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Vikas Sharma
Assistant Professor, Department of Biotechnology, Directorate of Research, S. K. Rajasthan Agricultural University, Bikaner, Rajasthan, India

Asha Kumari
PhD Research Scholar, Department of Biotechnology, Junagadh Agricultural University, Junagadh Gujarat, India

Ashok Kumar Meena
Assistant Professor, Department of GPB, S. K. N. Agriculture University, Jobner, Jaipur, Rajasthan, India

AK Sharma
Professor and Head, Department of GPB, ADR (Seeds), NSP, Groundnut In charge, S. K. Rajasthan Agricultural University, Bikaner, Rajasthan, India

Pooja Kumari Meena
PhD Research Scholar, Department of Agronomy, MPUAT Udaipur, Rajasthan, India

Anuradha Yadav
PhD Research Scholar, Department of Agronomy, Sri Karan Narendra Agriculture, University, Jobner, Jaipur, Rajasthan, India

Kalpana Gambhir
Research Scholar, Department of Pathology, Junagadh Agricultural University, Junagadh Gujarat, India

Corresponding Author:
Asha Kumari
PhD Research Scholar, Department of Biotechnology, Junagadh Agricultural University, Junagadh Gujarat, India

Advancing precision farming through microbial genomics and biotechnological tools: Innovations for improving crop productivity and soil health

Vikas Sharma, Asha Kumari, Ashok Kumar Meena, AK Sharma, Pooja Kumari Meena, Anuradha Yadav and Kalpana Gambhir

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Abstract
In agriculture sector application of precision farming implies to agricultural input based on soil types, climatic condition and crop need to maximize sustainable agriculture production with quality and profitability. Successful implementation of precision farming in agriculture depends on multiple components, including the extent to which conditions within a known field are managed, the acceptability of input recommendation amount and control to the degree of application microbial consortia. Among these, microbial genomics identified and biotechnological tools represent cutting-edge best strategies to sustainably enhance crop yield with soil health. This review explores recent advancing precision farming through microbial genomics, metagenomics, microbial resource management, and microbial-based biotechnological tools innovations for improving crop productivity and soil health. Emphasis is placed on how these innovations can contribute to site-specific management practices, integrates remote sensing technologies such as satellite and drones, to monitor crop conditions and captures early signs of diseases or pests infect. These tools enable people to intervene implement targeted sites treatments, lowering the need for large-scale bio-pesticides and minimizing crop losses, improve soil fertility, mitigate stresses, and promote ecological sustainability. Additionally, precision farming facilitates monitoring (real-time) of weather conditions, permitting farmers to adjust their irrigation schedules or implement protective measures in response to changing climatic conditions.

Keywords: Precision farming, microbial genomics, metagenomics, biotechnological tools, real-time monitoring

1. Introduction

Indian agriculture is well known for its multiple functions from facilitating environmental and food securities, employment and livelihood to nutritional (Patel *et al.*, 2020). In India, 182 million ha area out of the 328.7 million ha geographical area are more affected by soil degradation and erosion due to flooding, high wind velocity, water logging and chemical deterioration (Hussain *et al.*, 2021) [61]. On the one side, allowed of quantitative import eliminate restrictions in year 2001, made quality and cost competitiveness as two aspects to sustainable globalized stable market (Jambor *et al.*, 2016) [63]. Furthermore, in India food grain requirement is expected to be 480Mt up to 2050, with continuously increasing burden challenges and stresses faced by crops (Kumari *et al.*, 2020; Gupta *et al.*, 2022) [72, 149]. Opposite side, the higher input cost along with insufficient productivity will throw Indian farmers out of the economic competition. Once again, start of research on advanced technology improper time due to limited resources is one of the key issues of developing countries (Getahun *et al.*, 2024) [49]. In order to face burden and challenges, utilization of environment friendly and advanced technology involves their application and precision farming in agriculture to management of spatial and temporary variation (Karunathilake *et al.*, 2023) [66] combined with all prospectus of agricultural production point of view in order to improve their crop performance, optimizing returns on inputs, crop health, environmental quality enhancement and reducing environmental impacts (Maitra *et al.*, 2021; Sarkar *et al.* 2020) [82, 124], enhancing soil health and microbiome to activate soil microorganism (Dubey *et al.*, 2019; Shah *et al.*, 2022; Daunoras *et al.*, 2024) [37, 129, 33].

