in soil along with the nutrients.

Controlled Release of Nutrients Predictable: The availability of nutrients is retarded by bio-polymer coatings, which serve as a semi-permeable membrane. This film forms a water-resistant barrier, slowly penetrates water, gradually dissolves the fertilizer core, and the release pattern of nutrients is controlled to more closely match crop demand (Shi *et al.*, 2019) [170].

Arg of Use in CROFs: For instance, starch-based coatings were found to effectively control the release of nitrogen in organic fertilizers. The thickness of the coating and other aspects can be customized to a specified release pattern, which can supply nutrients at a steady rate, minimizing the loss of nutrients and enhancing the efficiency of the use of nutrients in organic system (Kumar *et al.*, 2021) [36, 37].

2. Encapsulation Techniques

Encapsulation is the wrapping of particles of organic fertilizer in a layer or matrix that changes the release of nutrients. Encapsulation methods are generally based on alginate, chitosan, and other organic certifiable materials (Yan *et al.*, 2020) [85].

More Precise Nutrient Delivery: Encapsulation enables a controlled release of the nutrients as the coating inhibits leaching and the rapid dissolution of the fertilizer. As a consequence, nutrients can be released at a slow rate triggered by environmental signals such as moisture, temperature or microbial activity, making it especially interesting in organic farming where managing availability of nutrients is difficult (Tzeng *et al.*, 2021) [80].

Example in CROFs: Encapsulation of sources of nitrogen and phosphorus fertilizer in alginate beads has been used and such fertilizers may release nutrients slowly as per the plant nutrient uptake. This technique enhances not only the availability of nutrients but also reduces the chance of nutrient loss which is very crucial for the system of organic production that focuses on sustainable manner (Majeed *et al.*, 2021) [49].

3. Layered Coating Methods

Multi-layer coatings approaches are based on the successive application of several coating layers of biopolymers with different functionalities to gain enhanced control on the nutrient release pattern. This method is particularly appropriate for organic fertilizers that must be provided in small but constant quantities.

Customizable Release Patterns: The multi-layer coating technology allows the dissolution of each coating layer to occur at a different rate, which results in a staggered nutrient release that corresponds to crop growth stages. Such a decay-like nutrient release alleviates the nutrient losses and ensures a steady nutrient supply, which is of great significance in long-season crops, and even more in organic systems (Shaviv, 2005) [68].

Example in CROFs: Layered coatings can be applied to organic sources of nutrients such as bone meal or compost, enabling nitrogen, potassium and phosphorus to be released at a slow pace. This flexibility is especially relevant since it enables farmers to tailor nutrient release patterns to specific crop and environmental needs (Corradini *et al.*, 2020) [14].

4. Hydrogel-Based Release Systems

Hydrogels are cross-linked hydrophilic polymers that can hold water and encapsulate fertilizers to release nutrients according to moisture condition. Hydrogels, when applied as a layer or blended in fertilizer granules/pellets, swell by absorbing water and provide nutrients due to dehydration.

Release of nutrients in response to moisture regulation in organic farming availability of nutrients based on soil moisture could be affected by algae hydrogels. This also renders them appropriate in drought-prone regions since they deliver nutrients only in the presence of moisture, thereby reducing the potential for nutrient loss during dry periods.

Example in CROFs: Hydrogel-based CROFs have been applied to increase nitrogen retention in the soil with a slow release of nutrients even in adverse weather conditions. Hydrogels also aid in retaining soil moisture which improves soil health and promotes higher resistance of plants (Rafiee *et al.*, 2021) [59].

Benefits of Controlled-Release Organic Fertilizers in Organic Systems

Enhanced Nutrient-Use Efficiency: CROFs enable release of nutrients in a controlled fashion, providing nutrients to plants when the need is highest, and reducing nutrient loss via leaching or volatilization. The targeted release also increases efficiency in the use of nutrients, a critical consideration in organic systems that depend on naturally slow release sources of nutrients (Ramesh *et al.*, 2022) [61].

Lower Environmental Impact: CROFs reduce the risk of nutrient runoff and leaching, which can result in the eutrophication of nearby water bodies. This gradual liberation of surpluses of nutrients into the environment is in line with the principle of organic agriculture, where the maintenance of ecological homeostasis is prioritized (Hagemann *et al.*, 2019) [28].

Healthy Soil and Crop Yields Over Time: With sustained nutrient availability, CROFs enable the preservation of soil health and productivity. Enhanced nutrient retention may also promote better soil microbial activity, which is a signature of a good soil system that leads to higher crop yield in the organic system (Subedi *et al.*, 2020) [78].

