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Site-Specific Nutrient Management and Plant Biostimulants For Enhancing Crop Productivity And Soil Health: A Review

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ABSTRACT

Site-specific nutrient management (SSNM) is the science and management of soil nutrients accounting for soil spatial and temporal variability to enhance productivity and environmental sustainability. It enhances productivity and quality in agriculture and agriculture-based activities while reducing resource use. Humic acids, seaweed extract, and plant growth-promoting rhizobacteria are among the biostimulants that improve the crop-microbiome system by promoting nutrient transport efficiency and optimizing the crop root structure. The purpose of this review is to give a full overview of the synergistic assimilation of Site-specific nutrient management (SSNM) and biostimulants as tools to improve crop and soil health. Chemical inputs are a major component of agricultural operations and can drive up short-term productivity, but lead to adverse long-term impacts on soil health and nutrient-use efficiency (NUE) and can cause pollution from agriculture in nonpoint source ways. Precision Nutrient Management (PNM) addresses these challenges by providing nutrients in real time in response to the metabolic needs of the crop through the use of real-time proximal crop sensors, satellite crop sensors, in-situ electrochemical soil diagnostics, and decision support systems (DSS). The effects of precision nutrient management and biostimulants on crop improvement and soil health were evaluated, considering the interaction between the two components, through 42 selected studies with special focus on existing challenges, gaps in research, and future perspectives. Existing evidence shows that the use of 25% synthetic inputs can be successfully replaced by integrating precision nutrient management and biostimulants in rainfed wheat systems to guarantee yield stability under environmental stress, improve nutrient use efficiency (NUE), enhance soil biological health, increase crop quality, reduce environmental losses, and present significant research contradictions such as the negative effect of mineral fertilizer co-application on soil microbial biomass carbon ($C_{mi}c$) and the feedback inhibition of microbial activity by high doses of mineral fertilizers. The problems encountered in adoption, gaps in standardization, and prospects such as engineered synthetic microbial consortia (SynComs) and smart nano-sensors are discussed, laying the foundation for the development of self-optimizing and climate-resilient biotechnology. A circular bio-economic solution is proposed in this review: the integrative Microbe-Sensor Closed Loop (MSCL) framework.

Keywords: *Site-specific Nutrient Management, Plant Biostimulants, Soil Health, Nutrient-use efficiency, Sustainability.*

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1. Introduction

The food needs of a growing world population (9.7 billion people by 2050) demand 60-100% more food production from agriculture (Ali *et al.*, 2024; Win *et al.*, 2025). This productivity gain is a great challenge in the present scenario where climate change, rapid degradation of land, exhaustion of natural resources, and soil organic matter

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are threats to the global sector (Topa *et al.*, 2025; Paramesh *et al.*, 2023). In the past, agricultural intensification was done by using synthetic mineral fertilizers (SMF) in blanket application to achieve high yields (Ali *et al.*, 2024; Varma *et al.*, 2021). But this is a traditional method that is not sustainable (Win *et al.*, 2025; Mashabela *et al.*, 2025). Over-chemicalization of soils leads to long-term damage to the biological health of the soil, loss of soil fertility, soil fragility, and significant environmental perturbations (Paramesh *et al.*, 2023; Topa *et al.*, 2025). These perturbations involve prevalent nonpoint sources of water pollution, eutrophication in water, and increasing greenhouse gas (GHG) emissions (Paramesh *et al.*, 2023; Basar *et al.*, 2025).

The manufacturing of synthetic N fertilizers is highly energy-intensive and one of the major sources of global GHG emissions (Ali *et al.*, 2024; Win *et al.*, 2025). The need to reduce these ecological impacts and mitigate the effects on the United Nations Sustainable Development Goals (SDGs) 2 (Zero Hunger) and 13 (Climate Action) requires a shift from a chemically intensive, input-oriented approach to better resource use and biologically active management strategies in modern agricultural science (Mashabela *et al.*, 2025; Topa *et al.*, 2025).

Integrated Nutrient Management (INM) has proven to be a more environmentally friendly approach, ensuring the most efficient use of synthetic fertilizers, organic amendments, and plant biostimulants (Ali *et al.*, 2024; Topa *et al.*, 2025; Paramesh *et al.*, 2023). In this paradigm, the conceptual move is from precision sensing/diagnosis to nutrient decision-making, precision application, integration of biostimulants, and finally, the crop, soil, and environmental sustainability responses (Rezaee Danesh, 2025; Mashabela *et al.*, 2025; Gorai *et al.*, 2021). Precision farming and plant biostimulants are two key aspects of advanced sustainable agronomy (Ali *et al.*, 2024; Baltazar *et al.*, 2021). The development of a thorough understanding of the potential for combining biological metabolic enhancers with digital sensing diagnostics is a critical step towards sustainable crop production and climate-resilient farming (Rezaee Danesh, 2025; Mashabela *et al.*, 2025).

Site-specific nutrient management (nutrient sensors, DSS, VRT) and plant biostimulants have been studied separately, but there is limited critical synthesis on how these two technologies can be combined at a single time to enhance nutrient-use efficiency, crop performance, and soil health. They are dealt with separately in much of the literature, and their interactions are generally not evaluated; there is little consideration of antagonisms (particularly at high rates of mineral nitrogen) or how they can be combined in practice.

This review aims to review the interactive benefits and drawbacks of precision nutrient management technologies and plant biostimulants to improve crop yields, nutrient use efficiency, and soil health. Propose a conceptual framework based on integration (Microbe-Sensor Closed Loop-MSCL). Identify current evidence, conflicting evidence, challenges in adoption, gaps in standardization, and research needs for the future (including in the field of SynComs and nano-sensors).