Precision farming in agriculture, facilitates a novel solution using an advanced approach for issues such as the need to balance productivity with respect to environmental issues (Mgendi *et al.*, 2024; Nath *et al.*, 2024; Fathi *et al.*, 2025) [88, 94, 44]. It is based on the implementation of advanced information technologies (Sishodia *et al.*, 2020; Fathi *et al.*, 2025) [44]. Precision farming is advanced agricultural technology that optimizes the profit by improving agricultural efficiency while protecting the environment with the eliminating of chemicals applied to the agricultural sectors (Finger *et al.*, 2019; Ahmad and Dar, 2020; Monteiro *et al.*, 2021; Yadav *et al.*, 2023; Farooqui *et al.*, 2024; Mansoor *et al.*, 2025) [45, 88, 91, 173, 44]. It can be defined as the management of inputs according to the needs of the specific sites of the fields with the application of variable rate application instead of conventional constant rate application (Finger *et al.*, 2019; Neupane *et al.*, 2019; Ahmad and Dar, 2020) [45, 99, 143]. Recent year the synergy both precision agricultural techniques and microbial-based inputs has become a main point of sustainable agriculture research and application (Sharma *et al.*, 2023; Zhang *et al.*, 2024) [134, 178].

At the center point of precision farming for sustainable agriculture is the integration of microbial biotechnology (Zaman, 2023; Singh *et al.*, 2024; Goyal *et al.*, 2023; Hayat *et al.*, 2025;) [177, 140, 51]. Plant growth-promoting microorganisms, such as rhizosphere microbes, passenger types endophytes and endophytes (Eid *et al.*, 2021; Lacava *et al.*, 2022;) [39, 74] are increasingly being identified as eco-friendly agent efficacy for inducing more nutrient uptake, promoting plant health, growth and boost immunity, mitigating abiotic impacts, and controlling phytopathogens (Sharma *et al.*, 2023) [134]. These bio-formulation-based solutions not only support precision tools but can be customized using data-driven system, making microbial formulation for application more efficient with specific purpose (Nayak *et al.*, 2024; Hajji-Hedfi *et al.*, 2025) [97, 55].

Now a days, advances in assessing soil- plant- microbiomes through next-generation sequencing (NGS) technology and metagenomic tools (Fadiji *et al.*, 2020; Seyma Gökdemir *et al.*, 2022; Navgire *et al.*, 2022; Nwachukwu *et al.*, 2022) [42, 127, 44, 102], providing an elaborated studying of microbial functions and activities under wide range of environmental conditions with agronomic traits (Ray *et al.*, 2020; Wu *et al.*, 2024) [141, 170]. These motives permitted the development of area-specific microbial- inoculants, precision-delivering (Arora *et al.*, 2024; Garg *et al.*, 2024; Argentel-Martínez *et al.*, 2025; Joshi *et al.*, 2025) [14, 48, 13, 64] through drones, smart sprayers, or variable rate technologies (VRT), which proper utilized microbial interventions with crop needs and environmental conditions (Parveen *et al.*, 2025; Sanooja *et al.*, 2025) [107, 121]. Moreover, decision support systems (DSS), real-time soil and plant monitoring enable acute delivery of bio formulation on predictive modelling of plant health, yield, growth and soil fertility (Mehedi *et al.*, 2024; Arevalo-Royo *et al.*, 2025) [86, 12]. This integration enhances and exposed the overall efficiency of bio formulations, resulting to improved agronomic performance with environmental sustainability (Raihan, 2024; Hayat *et al.*, 2025;) [112, 140]. Beneficial microorganisms mostly plant growth-promoting rhizobacteria, arbuscular mycorrhizal fungi, endophytes, and biocontrol agents play a crucial role in uptake nutrient availability, enhancing plant growth, yield and development, and increasing resistance to stresses (Verma *et al.*, 2019; El-Saadony *et al.*, 2022; Bhupenchandra *et al.*, 2024; [162, 41, 26] When applied within the area of precision agriculture, bio inoculants can be temporally utilized, increasing efficacy and reducing input wastage (Casa and Ronga, 2020; Anand *et al.*, 2023; Sharma *et al.*, 2023) [29, 11, 134].