Pilot Projects and Research Initiatives

Ongoing pilots and research projects across the globe prove that innovations in organic fertilizers—such as controlled-release organic fertilizers, bio-based fertilizers, precision agriculture technologies, and more—contribute to higher yields, better nutrient-use efficiency, and lower costs for organic farmers. These Systems illustrate the possibility to upgrade the organic system towards higher performance (productivity, sustainability/ecological and economic return) hand in hand with the best state of the art organic fertilization techniques.

1. Controlled-Release Organic Fertilizers for Sustainable Nutrient Management

A small study by the University of Florida on organic vegetable crops evaluated controlled-release organic fertilizers. The result was a 15% yield increase over conventional organic fertilizers and a 30% reduction in nutrient runoff. Bio-polymer-coated organic fertilizers had a sustained nutrient release and were well synchronized with nutrient requirement of crop plants and also reduced leaching loss (Hochmuth *et al.*, 2018) ^[30].

Cost-saving and Yield Enhancement: The trial growers noted that the controlled-release organic fertilizers required fewer applications than traditional forms, so they saved money on labor and had more reliable yields. The results showed that controlled-release technology may be the answer to the nutrient release timing issue in organic systems (Lawson *et al.*, 2020) ^[43].

2. Biochar-Enriched Organic Fertilizers in Field Trials

The Agriculture Department (USDA) is leading the charge in developing a pilot study program for growing organic corn and soybeans with biochar-amended organic fertilizers in the Midwest. The one was to increase soil health and nutrient holding. The findings showed biochar-fortified fertilizers can improve soil organic matter and nutrient retention, and this effect translated to 10-20% higher yields for three consecutive years. Moreover, this approach decreased the cost of the nitrogen fertilizer with 25% since the biochar extended the nutrient retention in the soil (Laird *et al.*, 2017) ^[40].

Environmental and Economic Recovery: The project results indicated that biochar enhanced soil physical properties and nutrient availability, and that a high-yielding organic sustainable solution for growers could be obtained (Galinato *et al.*, 2018) ^[21].

3. Precision Agriculture in Using Organic Fertilizer

In Italy a novel approach, based on drone mapping and soil sensors, to adapt applications of organic fertilizers in vineyard and olive grove was tested within the action of a pilot under the label of "Sustainable Precision Organic Farming" (SPOF). By employing soil and crop health mapping through drones, the farmers were able to apply the fertilizer more precisely, leading to 20% reduction in fertilizer use and 12% increase in crop yields (Milella *et al.*, 2019) ^[50].

Implications for Cost and Resource Efficiency: The project suggested that precision agriculture technology could offer input reductions with crop yield and quality

improvements, so that it might be of use for organic farmers who need to perform judicious resource management (Pisante *et al.*, 2020) ^[56].

4. Vermicompost Pilot Programs in Developing Countries

ICARDA had carried out pilots in India and Kenya to promote vermicomposting among smallholder organic farmers. Solid waste applications of vermicompost to organic tomato and maize increased yields by 30% and enhanced soil microbial activity, according to trials. By using farm waste, farmers can produce their own vermicompost and thus lessen their reliance on purchased inputs (Devkota *et al.*, 2019) ^[17] and vermicompost emerged as a cost-effective input.

Economic Viability of Vermicomposting for Small Farmers:

Vermicomposting lowers production cost and maintains soil fertility, which represents the principles of sustainable agriculture and may be a financially sustainable approach for small organic farms in resource-limited setting (Gurung and Tamang, 2021) ^[27].

5. Microbial Inoculants in Large-Scale Organic Farming

A Cornell University-led study examined the application of microbial inoculants such as nitrogen-fixing bacteria and phosphate-solubilizing fungi in New York organic wheat production systems. The project found that inoculants increased nitrogen uptake and phosphorus availability by 15% and 20%, respectively, in wheat. Application of inoculants has the potential to reduce the use of supplementary phosphorus fertilizers, with financial and environmental benefits (DeLuca *et al.*, 2021) ^[16].

Yield and Cost Efficiency: The results indicated that the microbes have the potential to increase nutrient availability/uptake, and thus, organic farmers can be offered a financially attractive and environmentally safe substitute to synthetic fertilizers (Kassam *et al.*, 2022) ^[32].