2. Review Methodology

2.1 Review Design

The article is a narrative review with a structured literature search. It synthesizes experimental and review-based evidence on site-specific nutrient management (SSNM) and plant biostimulants, including their interactions and their effects on crop productivity, nutrient use efficiency (NUE), and soil health. The steps of searching, screening, and selection are known to make the process transparent and reproducible, consistent with the general principles of the PRISMA guidelines for reporting literature reviews.

2.2 Literature Search Strategy and Databases.

The literature search was conducted on Scopus, Google Scholar, Dimensions.ai, and other sources, including Web of Science and ScienceDirect, as well as key papers in the field. The publications searched ranged from 2020 to 2025, with special attention to recent publications.

This search string included three concept blocks and Boolean operators:

- Block 1, precision nutrient management: “precision nutrient management” OR “site-specific nutrient management” OR “precision fertilization” OR “variable-rate fertilization” OR “precision agriculture”
- Block 2, biostimulants: “plant biostimulants” OR biostimulants OR “microbial biostimulants” OR “seaweed extract” OR “humic substances” OR “plant growth-promoting rhizobacteria”
- Block 3, outcomes: “crop productivity” OR “crop yield” OR “nutrient use efficiency” OR “soil health” OR “soil quality”

The three blocks were linked with AND, so retrieved records included precision nutrient management, biostimulants, and at least one agronomic or soil outcome. The terms in each block were linked by OR. The string was reformatted to match the syntax of each database, and then used on the titles and abstracts; 100 records were found in this initial search.

2.3 Eligibility Criteria

Inclusion Criteria
Studies were included if they: included nutrient management, precision management, site management, plant biostimulants, or their combinations; Reported or discussed crop productivity outcomes, nutrient use efficiency outcomes, soil health indicators (physical, chemical, or biological), or agronomic or environmental outcomes; provided a mechanistic understanding or field-scale performance evidence; were recent experimental studies or review articles (published 2020-2025); and were peer-reviewed and full-text in English.

Exclusion criteria

Studies were not included if they: Did not include those aspects of the review that did not make sense in the present context, such as precision agriculture without nutrient management or biostimulants without agronomic and soil outcomes; were more than one record of the same study; Did not have enough methodology or outcome data; were not peer-reviewed or were not available in full text; or the publications were outside the scope of the language and/or the publication period.

2.4 Screening and Selection of Studies

The screening was done in a phased manner. All 100 records were evaluated individually for relevance to precision nutrient management, biostimulants and their integration, Nutrient Use efficiency (NUE), soil health indicators, and related agronomic and/or environmental outcomes, both at the level of title and abstract and then, if necessary, at the full-text level. Recent studies that focused on mechanisms and field-scale performance were given priority. The stage narrowed it down to 50 records. Secondly, these 50 were screened, and duplicate records were removed and the eligibility criteria checked. When there were multiple records from the same database, they were identified by title, author, year of publication, and DOI, and only a single copy was retained. Following this step, 42 studies were chosen to be included in the final synthesis.

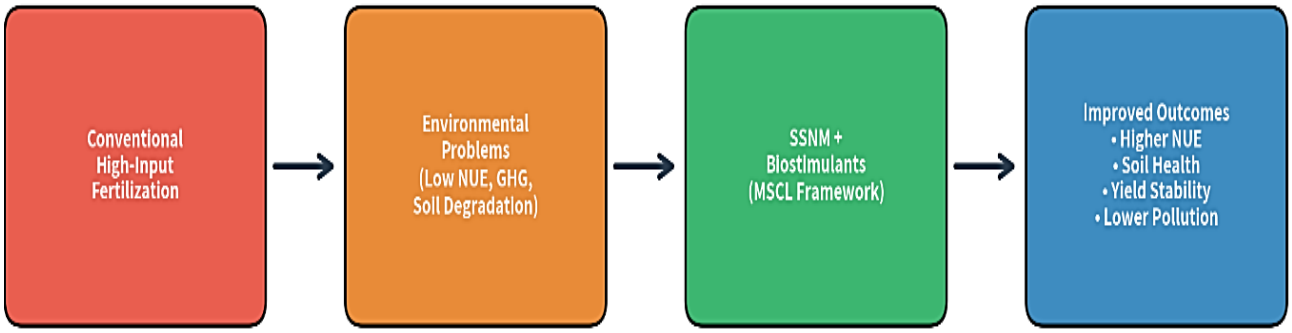
2.5 Evaluation and Synthesis of Selected Studies

Full-text reading was used to assess the 42 studies that were selected. Each was evaluated based on: scientific value of the review; transparency of study design and methods (experimental setting, crop, soil, and treatments); targeted outcomes and data quality and consistency; Mechanistic explanation and evidence of applicability to the field scale. Data collected in each study were categorized according to the following themes: precision nutrient management technologies, categories and modes of action for biostimulants, integration of precision nutrient management technologies and biostimulants, and effects on productivity and soil health. A qualitative synthesis, in which the studies were compared and contrasted, was used. No formal meta-analysis was performed due to crop, environment, and experimental design heterogeneity.