The applications of precision farming are more diverse and encompass different aspects of agricultural management practices (Shafi *et al.*, 2019; Shaheb *et al.*, 2022; Karunathilake *et al.*, 2023; Adewusi *et al.*, 2024) [128, 130, 66, 5]. One of the key factors is site-specific management strategy, where farmers can search and identify diversification in soil types and apply bio-fertilizers or irrigation supply accordingly (Singh *et al.*, 2020; Bedadi *et al.*, 2023; Galal *et al.*, 2024;) [140, 23, 46]. This targeted site-specific approach not only improves, increase crop growth and yield but also minimizes environmental losses by eliminating the use of chemical inputs (Tripathi *et al.*, 2015; Ahmad *et al.*, 2018; Singh *et al.*, 2019; Harish *et al.*, 2022) [157, 7, 137, 57]. Another way soil-plant-microbial application is precision farming, which involves optimizing seed placement and spacing to maximize yield potential (Ma *et al.*, 2019; Sharma *et al.*, 2023; Mgendi *et al.*, 2024; Wasay *et al.*, 2025) [171, 134, 88]. By involving component such as soil moisture and sufficient nutrient availability, farmers can ensure optimal seed germination and growth (Balyan *et al.*, 2024) [20].

Precision farming also integrates remote sensing technologies, act as form of satellite imagery and drones, to monitor crop health condition and detect earlier symptoms of attack diseases or pests (Sishodia *et al.*, 2022; Sabir *et al.*, 2024; Surendran *et al.*, 2024; Wang *et al.*, 2024; Aziz *et al.*, 2025) [141, 119, 150, 172, 17]. These tools enable farmers to intervene promptly and implement targeted bio-formulation treatments, reducing the excessive application of pesticides and minimizing crop losses (Vinod *et al.*, 2022; Nayak *et al.*, 2024; Singh *et al.*, 2025) [163, 197]. Additionally, in smart agriculture, precision farming facilitates real-time monitoring of weather, environmental and climatic conditions, allowing farmers to manage their irrigation schedules or application protective measures in response to modulating climatic conditions (Srinivasan *et al.*, 2018; Bwambale *et al.*, 2022; Xing *et al.*, 2024; Soussi *et al.*, 2024; Aarif *et al.*, 2025) [145, 28, 175, 142, 1].

It goals at enhanced or more profit of economic returns, as well as at minimizing the energy input cost with the environmental effect on agriculture. This farming method leads not only to the saving of natural resources and energy, but also to the control to jeopardize the environment. Though largely adopted in developed countries, the adoption of precision farming in India is yet to take a small level ground primarily due to its unique pattern of land holdings, poor infrastructure, lack of farmers awareness and inclination to take risk, socio-economic and demographic conditions. Thus, precision agriculture is effectively being concluded as a biointensive digital farming platform, wherein microorganisms work as biological tools of precision, enabling proper utilization of resource, climate resilience, and productivity enhancement in a sustainable order. This review main goals on the scientific manner advancements in microbial applications within precision farming system and exposes how these integrate practices can identified the future of sustainable agriculture.

2. Concept of Precision Farming

Precision farming is based on information and technology in agricultural management system to identify, analyze and manage soil-site (Finger *et al*. 2019; Neupane *et al*. 2019; Ahmad and Dar, 2020; Šarauskis*et al*. 2022) [45, 99, 8], spatial and temporal variability within fields to obtained optimum benefit, sustainable and protect environment against stress (Bwambale *et al*. 2022; Soussi *et al*. 2024; Xing *et al*. 2024; Aarif *et al*. 2025) [287, 142, 1]. In another way can be defined as the utilization of principles and technologies to manage spatial and temporal variability combined with all aspects in term of agricultural production specially improving crop yield and quality, and ecosystem (Hakkim *et al*. 2016; Finger *et al*. 2019; Ahmad and Dar, 2020; Sarkar *et al*. 2020; Maitra *et al*. 2021; Belal *et al* 2021) [56, 8, 124, 82]. Precision farming is the only best solution for identifying to causes of variability factor within the field and carefully tailor soil health and crop management to fit in all cultivated field (Belal *et al*. 2021; Pandey *et al*. 2021; Shaikh *et al*. 2022) [[25, 106, 131]. Aarif *et al*. (2025) [1] stated that precision farming is concerned with the proper management and solution of causes variability factor in term of space and time. It is an outgrowth of technological developments and the future of it rests on the reliability, reproducibility and understanding of these technologies.