6. Greenhouse Trials with Encapsulated Organic Fertilizers

In the Netherlands, Wageningen University conducted a greenhouse trial with tomatoes and lettuce to study the impact of the encapsulated organic fertilizer. The encapsulation technique applied biodegradable substances and modulated the rate of nutrient release. Studies showed that the supply of nutrients by encapsulated fertilizers is consistent throughout the entire growing period, which gave 20% higher crop yields and a reduction of 15% in the total fertilizer use (Verhagen *et al.*, 2020) ^[81].

Environmental implications: The trial demonstrated the potential for encapsulated fertilizers to reduce nutrient leaching in a soilless system and the environmental benefits of controlled-release organic fertilizers in organic systems (Hendriks *et al.*, 2021) ^[29].

Conclusion

Advances in organic fertilizer technology have led to increased efficiency, sustainability, and productivity of organic farming systems. Microbial inoculants, biochar and vermicompost are a few kinds of bio-based fertilizers that improve soil structure, microbial activity, and provision of

nutrients to the plants. Controlled-release organic fertilizers such as bio-polymer coatings, and hydrogel-based systems provide a controlled and accurate nutrient delivery, thus seem to reduce environmental losses, and contribute in maintaining the soil fertility. Soil sensors, drones, and data analytics now allow precision agriculture to tailor organic fertilizer application in real-time with site-specific recommendations. Pilot studies confirm enhanced crop yields, better nutrient-use efficiency, and diminished environmental impact. Although they have shortcomings, including variability of nutrient content, slow nutrient release, high transportation costs, and knowledge gaps, these innovations offer promising pathways towards sustainable and economically feasible organic agriculture. Future research is encouraged to capitalize on these technologies, overcome logistical and knowledge barriers, and broaden uptake for maximizing gains across a range of farming systems.