3. Conceptual Basis of Site-Specific Nutrient Management (SSNM)-Biostimulant Management

The conventional approach to agricultural fertilization is based on Liebig's Law of the Minimum, which often leads farmers to add mineral inputs beyond their needs to ensure they meet the production targets (Varma *et al.*, 2021; Gorai *et al.*, 2021). This over-intensive “apply enough” strategy has caused serious ecological issues (Win *et al.*, 2025; Basar *et al.*, 2025).
Site-Specific Nutrient Management (SSNM) provides a diagnostic basis for this transition (Varma *et al.*, 2021; Gorai *et al.*, 2021). Fixed-rate, fixed-time blanket fertilizer recommendations are not suitable in SSNM as they do not consider significant spatial and temporal differences in the nutrient-supplying capacity of the soil and the inherent fertility of the soil crops (Gorai *et al.*, 2021; Ram & Sun, 2025). However, SSNM recognizes spatial and temporal nutrient fluctuations within fields and inputs mineral nutrients according to the real-time nutrient needs of the crop during different physiological growth stages (Varma *et al.*, 2021; Getahun, 2024).
Figure 1 shows how the use of plant biostimulants in combination with SSNM creates a full closed-loop system called Microbe-Sensor Closed Loop (MSCL) (Rezaee Danesh, 2025) or a nested concentric system (Mashabela *et al.*, 2025). Both digital sensors and Decision Support Systems (DSS) define the best timing, rates, and placements of mineral fertilizers (Gorai *et al.*, 2021; Varma *et al.*, 2021), and biostimulants can increase the biological ability of the crop-rhizosphere system to capture, mobilize, and assimilate the inputs provided by mineral fertilizers (Baltazar *et al.*, 2021; Cheng *et al.*, 2024; Basar *et al.*, 2025).

Fig.1 Conceptual Pathway from Conventional to Site-Specific Nutrient-Biostimulant System



4. Relationship between SSNM, PNM, and INM.

4.1 Site-Specific Nutrient Management (SSNM)

Site-Specific Nutrient Management (SSNM) provides nutrients synchronously according to the nutrient demand of the crop and considering the spatial and temporal variability of the inherent soil nutrient supply and nutrient-supplying capacity of the crop within the field. It does not accept blanket or fixed-rate recommendations (Gorai *et al*., 2021; Varma *et al*., 2021). In this way, tools like chlorophyll meters (SPAD), Leaf Color Charts, proximal canopy sensors (GreenSeeker), and decision support systems (Nutrient Expert, Rice Crop Manager) are used to diagnose on-the-go crop needs and provide customized recommendations (Gorai *et al*., 2021; Sagar *et al.*, 2023; Getahun, 2024).

4.2 Precision Nutrient Management (PNM): Technologies and Decision-Making

Precision nutrient management is based on using a wide variety of sensor systems, remote sensing platforms, spatial geostatistics, and predictive modeling for managing field variability (Varma *et al.*, 2021; Gorai *et al.*, 2021; Getahun, 2024; Ram & Sun, 2025).

I. **Sensing and Diagnostics of Crops:** Table 1 summarizes the Key crop sensing technologies used in precision nutrient management:

- **Chlorophyll Meters:** Rapid and non-destructive estimation of tissue nitrogen can be carried out through hand-held chlorophyll meters (Minolta SPAD-502) (Varma *et al.*, 2021; Gorai *et al.*, 2021).
- **Leaf Color Charts (LCC):** These are visual comparison charts that are used in the field to quickly assess the N status of crops and make current decisions on nitrogen top dressings for rice and maize (Varma *et al.*, 2021; Sagar *et al.*, 2023).
- **Proximal Canopy Sensors:** The active optical sensors are those that beam light onto the crop canopy, and the reflected electromagnetic radiation is measured in the red and near-infrared (NIR) wavebands, such as GreenSeeker and Crop Circle (Varma *et al.*, 2021; Getahun, 2024). These sensors are used to derive vegetation indices, mainly the Normalized Difference Vegetation Index (NDVI), which yields real-time estimates of biomass, Leaf Area Index (LAI), and Nitrogen Stress (Gorai *et al.*, 2021; Ram & Sun, 2025).
- **Tractor-Mounted Scanning Platforms:** Passive multispectral scanners, such as the Yara N-Sensor, which use ambient sunlight to analyze crop canopy light reflectance at specific wavebands that are related to chlorophyll content and biomass, are the types of sensors used with tractor-mounted scanning platforms (Getahun, 2024; Gorai *et al.*, 2021).

Technology	Example Devices	Primary Output / Use
Chlorophyll Meters	Minolta SPAD-502	Rapid non-destructive leaf N estimation
Leaf Color Charts	LCC (IRRI)	Visual in-situ N status for top-dressing decisions
Proximal Canopy Sensors	GreenSeeker, Crop Circle	NDVI → biomass, LAI, N stress mapping
Tractor-Mounted Sensors	Yara N-Sensor	Real-time on-the-go variable rate N application

Table 1. Key crop sensing technologies used in precision nutrient management

II. Soil and Subsurface Diagnostics

Advanced soil proximal sensing has moved from destructive soil extraction in the laboratory to real-time and non-destructive soil analysis in the field, with high resolution (Gorai *et al.*, 2021; Ram & Sun, 2025; Rezaee Danesh, 2025):

- **Spectroscopic Soil Sensors:** Visible and near-infrared (VNIR) or mid-infrared (MIR) spectroscopy (Ram & Sun, 2025; Gorai *et al.*, 2021) can be used to estimate soil organic carbon (SOC), soil organic matter, soil clay content, and soil total nitrogen.
- **Laser-Induced Breakdown Spectroscopy (LIBS):** In-situ measurement of soil total carbon, total nitrogen, potassium, micronutrient elements, and heavy metals (Gorai *et al.*, 2021; Ram & Sun, 2025).
- **Contact Electrochemical Sensors:** Ion-Selective Electrodes (ISEs) and Ion-Sensitive Field-Effect Transistors (ISFETs) are used to directly measure the concentration of ions in soil solutions or paste extractants (Gorai *et al.*, 2021; Rezaee Danesh, 2025).