Precision farming is general way an information and technology-based farm management system to identify, analyze and manage variability within fields for protection of the land resources (Shafi *et al*. 2019; Adewusi *et al*. 2024; Junior *et al*. 2024) [28, 5, 66]. In this mode of farming can be used new information technologies to make better decisions about many aspects of crop production (Shaheb *et al*. 2022; Karunathilake *et al*. 2023) [130, 66]. Precision farming is looking at the higher efficiencies that can be realized by understanding and dealing with the natural variation found within a field (Soussi *et al*. 2024; Aarif *et al*. 2025) [142, 1] that goal is not to obtain the same yield everywhere, but rather to manage and distribute inputs on a site-specific basis to maximize long term cost/benefit (Neupane *et al*. 2019; Yadav *et al*. 2023; Bedadi *et al*. 2024;) [99, 173, 28]. Applying the similar inputs across the entire field can't be suitable for longer time be the best choice. Precision farming is directly involved with site-specific management (SSM) system. It is the view of working the right thing, place and time (Singh *et al*. 2020; Galal *et al*. 2024) [140, 46]. This idea is an old as agriculture, but today's development of mechanization of agriculture in the 20th century there was more economic pressure to neglect large fields with uniform agronomic management practices. Precision farming facilitates a way to automate SSM applying information technology, thereby implementing SSM practical in commercial agriculture (Singh *et al*. 2020) [140].

In summary, the basic concept of precision farming is to maximum utilization of input resources as measured by outputs, which is to optimize inputs accord with field variability in order obtained to maximize yields, lowering production costs and environmental effect on agricultural management practices, by giving the low input at the right place and time.

3. Principles of Precision Farming

Over all the earth is identical and variation may be seen in any of the soil/crop/ weather/climatic factors (Webber *et al*. 2022) [168]. Variation is found in all over agricultural fields and variability in soil productivity and fertility, moisture content, soil texture, soil organic matter topography, pest population, pathogen intensity, weed density (Kitchen and Clay, 2018; Beaudoin *et al*. 2023; Omer *et al*. 2024) [69, 22, 103].

There are three basic principles of precision farming which are as follows:

3.1 Understanding the variability

Several years of yield data from the same field usually have both spatial type and temporal variability (Karunathilake *et al*. 2023) [66]. Often it is a difficult to explain components like soil conditions, climatic factors and management (Osman, 2018; Beaudoin *et al*. 2023) [104, 22]. Hence, the art of precision farming lies in the basic principle of looking the variability both in terms of time and space (Singh *et al*. 2020; Galal *et al*. 2024) [140, 46].

3.2 Assessing or measuring the variability

In precision farming, variability in time also plays an important role. The recommended dose of nutrient of current season may not be needed during the next season. Hence, for taking various management strategy decisions (Shafi *et al*. 2019; Adewusi *et al*. 2024) [28, 5], one should evaluate in season nutrient deficiencies with the help of next generation technologies (Fadiji *et al*. 2020; Nwachukwu *et al*. 2022; Navgire *et al*. 2022; Seyma Gökdemir *et al*. 2022) [42, 102, 95, 44]. Hence, second principle of this farming is kept timely record of data and analysis of the variant information of soil, crop and environment by using the relevant information technologies like remote sensing, global positioning systems. and yield monitors (Finger *et al*. 2019; Yadav *et al*. 2023; Ahmad and Dar, 2020; Mansoor *et al*. 2025; Monteiro *et al*. 2021; Farooqui *et al*. 2024) [45, 173, 124, 85, 91, 43].

3.3 Managing the variability

The third important principle align with precision farming is managing the variability with the site-specific agronomic recommendations (Singh *et al*. 2020;) [140]. After rapidly identifying and analyzing the variability within the fields, each field is to be divided into proper management areas such as high yield, low yield, high fertility, low fertility, acidic and ill drained (Maitra *et al*. 2021; Sarkar *et al*. 2020) [82, 124]. Then, according to the basic circumstances of a field, management decisions for seed sowing, nutrient management practices, plant protection measures against phytopathogen are to be taken up (Sharma *et al*. 2023) [134].

The properties, which have declared influence on crop growth and yield, do very significantly both time and space (Galal *et al*. 2024) [23]. The farmers should have the ability to locate the patches where growth and yield variability occur. Hence, in identifying the reasons for variability in crop growth, hyper spectral imagery or airborne digital photography is to be taken at periodical intervals (Xing *et al*. 2024) [175]. Such type of technology tells the real cause of variations such as nutrient deficiencies in soil and plant system, biotic stresses (disease patches) and abiotic stresses (moisture type stress) (Soussi *et al*. 2024; Aarif *et al*. 2025) [142, 1].