References

1. Abel S, Peters A, Trinks S, Schonsky H, Facklam M, Wessolek G. Impact of biochar and hydrochar addition on water retention and water repellency of sandy soil. *Geoderma*. 2013;202:183-191.
2. Arancon NQ, Edwards CA. Vermicompost production and its effects on soil health and plant growth. *Agriculture, Ecosystems and Environment*. 2019;240:75-82.
3. Assefa S, Tadesse S. The principal role of organic fertilizer on soil properties and agricultural productivity-a review. *Agric Res Technol Open Access J*. 2019;22(2):1-5.
4. Atiyeh RM, Subler S, Edwards CA, Bachman G, Metzger JD, Shuster W. Effects of vermicomposts and composts on plant growth in horticultural container media and soil. *Pedobiologia*. 2000;44(5):579-590.
5. Avasiloaiei DI, Calara M, Brezeanu PM, Gruda NS, Brezeanu C. The evaluation of carbon farming strategies in organic vegetable cultivation. *Agronomy*. 2023;13(9):2406.
6. Baker JM, Ochsner TE, Venterea RT, Griffis TJ. Tillage and soil carbon sequestration—What do we really know? *Agriculture, Ecosystems and Environment*. 2007;118(1-4):1-5.
7. Barker AV, Pilbeam DJ, editors. *Handbook of plant nutrition*. 2nd ed. Boca Raton: CRC Press; 2015.
8. Bharadwaj V, Singh R. Knowledge and adoption gaps in organic fertilizer use among farmers. *Journal of Agricultural Extension*. 2021;16(3):245-253.
9. Bongiovanni R, Lowenberg-DeBoer J. Precision agriculture and sustainability. *Precision Agriculture*. 2004;5(4):359-387.
10. Boru M. Review of organic fertilizer and its role in organic farming. *International Journal of Energy and Environmental Science*. 2025;10(2).
11. Brassard P, Godbout S, Raghavan V. Soil biochar amendment as a climate change mitigation tool: key parameters and mechanisms involved. *Journal of Environmental Management*. 2016;181:484-497.
12. Cai S, Xu S, Zhang D, Liang Y, Zheng X, Zhu H. Organic Fertilizer Substitution Modulates Soil Properties and Microbial Communities in a Vegetable-Earthworm Co-Cultivation System. *Microorganisms*. 2025;13(12):2742.
13. Cambouris AN, Zebarth BJ, Ziadi N. Precision agriculture for nutrient management. *Precision Agriculture*. 2019;20(6):1216-1233.
14. Corradini E, Moura MRD, Mattoso LHC. Layered biopolymer coatings for controlled-release fertilizers in organic agriculture. *Carbohydrate Polymers*. 2020;235:115953.
15. Das D, Sengupta S. The role of microorganisms in agriculture: Enhancing soil health, crop productivity, and sustainable farming practices. *International Journal of Agriculture and Food Science*. 2024;6(2):163-165.
16. DeLuca T, Garcia M, Anderson C. Role of microbial inoculants in sustainable nutrient management for organic wheat. *Agronomy Journal*. 2021;113(1):222-230.
17. Devkota B, Dahal PR, Bhandari B. Vermicomposting in smallholder farming: Impact on crop yield and soil fertility. *Journal of Organic Agriculture*. 2019;5(2):101-109.
18. Dikshit AK, Lal R. Cost-effectiveness and environmental benefits of precision agriculture. *Sustainable Agriculture Reviews*. 2020;42:217-240.
19. Dos Reis GA, Martínez-Burgos WJ, Pozzan R, Pastrana Puche Y, Ocán-Torres D, de Queiroz Fonseca Mota P, *et al*. Comprehensive review of microbial inoculants: Agricultural applications, technology trends in patents, and regulatory frameworks. *Sustainability*. 2024;16(19):8720.
20. Ferreira OE, Silva HDM, Alves AB, de Aguiar MG, Pimenta LPS, Costa GHG, *et al*. Biochar enhances soil interactions and the initial development of sugarcane. *Scientific Reports*. 2024;14(1):27610.
21. Galinato SP, Gellar JP, Laird DA. Economic assessment of biochar-enriched organic fertilizers in corn production systems. *Renewable Agriculture and Food Systems*. 2018;33(2):105-116.
22. Getahun S, Kefale H, Gelaye Y. Application of precision agriculture technologies for sustainable crop production and environmental sustainability: A systematic review. *The Scientific World Journal*. 2024;2024(1):2126734.
23. Glaser B, Birk JJ. State of the scientific knowledge on properties of biochar: An update. *GCB Bioenergy*. 2019;10(6):349-372.
24. Gomiero T, Pimentel D, Paoletti MG. Environmental impact of different agricultural management practices: conventional vs. organic agriculture. *Critical Reviews in Plant Sciences*. 2011;30(1-2):95-124.
25. Goss MJ, McMullen LD, Ball Coelho B. Risks of pathogen transfer in organic farming. *Agricultural Health and Safety*. 2020;15(2):138-147.
26. Gupta S, Ramasamy S. Nutrient imbalance challenges in organic fertilizer use. *Journal of Soil Science*. 2020;45(1):102-112.
27. Gurung T, Tamang R. Vermicompost in organic farming: Economic benefits for smallholders in resource-limited settings. *Journal of Soil Science and Plant Nutrition*. 2021;21(3):839-851.
28. Hagemann N, Subedi R, Orsetti S. Organic fertilizers with controlled nutrient release: Environmental impacts and resource efficiency. *Science of The Total Environment*. 2019;651:2766-2777.