III. The technology of Decision Support Systems (DSS)

To transform the complex sensor data sets into agronomic actions, predictive decision support software is used (Sagar *et al.*, 2023; Gorai *et al.*, 2021; Varma *et al.*, 2021). The field-specific parameters are combined in decision support tools such as Nutrient Expert (NE) and Crop Manager, which include customized N, P, and K fertilization schedules (Sagar *et al.*, 2023; Gorai *et al.*, 2021). Custom rice Crop Management (RCM) based recommendations have been shown to achieve 13.17% greater grain yield in summer rice systems (Sagar *et al.*, 2023). Finally, systems known as Variable Rate Technology (VRT) incorporate this predictive information and combine it with the GPS/GNSS receiver on the tractor-mounted spreader to automatically adjust nutrient application rates within specific areas defined as management zones (Getahun, 2024; Gorai *et al.*, 2021; Ram & Sun, 2025).

4.3 Integrated nutrient management (INM)

Integrated nutrient management (INM) is an agronomic approach that integrates mineral fertilizers, organic amendments, and biological inputs (including biostimulants) to ensure high nutrient availability and utilization, as well as soil health (Ali *et al.*, 2024; Paramesh *et al.*, 2023; Topa *et al.*, 2025). Unlike SSNM/PNM, which focuses on the precision of nutrient mineral fertilizer application (when, where, and how), INM focuses on nutrient source combinations.

These relationships between SSNM, PNM, and INM have been explained in Table 2 below:

Term	Full Form	Core Focus	Relationship
SSNM	Site-Specific Nutrient Management	Tailors nutrient rates, timing, and placement to spatial and temporal variations in soil properties and crop nutrient demand within a field, using soil tests, sensors, and decision-support tools.	A diagnostic and application approach within precision agriculture.
PNM	Precision Nutrient Management	Uses site-specific nutrient management alongside digital technologies, such as remote sensing, proximal sensors, variable-rate technology (VRT), and decision-support	A broader approach that encompasses SSNM and emphasizes technology-driven nutrient management.

Term	Full Form	Core Focus	Relationship
		systems (DSS).	
INM	Integrated Nutrient Management	Combines mineral fertilizers, organic amendments, and biological inputs, including biostimulants, to optimize nutrient supply and improve soil health.	An input-combination strategy. Integrating PNM/SSNM with biostimulants can refine INM by adding data-driven diagnosis and precision in nutrient management.

Table 2. Relationship Between SSNM, PNM, and INM

5 Microbe-Sensor Closed Loop (MSCL) Framework

The Microbe-Sensor Closed Loop (MSCL) framework is put forward as an integrative conceptual approach that explicitly links digital precision diagnostics with biological enhancement of the crop – rhizosphere system (Rezaee Danesh, 2025; Mashabela *et al*., 2025).

The key points of the MSCL:

- The nutrient status and spatial variability of the crop are sensed and diagnosed in real time using sensors (proximal crop sensors, electrochemical soil sensors, remote sensing) (Gorai *et al.*, 2021; Varma *et al*., 2021; Ram & Sun, 2025).
- Decision-support systems transform the sensor information into recommendations based on site-specific rate, timing, and placement (Sagar *et al.*, 2023; Gorai *et al*., 2021).
- Variable Rate Technology can supply mineral nutrients with accurate measurements (Getahun, 2024; Gorai *et al*., 2021).
- Biostimulants, such as seaweed extracts, protein hydrolysates, seaweed, PGPR, and AMF, increase plants' ability to capture and assimilate the supplied nutrients by upregulating high-affinity transporters (NRT2.1, PHT1); stimulate H^+-ATPase activity; expand root architecture; and change the rhizosphere microbiome (Basar *et al*., 2025; Cheng et al., 2024; Baltazar *et al*., 2021; Mashabela *et al*., 2025).
- The loop is closed with continuous sensing and microbial feedback to optimize progressively (Rezaee Danesh, 2025).

The aspect of MSCL that is different from the previous approaches:

Conventional Precision Agriculture / PNM is mostly dedicated to the mineral fertilizer "sense → decide → apply" process. Does not systematically incorporate biological enhancers that affect root physiology and microbial community function (Gorai *et al.*, 2021; Varma *et al.*, 2021).
Most commonly, standard INM includes mineral, organic, and biological nutrient sources, but there is no real-time digital feedback and variable rate delivery that matches the biological activation of the nutrients (Ali *et al.*, 2024; Paramesh *et al*., 2023).
MSCL purposely creates a closed loop where digital diagnostics are a one-for-you input of minerals, and biostimulants provide a one-for-you increase in the biological efficiency of mineral uptake. This double regulation is designed to enable some synthetic inputs to be used and simultaneously increase or preserve yield and soil health (Rezaee Danesh, 2025; Mashabela *et al*., 2025; Moradi & Sioosemardeh, 2025).
Additional engineered synthetic microbial consortia (SynComs) and smart nanobiosensors are also anticipated to be incorporated into the framework in the future to further close and automate the loop (Mashabela et *al*., 2025; Khoulati *et al*., 2025; Rezaee Danesh, 2025).