4. Need of Precision Farming

The popularity of precision farming in developed countries results in maximization of agricultural productivity with application of different technologies like satellite using technologies and geographical information systems (Cheema *et al*. 2023; Nowak, 2021) [31, 101]. The application of precision farming in agriculture through microbial inoculation like bio- herbicides, bio- fertilizers and bio-pesticides proves economically (Sarbani *et al*. 2020; Sharma *et al*. 2020) [123, 148], and environmentally with optimization use of water, other than farm implement (Sharma *et al*. 2023; Meta *et al*. 2025) [134, 87]. Therefore, Farmers straight away from timely requirement and reliable information source regarding supply of basic inputs obtained for sustainable agricultural production and the challenges led by the changing environmental condition faced, and developments technology not only useful, but also necessary to keep competitive (El Bilali *et al*. 2018; Khan *et al*. 2021) [40, 68].

Farmers need sufficient knowledge and acute information about advanced precision farming practices, market establishment, and novel policy forming with respect to agriculture biotechnology (Barnes *et al*. 2019; Rusmayadi *et al*. 2023) [21, 118]. It also needs explore to pre warning systems to negligible effect of the risk of losses, prevent of spread of phytopathogens due to unfavorable weather climatic conditions (Roberts *et al*. 2021; Ukhurebor *et al*. 2022; Delfani *et al*. 2024) [117, 159, 34].

5. Objectives of Precision Farming

In terms of objective precision farming provides the ability to automate, simplify and data analysis of information (Morais *et al*. 2019; Raj *et al*. 2022; Mohyuddin *et al*. 2024) [92, 113, 90]. After looking the variability precision farming permitted management results and implemented in a time and places on small point within larger fields, ultimately results increased production per ha and efficiency per unit of input (Loures *et al*. 2020; Mizik, 2023) [80, 87]. After looking the land information, goes to improve every aspect of land uses for the higher productivity (Larsson *et al*. 2023) [77]. This is not to say that there is no actual risk or potential environmental affect; however, the losses of environmental damage are reduced (Wallimann-Helmer, 2015) [164].

6. Components of Precision Farming

Precision farming based on the mainly three fundamental components first data base, second technology and third management practices (Morais *et al*. 2019; Saiz-Rubio *et al*. 2020; Arif *et al*. 2025) [92, 120, 1]. Data base precision farming offers, spatially or temporally fields variability, soil properties, crop attributes, weed and insect-pest population, and harvest data are important to be developed to realize the potential agriculture growth (Reddy *et al* 2017; Rajabpour *et al*. 2024; Aziz *et al*. 2025) [116, 114, 17]. Technology precision farming offers recent information and space technologies for monitoring images crop yields and sensing soil variables are novel tools supports to make success (Shaheb *et al*. 2022; Getahun *et al*. 2024) [130, 49]. When detecting and evaluating soil and crop condition, satellite-based information technology like personal computer, Global Positioning System and Geographic Information System (Mani *et al*. 2021; Trivedi *et al*. 2022) [84, 158]. Remote sensing techniques can also be optimized to detect soil related variables, pest, insect and disease incidence, and abiotic stress (Abd El-Ghany *et al*. 2020; Dhaliwal *et al*. 2024; Zhang *et al*. 2024) [2, 35, 178]. The basic overview of precision farming is not only to detect the field variability, but also able to use various inputs seed sowing to bio formulation application at differing rates almost simultaneously in real time in order to requirements (Khan *et al*. 2021; Behl *et al*. 2024) [68, 24]. Variable rate application machinery could be used to manage, field application of inputs like seed, bio-pesticides, bio-fertilizers and bio-agents at the exact place in the field at the optimum amount, at the exact time and for the right reasons (Šarauskis *et al*. 2022; Ibáñez *et al*. 2023) [122, 62]. Third component of precision farming management, makes planning both easier and complex way. The ability to integrate the information and the existing technology into a comprehensive and operational system (Wolfert *et al*. 2017; Aarif *et al*. 2025) [169, 1]. A farmer compulsory adopts a new level of management system implicit in the field. This is an increased level of the knowledge regarding to application and other aspects of the Precision farming such as RS, GIS and GPS, through advanced biotechnologies approaches (Toromade and Chiekezie *et al*. 2024) [156].

7. Methodology of Precision Farming in Agriculture

Precision farming is acting as mainly two methodologies for implementing agriculture or field. Each method has unique benefits and can even be used in a complementary and combined fashion (Table1) (Vecchio *et al*. 2022; Kaur *et al*. 2024) [161, 98].