29. Hendriks C, Verhagen J, de Groot C. Controlled-release encapsulated fertilizers in organic greenhouse systems. *Acta Horticulturae*. 2021;1314:151-160.
30. Hochmuth G, Olson S, Sinclair T. Controlled-release organic fertilizers in vegetable crops: A pilot study. *HortScience*. 2018;53(7):941-948.
31. Huang Y, Lan Y, Thomson SJ. Remote sensing and drone technologies in precision agriculture: An overview. *Computers and Electronics in Agriculture*. 2018;138:1-5.
32. Kassam A, Stoop W, Uphoff N. Potential of microbial inoculants for yield improvement in organic wheat farming. *Agricultural Research*. 2022;11(3):345-357.
33. Khan MT, Aleinikoviene J, Butkeviciene LM. Innovative organic fertilizers and cover crops: Perspectives for sustainable agriculture in the era of climate change and organic agriculture. *Agronomy*. 2024;14(12):2871.
34. Khanna M, Harms N. Use of data analytics in precision agriculture. *Agricultural Economics*. 2020;51(2):299-311.
35. Kibaret KB, Langat AK, Ochieng EO. Effect of organic fertilizers on soil fertility and crop performance. *International Journal of Agronomy and Agricultural Research*. 2018;11(4):107-115.
36. Kumar R, Hegde DM, Meena RK. Organic farming and its impact on soil and crop yield: A review. *Progress in Agriculture*. 2021;21(1):12-23.
37. Kumar S, Gupta R, Pandey V. Bio-based polymer coatings for controlled-release organic fertilizers. *Journal of Agricultural and Food Chemistry*. 2021;69(20):5883-5893.
38. Kumar V, Pradhan S. Heavy metal contamination in organic fertilizers. *Environmental Toxicology*. 2022;30(3):567-574.
39. Laird D, Fleming P, Wang B, Horton R, Karlen D. Biochar impact on nutrient leaching from a Midwestern agricultural soil. *Geoderma*. 2010;158(3-4):436-442.
40. Laird D, Novak J, Collins H. Biochar-enriched organic fertilizers: A field trial in organic corn production. *Environmental Research Letters*. 2017;12(11):113003.
41. Lal R. Organic fertilizers in soil health management. *Soil Systems*. 2021;5(1):64-72.
42. Lamb DW, Frazier P, Adams P. Comparison of UAV and ground-based data for assessing crop health in organic farming. *Remote Sensing of Environment*. 2021;257:112354.
43. Lawson P, Hochmuth R, Simonne E. Controlled-release fertilizers in organic farming systems. *Journal of Organic Agriculture*. 2020;6(1):65-73.
44. Lee I, Liu Y, Zhao L. Soil sensors in precision agriculture for nutrient management. *Sensors*. 2020;20(3):817.
45. Lehmann J, Joseph S, editors. *Biochar for environmental management: science, technology and implementation*. 2nd ed. London: Routledge; 2019.
46. Lim SL, Wu TY, Lim PN, Shak KPY. The use of vermicompost in organic farming: overview, effects on soil and economics. *Journal of the Science of Food and Agriculture*. 2015;95(6):1143-1156.
47. Liu X, Zhang Y, Guo Q. Organic fertilizers for soil health improvement and sustainable agriculture. *Agronomy*. 2021;11(9):1763.
48. Liu X, Zhang Y, Li Y. Comparative yield analysis of organic vs synthetic fertilizers. *Agronomy Journal*. 2018;110(4):1294-1302.
49. Majeed A, Abbasi MK, Hameed M. Role of alginate encapsulation in sustainable nutrient management. *Journal of Soil Science and Plant Nutrition*. 2021;21(1):59-72.
50. Milella A, Perboni A, Bonciarelli F. Drone-based mapping and sensor applications for organic fertilization in vineyards. *Agriculture*. 2019;9(6):138.
51. Mulla DJ. Twenty-five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps. *Biosystems Engineering*. 2013;114(4):358-371.
52. Muller A, Schader C, Scialabba NE. Yield differences in organic and conventional farming. *World Agriculture*. 2019;8(3):207-218.
53. Oliver MA, Bishop TF, Marchant BP, editors. *Precision agriculture for sustainability and environmental protection*. Abingdon: Routledge; 2013.
54. Panday D, Bhusal N, Das S, Ghalehgolabbehbahani A. Rooted in nature: The rise, challenges, and potential of organic farming and fertilizers in agroecosystems. *Sustainability*. 2024;16(4):1530.
55. Parr M, Letourneau DK, Kromer A. Integrated farming systems for sustainable agriculture: A global overview. *Field Crops Research*. 2020;150(1):1-14.
56. Pisante M, Marinari S. Precision organic agriculture for sustainable crop production. *Sustainability*. 2020;12(8):3350.
57. Pradhan S, Patra AK, Biswas DR. Variability in nutrient content of organic fertilizers. *Agricultural Reviews*. 2021;42(2):86-94.
58. Priya E, Sarkar S, Maji PK. A review on slow-release fertilizer: Nutrient release mechanism and agricultural sustainability. *Journal of Environmental Chemical Engineering*. 2024;12(4):113211.
59. Rafiee A, Sabour M, Tehrani FS. Hydrogel-based nutrient release systems for water-scarce agriculture. *Journal of Applied Polymer Science*. 2021;138(28):50613.
60. Rahman M, Hossain A, Dutta D. Labor demand in organic fertilizer application. *Agricultural Labor Studies*. 2021;15(4):98-108.
61. Ramesh V, Varma A, Singh A. Controlled-release fertilizers in organic farming: Prospects and challenges. *Agronomy*. 2022;12(1):112-123.
62. Rillig MC, Muller LAH. Soil biodiversity and ecosystem functioning in organic farming. *Trends in Plant Science*. 2019;24(6):519-528.
63. Saravanan R, Meena S. Training gaps in organic fertilizer use for sustainable agriculture. *Journal of Rural Development*. 2021;39(4):563-574.
64. Schütz L, Gättinger A, Meier M, Müller A. Microbial inoculants as a key component of sustainable soil management in organic agriculture. *Agronomy*. 2021;11(3):567-582.
65. Schutz L, Gättinger A, Meier M, Müller A, Boller T, Mader P, *et al.* Improving crop yield and nutrient use efficiency via biofertilization—A global meta-analysis. *Frontiers in Plant Science*. 2018;8:2204.
66. Shamshiri RR, Kalantari F, Ting KC. Smart data in precision agriculture: Machine learning applications for