Component	Key Technologies / Agents	Primary Function
Sensing & Diagnostics	SPAD, GreenSeeker, NDVI, VNIR/MIR, LIBS, ISE/ISFET	Real-time detection of nutrient status & spatial variability
Decision Support	Nutrient Expert, Rice Crop Manager, ML models	Generate site-specific rate, timing & placement recommendations
Precision Delivery	VRT, GPS/GNSS spreaders, drip fertigation	Apply nutrients exactly where and when needed
Biological Enhancement	Humic acids, SWE, protein hydrolysates, PGPR, AMF	Upregulate transporters, expand roots, mobilize nutrients
Feedback & Optimization	Nanobiosensors, metagenomics, SynComs	Close the loop for continuous self-optimization

Table 3. Components of the proposed Microbe-Sensor Closed Loop (MSCL) framework

6 Plant Biostimulants

A plant biostimulant induces natural plant nutrition processes apart from its nutrients (Baltazar *et al.* 2021; Mashabela *et al.* 2025; Li *et al.* 2022). This means that the inclusion of biostimulants is a move in the direction of a metamorphosis in agriculture from a purely input-based approach towards the coordinated regulation of biological processes (Mashabela *et al.*, 2025; Khoulati *et al.*, 2025). Biostimulants are not just nutrients; they induce an upregulation of physiological metabolic pathways, root system development, enhancement of membrane permeability, and encourage beneficial plant-microbe interactions (Baltazar *et al.*, 2021; Cheng *et al.*, 2024; Basar *et al.*, 2025). This biological activation synchronously optimizes the plant's ability to absorb nutrients with the application of variable-rate fertilizer, maximizing nutrient recovery and minimizing undesirable environmental losses (Rezaee Danesh, 2025; Gorai *et al.*, 2021).

6.1 Classification and Mechanisms of Plant Biostimulants

According to EU Regulation 2019/1009, plant biostimulants are characterized according to their functional capacity to stimulate plant nutrition without the addition of nutrients, and therefore contribute to the improvement of nutrient-use efficiency, abiotic stress tolerance, crop quality, and availability of confined nutrients in the soil-plant system (Baltazar *et al.*, 2021; Li *et al.*, 2022; Mashabela *et al.*, 2025).

6.2 Generational Classifications of Biostimulants

Biostimulants could be classified based on their generations. The technology development of biostimulants can be divided into four generations (Mashabela *et al.*, 2025), as shown in Table 4:

1. **Biostimulants 1.0 (Empirical Natural Extracts):** Crude extracts derived from observations with minimal molecular or mechanistic understanding of the benefits (Mashabela *et al.*, 2025).
2. **Biostimulants 2.0 (Standardized Formulations):** Standardized extracts with known and scientifically proven physiological and stress-alleviation effects containing identified active compounds (Mashabela *et al.*, 2025; Baltazar *et al.*, 2021).
3. **Biostimulants 3.0 (Precision Bioengineering):** Formulated microbial inoculants and molecularly mapped formulations (Mashabela *et al.*, 2025).
4. **Biostimulants 4.0 (Digitally Integrated Smart Systems):** Genomics-guided, multi-modal formulations in direct interaction with digital agriculture platforms, smart delivery systems (nanotechnology), and predictive machine learning models (Mashabela *et al.*, 2025; Khoulati *et al.*, 2025).

Generation	Description	Key Characteristics
1.0	Empirical Natural Extracts	Crude extracts; observational benefits; limited mechanistic understanding
2.0	Standardized Formulations	Identified active compounds; verified physiological benefits
3.0	Precision Bioengineering	Engineered microbial inoculants; molecularly mapped formulations
4.0	Digitally Integrated Smart Systems	Genomics-guided; nano-delivery; ML/AI integration with digital platforms

Table 4. Generational evolution of plant biostimulants (Mashabela et al., 2025)

6.3 Major Categories and Molecular Modes of Action.

Biostimulants can be divided into microbial and non-microbial (Ali *et al.*, 2024; Baltazar *et al.*, 2021; Basar *et al.*, 2025), Table 5:

- **Humic Substances (Humic and Fulvic Acids):** These are dark-colored polyelectrolytic macromolecules that stimulate the activity of the plasma membrane H^+-ATPase, thereby supporting the growth of roots and lateral root hair density (Baltazar *et al.*, 2021; Basar *et al.*, 2025; Cheng *et al.*, 2024).
- **Seaweed Extracts (SWE).** Derived from macroscopic marine brown algae, such as Ascophyllum nodosum, Ecklonia maxima, and Kappaphycus alvarezii. Structural polysaccharides, betaines, polyphenols, and phytohormones are complex compounds found in SWEs (Baltazar *et al.*, 2021; Basar *et al.*, 2025).
- **Protein Hydrolysates and Amino Acids:** Peptides and free amino acids, which are released by the method of protein digestion of by-products from plants or animals (Baltazar *et al.*, 2021; Li *et al.*, 2022).
- **Beneficial Microorganisms (PGPR, AMF, Beneficial Fungi):** Bacillus spp., Pseudomonas spp., Azospirillum spp., arbuscular mycorrhizal fungi (AMF), and Trichoderma spp. (Ali *et al.*, 2024; Cheng *et al.*, 2024; Rezaee Danesh, 2025).

Category	Examples	Main Modes of Action
Humic Substances	Humic & Fulvic acids	Stimulate H^+-ATPase; promote root hair density; complex micronutrients
Seaweed Extracts	A. nodosum, E. maxima	Betaines, polysaccharides, phytohormones; stress tolerance & photosynthesis
Protein Hydrolysates	Plant/animal-derived peptides & amino acids	Signaling molecules; N metabolism; ROS scavenging
Beneficial Microbes	Bacillus, Pseudomonas, AMF, Trichoderma	N-fixation, P-solubilization, phytohormone production, ISR

Table 5. Major categories of biostimulants and their primary modes of action

7. Nutrient Use Efficiency and Interactions between Nutrients and Biostimulants

Improving Nutrient-Use Efficiency (NUE) is a fundamental challenge in sustainable agronomy (Varma *et al.*, 2021; Basar *et al.*, 2025). The effects of biostimulants on mineral nutrition can be observed at the molecular level through their direct action on the mineral nutrition system, which includes changing the structure of the root system, activation of nutrient transport pathways, and regulation of the stoichiometry of rhizosphere microbial communities (Baltazar *et al.*, 2021; Cheng *et al.*, 2024; Basar *et al.*, 2025).