Table 1: Major differences between Map based and Sensor based Precision agriculture systems:

S. No.	Parameter	Map Based	Sensor Based
1.	Methodology	In map-based system need Grid Sampling - lab studies - location specific maps and use of variable rate applicator	Real time sensors - Feedback control measures and use of variable rate applicator
2.	GPS or DGPS	More required	Not need
3.	Laboratory analyses in Plant and Soil	Need	Not requirement
4.	Mapping system	Necessary	May not necessary
5.	Time requirement	High	As comparatively less
6.	Limitations criteria	Cost of soil testing high and analyses limits restrict	Lack of sensors for monitoring crop and soil information
7.	Operation technique	Very difficult	As compare to easy
8.	Sampling need	Average 2.5 acres	Individual site
9.	Relevance popularity	Developing countries	Developed countries

8. Microbial genomics: unlocking the agricultural microbiome

Next-generation sequencing and metagenomics, high-throughput genomic tools have revolutionized our clear understanding about soil and plant microbiomes (Lahlali *et al*. 2021; Abdi *et al*. 2024; bin Radzali *et al*. 2025) [75, 3, 27]. Microbial community provides information of microbial diversity, multiple functional potential, and interactions with crops environments (Nizamani *et al*. 2024; Xiao *et al*. 2023) [100, 171]. The concept of the agricultural microbiome, encompassing soil, rhizosphere, phyllosphere, and endophytic microorganisms, has emerged as a critical component influencing crop productivity, health, and agroecosystem (Pattnaik *et al*. 2020; Suman *et al*. 2022) [110, 149].

8.1 Advances in Microbial Genomics for Agriculture

Traditional culture-dependent technologies have only a limited view of microbial diversity, very low nearly 1% of soil microbial species (Su *et al*. 2012) [147]. In contrast, modern genomic technologies offer comprehensive study, culture-independent strategy into the structure and function of microbial communities (Sharma *et al*. 2014; Garg *et al*. 2024; Clagnan *et al*. 2024) [132, 48, 32]. Key technological advancements include-Amplicon-based Sequencing is a targeted sequencing of marker genes for examples 16S rRNA for prokaryotes like bacteria or ITS regions for eukaryotes like fungi, enables identification and characterization taxonomic traits associated with plant-microbial communities (Kundel *et al*. 2020) [73]. Shotgun metagenomics provides facilities in-depth insights into the whole genetic relationship of the soil or plant-associated microbiome, allowing simultaneously explore of microbial taxonomic diversity and functional potential (Rajguru *et al*. 2024; Yousuf *et al*. 2025) [115, 176]. Meta-transcriptomics and Metaproteomic are revealing active gene expression profiles and protein functions within microbial communities, providing information about functional a clear understanding of microbe-microbe relationship and plant-microbe interactions (Srikanth *et al*. 2025; Yadav *et al*. 2025) [144, 174]. Genome-resolved metagenomics reconstruction of high-quality metagenome-assembled genomes (MAGs) from environmental samples offers strain-specific resolution, facilitating the novel discovery of beneficial microbes with various functional traits important for precision agriculture (Cerk *et al*. 2024; Pinto *et al*. 2024) [30, 111].

8.2 The Agricultural Microbiome and Its Role in Precision Farming

The agricultural microbiome, particularly the rhizosphere and endophytic microbiota, plays an important role in enhancing plant growth, health, nutrient uptake, resistance against stresses biotic as well as abiotic (Anand *et al*. 2024; Ullah *et al*.2025) [11, 160]. Understanding these microbial communities through genomic high throughput strategies contributes significantly to precision farming by deciphering microbial diversity identification of beneficial microbial taxonomy mostly PGPR directly involved in nitrogen-fixation, inorganic phosphate-solubilization, and antagonistic activities against to phytopathogens (Timofeeva *et al* 2023; Rajguru *et al*. 2024; Tariq *et al*. 2025) [155, 115, 151]. In functional potential assessment genomic data reveal the presence of genes involved in plant growth promotion activities like nitrogen fixation, phosphorus solubilization and production of phytohormones e.g., IAA, gibberellins, siderophore production, and antimicrobial compound biosynthesis (dos Reis *et al*. 2024; Argentel-Martínez *et al*. 2025) [36, 13]. Microbiome-plant interactions are identified microbial genomics elucidates how plant genotypes, soil types, and agricultural practices influence microbial community structure and functionality, enabling the design of crop- location-specific microbial management practices (Liu *et al*. 2022) [78].