- plant health monitoring. *Agricultural and Biosystems Engineering*. 2018;63(4):823-832.
67. Sharma V, Singh H. Economic and logistical barriers in organic fertilizer distribution. *International Journal of Agronomy and Agricultural Research*. 2020;9(2):45-52.
68. Shaviv A. Advances in controlled-release fertilizers. *Journal of Plant Nutrition*. 2005;28(2):983-994.
69. Sheikh MM, Riar TS, Pervez AKM. Integrated farming systems: A review of farmers friendly approaches. *Asian Journal of Agricultural Extension, Economics and Sociology*. 2021;39(4):88-99.
70. Shi R, Gao S, Yu X. Advances in bio-polymer-coated controlled-release fertilizers. *International Journal of Biological Macromolecules*. 2019;132:1207-1217.
71. Singh H, Northup BK, Rice CW, Prasad PV. Biochar applications influence soil physical and chemical properties, microbial diversity, and crop productivity: a meta-analysis. *Biochar*. 2022;4(1):8.
72. Singh JS, Pandey VC, Singh DP. Efficient use of bio-based fertilizers in organic farming systems. *Ecological Engineering*. 2020;132:190-199.
73. Singh P, Prasad R. Labor and time investment in organic farming. *Journal of Sustainable Agriculture*. 2021;35(1):75-84.
74. Singh R, Kaur G, Saini M. Role of organic fertilizers in soil biodiversity and sustainability. *Soil and Tillage Research*. 2022;207:105057.
75. Sinha RK, Agarwal S, Chauhan K, Valani D. The wonders of earthworms and its vermicompost in farm production: Charles Darwin's 'friends of farmers', with potential to replace destructive chemical fertilizers. *Agricultural Sciences*. 2010;1(02):76.
76. Sinha RK, Valani D, Soni B. Earthworms and vermiculture biotechnology: Role in sustainable waste management and soil health. *Environmental Science and Pollution Research*. 2018;21(16):9488-9498.
77. Soussi A, Zero E, Sacile R, Trincherio D, Fossa M. Smart sensors and smart data for precision agriculture: a review. *Sensors*. 2024;24(8):2647.
78. Subedi R, Bertora C, Zavattaro L. Controlled-release fertilizers and organic farming: Insights and future directions. *Sustainability*. 2020;12(4):1426.
79. Tonfack LB, Mih AM, Ngo NT. Constraints to organic fertilizer adoption in Cameroon. *African Journal of Agricultural Research*. 2019;14(5):310-318.
80. Tzeng C, Liu H, Hwang S. Application of chitosan encapsulation in nutrient management for organic crops. *Polymers*. 2021;13(14):2397.
81. Verhagen J, Hendriks T, Blok C. Encapsulated organic fertilizers for efficient nutrient management in greenhouse horticulture. *Horticultural Science*. 2020;35(5):491-498.
82. Verma VK, Vaghela PK, Singh NB, Kumar M. Impact of organic modules on higher value crop mustard (*Brassica juncea* L.). *Int J Res Agron*. 2024;7:650-658.
83. Wheeler T, Reynolds C, Singh V. Sensor technologies and their role in organic agriculture. *Agricultural and Environmental Letters*. 2021;6(1):122.
84. Yadav M, Goyal A, Meena R. Micronutrient deficiencies in organic farming. *Soil and Plant Nutrition*. 2021;31(1):80-87.
85. Yan W, Jiang L, Wang X. Encapsulation technology in organic fertilizers: An overview. *Agriculture*. 2020;10(4):157.
86. Yao Y, Gao B, Zhang M, Inyang M, Zimmerman AR. Effect of biochar amendment on sorption and leaching of nitrate, ammonium, and phosphate in a sandy soil. *Chemosphere*. 2012;89(11):1467-1471.
87. Zhang C, Kovacs JM. The application of small UAVs for precision agriculture: Remote sensing for crop management. *Remote Sensing*. 2012;4(9):1032-1054.