7.1 Genetic Up-Regulation of Transporter Genes

Non-microbial biostimulants and microbial inoculants, when applied to the foliar or root tissue, upregulate the expression of genes involved in the uptake of nutrients by the roots of plants (Baltazar *et al.*, 2021; Mashabela *et al.*, 2025; Cheng *et al.*, 2024). It has been confirmed for important gene families, namely NRTs (Nitrate Transporters) like the high-affinity nitrate transporter NRT2.1 and PTs (Phosphate Transporters) like the PHT1 family (Mashabela *et al.*, 2025; Baltazar *et al.*, 2021).

7.2 Root Architecture and Nutrient Foraging

Biostimulants have been shown to induce changes in the morphology of the root system, increasing root length, number of main roots, and dry matter content in the root, Figure 2; (Johnson *et al.*, 2024; Cheng *et al.*, 2024; Baltazar *et al.*, 2021). As immobile soil nutrients such as phosphorus (P) and zinc (Zn) are captured during this architectural expansion, it becomes essential to maintain soil health (Rezaee Danesh, 2025; Ali *et al.*, 2024).

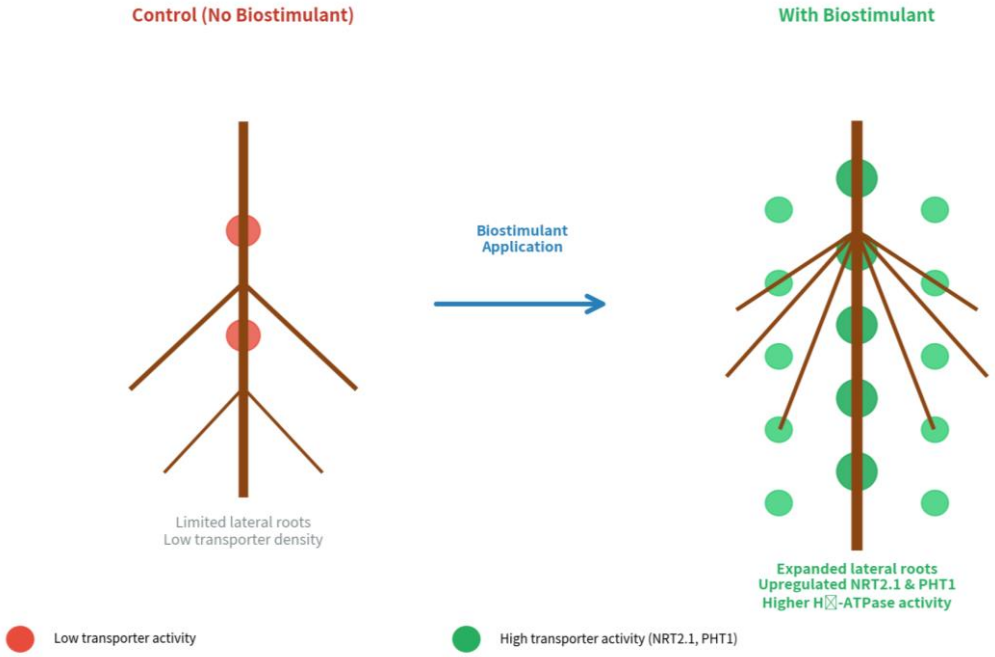


Fig 2. Biostimulant Effect on Nutrient Transporters and Root Architecture

7.3 Conflict of Evidence: High Mineral Nitrogen Rates and Feedback Suppression

The scientific literature often presents a big dichotomy around the effectiveness of microbial symbiotic N-fixing and P-solubilizing biostimulants with various mineral fertilizer application rates:

- Under Low Nutrient/Deficient Regimes, microbial biostimulants can effectively colonize the rhizosphere, which results in a significant increase in plant growth, nutrient uptake, and shoot biomass (Cheng *et al.*, 2024; Basar *et al.*, 2025; Wadduwage *et al.*, 2024).
- In High Mineral Nitrogen Regimes (intensive synthetic nitrogen application rate), the effects of symbiotic N-fixing and P-solubilizing microbial biostimulants were found to be statistically insignificant on grain yield or N recovery efficiency (NRE) (Gajula *et al.*, 2025; Wadduwage *et al.*, 2024). Biostimulant application was not effective under high N input and can suppress the plant's root exudation, depriving introduced microbes of carbon substrates, and can reduce soil microbial biomass carbon ($C_{mi}c$) and basal respiration (Gajula *et al.*, 2025; Wadduwage *et al.*, 2024).

Condition	Observed Effect	Key References
Low / Deficient N or P	Successful colonization; increased growth, uptake & biomass	Cheng *et al.*, 2024; Basar *et al.*, 2025; Wadduwage *et al.*, 2024
High Mineral N Rates	Zero or negative impact on yield & N recovery; suppressed root exudation	Gajula *et al.*, 2025; Wadduwage *et al.*, 2024

Table 6. Summary of evidence conflict regarding microbial biostimulant efficacy under different N regimes

8. The Integration of Site-specific Nutrient (SSNM) and Biostimulants

There is a need to spatially and temporally synchronize precision diagnostic technology with biological biostimulant delivery to transition to sustainable intensification (Rezaee Danesh, 2025; Mashabela *et al.*, 2025).