8.3 Recent Insights from Microbial Genomics in Agriculture

Emerging research exposes several significant studies demonstrating application of microbial genomics in precision farming for soil fertility and microbial indicators. Microbial genomic studies have identified their taxonomy that serve as bioindicators (Semenov *et al*. 2025) [125] of soil health and fertility, members of genera Actinobacteria, Proteobacteria, and Firmicutes, which are mainly associated with various nutrient cycling and disease suppression soil-plant-pathogen (Lalande, 2022) [76]. Microbiome engineering potential are helpful for metagenomic studied guide the formation of synthetic microbial consortia or targeted bioinoculants to improve crop attributes performance under various environment (Adeniji *et al*. 2025; Tariq *et al*. 2025) [4, 151]. Crop-specific microbiome utilize under high-throughput sequencing has demonstrated that crop specific beneficial microbes from the soil microbiome, a phenomenon that can be enhanced abilities to establish favorable microbial associations with crops (Spooren *et al*. 2022; Astapati *et al*. 2023) [143, 116]. Resilience to abiotic stresses studies employing metagenomics and meta-transcriptomics have shown that certain microbial communities increased drought, salinity, and heat tolerance to crops, and biotic stresses studies genomic analyses of disease-suppressive soils reveal microbial assemblages enriched in biocontrol agent's genera mostly *Pseudomonas*, *Bacillus*, *Streptomyces*, and *Trichoderma*, providing ecological alternatives and eliminate to chemical pesticides. overall, the microbiome's play role in climate-smart agriculture (Pal *et al*. 2025; Yadav *et al*. 2025) [105, 174].

8.4 Integration of microbial genomics with precision farming technologies

Microbial genomics and precision farming tools opens novel opportunities for sustainable agriculture such as site-specific microbial management through genomics-guided application of biofertilizers, biopesticides, and microbial consortia in specific soil types, climatic conditions, and crop varieties (Nowak, 2021; Cheema *et al*. 2023; Sharma *et al*. 2023; Meta *et al*. 2025) [101, 31, 134, 87]. Real-time microbiome monitoring through development of genomics-based biosensors and moveable sequencing platforms e.g., nanopore sequencing enables rapid, act as field monitoring of soil microbiome dynamics, disease incidence, or nutrient imbalances (Ghosh *et al*. 2024) [50]. Integration of microbiome data with environmental stresses data, phenotypic, and agronomic datasets through smart artificial intelligence (AI) tools and machine learning platform, allowing farmers taking valuable decisions regarding microbial interventions (Mancini *et al*. 2024) [83].

8.5 Future Directions and Challenges

Today's advancement of agriculture sector through precision farming technologies like GIS, GPS and remote sensing technologies are changing the way we will look. The success story of precision agriculture will be evaluated by various type of information, data that is provided to the farmer, they were convinced quickly and study on precision agriculture has been initiated in many research institutions. Despite significant advances, several challenges remain scalability and field efficacy of microbial technologies, complexity of microbiome-crop-environment interactions, data integration and interpretation in real-time and regulatory and biosafety considerations. Future research should be focus on multi-omics approaches, AI-driven microbiome analytics, and developing region-specific microbial solutions tailored to diverse agro ecosystems. Despite remarkable progress, several challenges must be addressed and accepted to evaluated the efficacy of microbial genomics in precision farming and translational gap is a bridging the gap between laboratory-based genomic discoveries and field-level application remains a major bottleneck (Gupta *et al*. 2024) [35]. Microbiome stability and functionality are long-term field studies to understand the stability, resilience, and ecological interactions with microbial communities. Handling and interpreting the high amount of genomic data demand in advanced bioinformatics tools, standardized pipelines, and interdisciplinary expertise (Kumar *et al*. 2021; Mukherjee *et al*. 2023; Liu *et al*. 2025) [71, 93, 174]. Development and application of microbial-based product with biosafety regulations to ensure human health and environmental prospectus. Capacity building, knowledge dissemination, and affordable explore to microbial technologies are important for widespread adoption at the field level (Akinsemolu *et al*. 2023; Bakr *et al*. 2025) [9, 18]. Overall microbial genomics provides opportunities to harness the power of the agricultural microbiome for enhancing crop productivity, sustainability, and resilience. By integrating these novel tools with precision farming practices, agriculture can transition toward a sustainable, efficient, and environmental responsible future.

9. Biotechnological tools for precision microbial management

Integration of biotechnology approaches with precision agriculture enables targeted manipulation of microbial consortia for improved crop attributes performance (Negi *et al*. 2024) [98]. Notable approaches include microbial inoculants and biofertilizers engineered or native microbial strains for direct role in nitrogen fixation, solubilization of inorganic phosphorus, and stress tolerance (Sudheer *et al*. 2020) [148]. Synthetic microbial consortia are designing multi-strain formulations for synergistic plant-microbe interactions (Wang *et al*. 2024; Wu *et al*. 2024) [165, 170]. CRISPR-based microbial genome editing techniques used to precision improvement of beneficial traits in rhizobacteria and endophytes. Microbiome engineering through manipulation of indigenous microbial consortia for bio stimulants or selective management (Thankappan *et al*. 2024) [154].

10. Precision agriculture platforms for microbial application

Modern precision farming tools provide efficient and accurate, delivery and monitoring of microbial technologies, including sensor-based soil health monitoring assessment of soil microbial activity and nutrient status (Mansoor *et al*. 2025) [44]. Site-specific delivery of microbial formulations to optimize crop response and decision support systems and integrating microbial data information with agronomic models for better management (Gallardo *et al*. 2020; Ashoka *et al*. 2023) [47, 15].

11. Advantages of Precision Agriculture

The system of precision farming in agriculture offers a range of effective benefits in terms of profitability, crop quality, productivity, food safety, sustainability, on-farm quality of life, environmental protection, and rural economic development (Afzal and Bell *et al*. 2023) [6]. The synergistic use of microbial genomics and biotechnological tools within precision agriculture contributes to enhanced nutrient uptake efficiency, suppression of soil-borne pathogens, improvement of soil organic matter content (Thakur *et al*. 2023; Singh *et al*. 2024) [153, 140]. By applying production inputs based on site specific needs of the fields, the excessive and inappropriate use of chemicals/inputs can be avoided (Dutta *et al*. 2017) [38]. Thus, there will be reduction in cost of cultivation. lowered the rate of bio-formulation and obtained environmental benefit when they site specifically applied to control various disease. Many scientists around the world obtained higher or equal crop yields with the application of variable rate of microbial inoculants where many times the chemicals usage is reduced according to local field variations (Khan *et al*. 2024; Hubballi *et al*. 2023) [60]. Thus, there will be higher production efficiency of bio-inoculants applied. Balasubramani and Vincent (2021) [19] recorded increased nitrogen use efficiency with precision agriculture and they stated that NO_3^- can be efficiently removed from shallow underground water table and water quality also. Reduction in pollution due to site specific application of inputs depending upon the spatial and temporal variations.

12. Limitations of Precision Agriculture

Sophisticated equipment is required for collecting data related to spatial and temporal variations of soils, plants and environment. Accurate analysis of the data is required for facilitating support for decision making which in turn depends on the skill of the user. There is lack of basic knowledge, inadequate information, sampling procedures, lack of site -specific bio-fertilizer recommendations, and qualified agronomic services (Kumar *et al*. 2024) [14]. There are various technological barriers that related to machinery, remote sensing, sensors, GPS, software etc. At present time, multiple technologies are used in their infancy and pricing of equipment, and services is hard to pin down (Gusev *et al*. 2022) [54]. The success of precision agriculture depends largely on how well and how quickly the knowledge needed to guide the new technologies can be found (India spends only 0.3% of its agricultural Gross Domestic Product in Research and Development) In India major problem is the small field size (Patel *et al*. 2019) [108]. More than 58 percent of operational holdings in the country have size less than 1 ha only some states- Punjab, Rajasthan, Haryana and Gujarat almost 20 per cent of agricultural lands have operational holding size approximately 4 ha.

13. Conclusion

Microbial genomics and biotechnological tools offer transformative potential for precision agriculture. Their integrated strategies can be enhanced to crop productivity, health, and ecological sustainability. Continued interdisciplinary scientific research and technological innovation are more essential to realize the full potential of microbial based precision farming. It can be defined as a novel strategy to farming in which uses advanced technologies to enhanced crop yields with minimizing risk, waste and reducing environmental effects. These integrated techn0logies are the only way to fulfil requirement of food for feed the upcoming generations as the productivity of agricultural land is decreasing day by day due of excessive use of chemical fertilizers and unawareness of the people mainly in developing countries like India. These technologies are facilitating the future prospects scope for switching over to modern agriculture leaving the traditional one by utilizing the right resources in proper time management, which results in an ecofriendly sustainable agriculture. The power of this technology has already been demonstrated, but in practical way, successful delivery is difficult as it according to needs large scale commercial application to realize the benefits. The basic goal of integrating farming to optimize yield with minimum input and reduced environmental pollution is highly required for developing countries to face the challenge of sustainability. Development of advancing precision farming through microbial genomics and biotechnological tools has been largely market-driven but its future growth needs collaboration between private and public sectors. these technologies look promising as a future farming tool, however its effective use in Indian agriculture is yet to be realized.

14. Conflict of Interest

The Authors declare no conflict of interest

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