8.1 Temporal and Spatial Synchronization.

Spatial-temporal nutrient deficiencies and early plant stress are detected by precision sensing technologies, and therefore, variable rate applications (VRA) can be achieved with a high degree of precision (Gorai *et al.*, 2021; Getahun, 2024; Rezaee Danesh, 2025):

- **Starter and Seed Priming:** Microbial inoculants (PGPR/AMF) and humic drenching have been applied during sowing or transplanting to ensure good early root establishment and early-season nutrient solubilization (Cheng *et al.*, 2024; Rezaee Danesh, 2025).
- **Foliar Corrective Applications:** Foliar sprays of seaweed extracts, fulvic acid, potassium silicate, amino acids, etc., are given when the canopy sensors detect early N stress or water stress at critical vegetative growth stages (Rajput *et al.*, 2024; Moradi & Sioosemardeh, 2025).

8.2 Field-Scale Viability of Synthetic Input Substitution

The use of both biological and precision inputs has been shown to be effective in breaking yield-penalty barriers in field evaluations (Moradi & Sioosemardeh, 2025; Rajput *et al.*, 2024).

From Table 6, in rainfed wheat, yield parity was obtained by replacing 25% of the chemical fertilizers with Biofertilizers and foliar fertilizers with seaweed extracts and amino acids (Moradi & Sioosemardeh, 2025). Humic acid + nanoparticles of phosphorus increased the dry matter content of red cabbage roots by up to 32.2% (Johnson *et al.*, 2024). The Custom Rice Crop Manager recommendations led to a 13.17% increase in yield of rice systems (Sagar *et al.*, 2023). Consistent with these findings, deficit irrigation in combination with soil biological amendments resulted in higher flag-leaf N, P, Zn, and water use efficiency when foliar biostimulants were applied (Rajput *et al.*, 2024). Selective enrichment of beneficial genera (Sphingomonas, Ensifer, Sinorhizobium) following root flushing with a humic-acid-rich biostimulant (Cheng e*t al.*, 2024).

Finding	Crop / Condition	Reference
25% synthetic fertilizer replacement-maintained yield	Rainfed wheat under water stress	Moradi & Sioosemardeh, 2025
Improved flag-leaf N, P, Zn & WUE	Semi-arid wheat under deficit irrigation	Rajput *et al.*, 2024
Root dry matter up to 32.2%	Red cabbage + humic acid + P nanoparticles	Johnson *et al.*, 2024
Enrichment of beneficial genera (Sphingomonas, Ensifer)	Tomato rhizosphere (root flushing)	Cheng *et al.*, 2024

Table 7. Key field evidence supporting integration benefits

9. Impact on Crop Growth, Yield and Quality

Precision technology and biostimulants are systematically used to improve morphological growth, photosynthetic efficiency, yield, and quality of the crop (Ali *et al.*, 2024; Baltazar *et al.*, 2021; Johnson *et al.*, 2024).

9.1 Morphological and Photosynthetic Attributes

- **Root Development:** In red cabbage, the use of a humic-acid-based biostimulant containing phosphorus nanoparticles (PNP) had a marked effect on the growth of root length and lateral root development (Johnson *et al.*, 2024).
- **Yield and Water-Use Efficiency:** Under water-limited conditions, the synergistic effect of soil biological amendments and foliar biostimulants resulted in high nutrient uptake and maximum yield and water-use efficiency in wheat crops grown in semi-arid conditions (Rajput *et al.*, 2024).
- **Photochemical Yield:** Maize optimized photochemical parameters and grain yield by precision drip irrigation and foliar biostimulants and micronutrients.

9.2 The Quality of Crops and Biofortifications.

The use of biostimulants in crop nutrition strategies modifies the secondary metabolism of plants and thus contributes to the improvement of harvest quality (Baltazar *et al.*, 2021; Basar *et al.*, 2025). Seaweed extracts applied through foliar treatment to sweet cherry and grapevine not only increased the soluble solids, polyphenols, and vitamin C content of the fruits but also decreased the cracking of fruits (Baltazar *et al.*, 2021).

10. Impact on Soil Health and Soil-Plant-Microbiome Interactions

The practice of Integrated Nutrient Management (INM) improves both the physical, chemical, and biological characteristics of soils (Paramesh *et al.*, 2023; Topa *et al.*, 2025; Cheng *et al.*, 2024).

10.1 Soil Physical and Chemical Rehabilitation.

Soil Physical and Chemical rehabilitation methods. The increase in intensive chemical fertilization leads to soil compaction, soil acidification, and loss of organic carbon (Paramesh *et al.*, 2023; Topa *et al.*, 2025). On the other hand, long-term planting of INM has a positive effect on soil aggregation, decreases the bulk density, increases the total porosity, and enhances the water-holding capacity (Paramesh *et al.*, 2023).

10.2 Rhizosphere Microbiome Structural Reprogramming

The tomato rhizosphere soil showed significant taxonomic changes, with beneficial genera of nitrogen-fixing and phosphorus-solubilizing bacteria being selectively increased by humic-acid-rich biostimulants like Sphingomonas, Ensifer, and Sinorhizobium (Cheng *et al.*, 2024). The effects were significantly better with soil flushing than foliar spraying, as done by Cheng *et al.* (2024).

10.3 Conflict of Evidence: Inorganic Fertilizer-induced Dysbiosis.

However, when biostimulants are used along with full rates of synthetic inorganic fertilizers, the biological benefit is lost and can also have a detrimental effect on soil microbial biomass carbon ($C_{mi}c$) and basal soil respiration (Wadduwage *et al.*, 2024).

11. Environmental and Economic Sustainability

11.1 Global Mitigation of Greenhouse Gas Emissions and Pollution

Site-specific nutrient management in the rice-wheat system has been found to reduce greenhouse gas emissions (GHG) while increasing yields and farm income (Paramesh *et al*., 2023; Topa *et al*., 2025). Applying organic manure and retaining the residue through an integrated nutrient management system leads to significant methane reduction (Paramesh *et al.*, 2023). The application of stabilized nitrogen fertilizers along with staged precision applications based on sensors reduces gaseous losses of ammonia and nitrous oxide (Varma *et al.*, 2021; Gorai *et al.*, 2021). Precise percentage reductions in greenhouse gas reduction and pollution mitigation across the full set of 42 papers are not aggregated

11.2 Market Potential and Barriers To Smallholder Adoption

Meta-analysis evidence suggests that site-specific nutrient management with biostimulants can improve farmers' net income by increasing crop returns, reducing production costs, or both (Rajput *et al.*, 2024). Mobile decision support applications for farmers are cost-effective, which can help reduce capital costs and make access to digital infrastructure a more democratizing factor for smallholder farmers (Rezaee Danesh, 2025; Gorai *et al.*, 2021). The comparative performance of conventional and integrated systems on key sustainability indicators such as NUE, yield stability, GHG reduction, etc., has been shown in Figure 3.

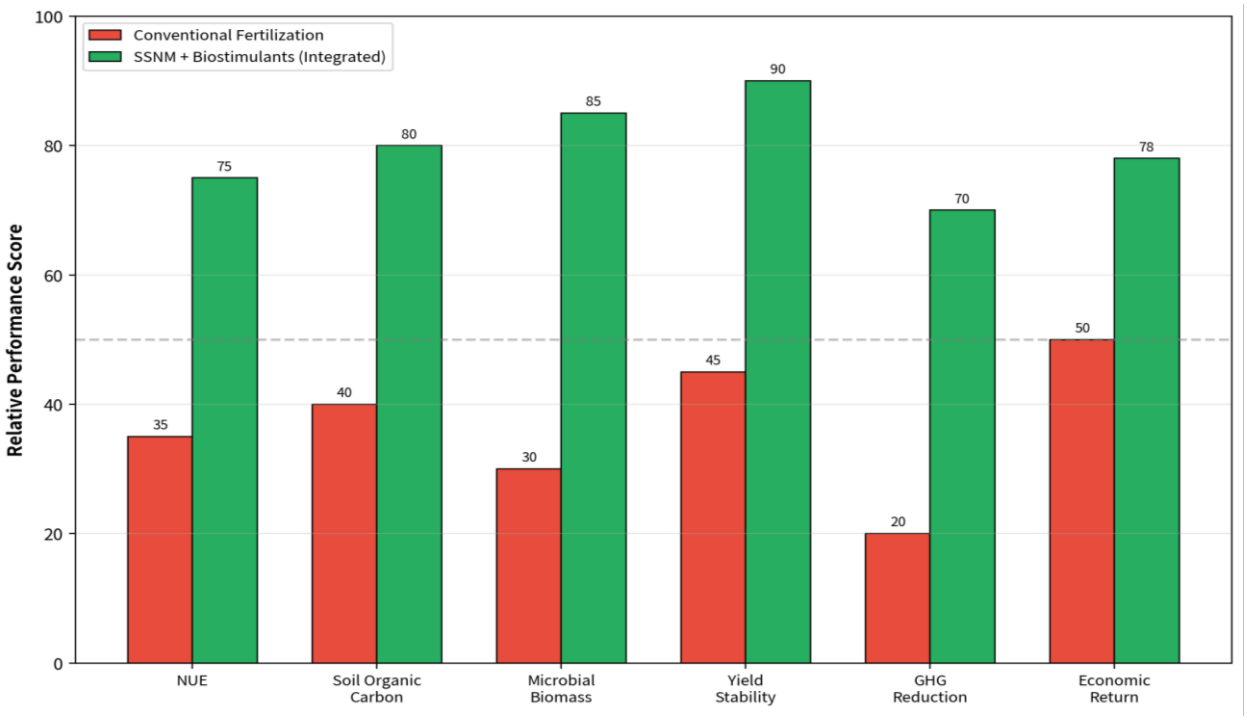


Fig. 3 Comparative Performance of Conventional VS Integrated Systems on Key Sustainability Indicators

11.3. Challenges and Limitations

Significant challenges hinder scaling these approaches to the field level, including spatial and temporal field variability along with inconsistent inoculant persistence, regulatory and standardization gaps in the biostimulant sector, input antagonism in which high rates of chemical fertilizers reduce microbial biostimulant activity, and deficits in technical skills together with data interoperability problems.

12. Conclusions

Sustainable modern crop production requires a shift from high-input chemical practices to integrated precision-biological management systems that combine site-specific nutrient management with plant biostimulants to enhance yield, quality, and long-term soil health. Sensors, decision-support systems, and variable-rate technology optimize fertilizer use according to spatial-temporal crop needs, while beneficial microbes and other biostimulants improve root nutrient uptake, expand foraging capacity, and reshape the rhizosphere microbiome for better nutrient mobilization. However, high synthetic nitrogen rates can create antagonistic effects and rhizosphere dysbiosis that reduce microbial viability, and adoption remains limited by technology costs, unpredictable inoculant survival, and the absence of uniform global regulations. Progress will depend on testing effective microbial consortia, formulating nano-encapsulated controlled-release biostimulants, and integrating nanobiosensors with cloud-based AI analytics, ultimately enabling more sustainable, climate-smart agriculture that uses fewer resources while strengthening natural regulation.

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