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Bioformulations for sustainable production of cereals in U.P: Mechanisms, agronomic responses, constraints, and pathways to adoption

Trilok Nath Rai[1], Kedar Nath Rai[2], Sanjeev Kumar Rai[3], Rajeev Kumar Rai[4], Mohit Singh[5]
[1] Department of Soil Science & Agricultural Chemistry, Krishi Vigyan Kendra (ICAR-CSSRI), Dhikunni, Sandila, Hardoi, Uttar Pradesh, India
[2] Associate Professor and Head, Department of Soil Science & Agricultural Chemistry, Kamla Nehru Institute of Physical and Social Sciences, Sultanpur, Uttar Pradesh, India
[3] Department of Soil Science & Agricultural Chemistry, Kamla Nehru Institute of Physical and Social Sciences, Sultanpur, Uttar Pradesh, India
[4] Department of Nursing,Institue of Nursing & Paramedical Sciences Sultanpur, Uttar Pradesh, India
[5] Agriculture Extension, Krishi Vigyan Kendra (ICAR-CSSRI), Dhikunni, Sandila, Hardoi, Uttar Pradesh, India

Abstract
Uttar Pradesh agriculture faces declining soil fertility, inconsistent nutrient availability, combined heat and drought stress, high input costs, and poor farmer access to fertilizers, constraints that disproportionately affect major grass crops such as; maize, sorghum, pearl millet, rice, wheat, and forage grasses, underpinning regional food, feed, and livestock systems. Bio fertilizers offer a biological complement to mineral fertilization. This systematic review synthesized peer reviewed studies (2020–2026) from Google Scholar and web indexed scholarly articles on arbuscular mycorrhizal fungi, plant growth promoting rhizobacteria, nitrogen fixing and phosphate solubilizing microorganisms, cyanobacteria, and microbial consortia in U.P. grass crop systems, screened against defined inclusion criteria for field and pot-based studies reporting crop or nutrient outcomes. Of the studies reviewed, maize trials showed the most consistent yield responses (25% yield increase), while evidence for sorghum, pearl millet, rice, wheat, and forage grasses remained fragmented. Microbial inoculants in maize improved nutrient acquisition (by >14%), root development (>19.5%), and stress resilience, though outcomes depended strongly on soil properties, genotype, native microbial populations, inoculant quality, fertilizer regime, and water availability. Bio fertilizers are therefore most effective as targeted components of integrated soil fertility management rather than as substitutes for mineral fertilizers. Key adoption barriers include inconsistent field efficacy, weak quality control, poor shelf life, limited local production, and insufficient economic data. Future research should prioritize locally adapted strains, multilocation trials, coinoculation, and long-term economic and soil health assessment.

Keywords: Bio- formulation, AMF, PGPR, grass crops, nutrient use efficiency

Introduction
Agricultural productivity in U.P. is constrained by various interacting challenges such as; poor soil fertility, water scarcity, climate change, weak good agronomic practices (GAP), and poor access to farm inputs. Soil nutrient depletion is extensive, while mineral fertilizers are often unaffordable, unavailable, and poorly matched to soil nutrient status. At the same time, drought and heat significantly limit crop performance even when nutrients are adequately supplied. Fertilizer strategy must therefore be considered together with soil health and climate resilience (Dimkpa *et al*., 2023) [9]. Grass crops occupy a key role in these production systems. Rice, wheat ,Maize are a major staple food in India (Galani *et al*., 2022) [11], sorghum and pearl millet are important in dry environments (Wilson & VanBuren, 2022) [36], rice is important in irrigated and lowland systems, wheat contributes to food supply in highland and irrigated areas (Yobom & Le Gallo, 2022) [37] and forage grasses underpin livestock production system (Moorby & Fraser, 2021) [26]. These cultivated crops differ in root architecture, nutrients demand, microbial associations, and responses to environmental stresses. Consequently, an inoculant that performs well in a phosphorus deficient maize field cannot automatically be expected to perform similarly in flooded rice or semi-arid millet (Moorby & Fraser, 2021) [26].

In this review, bio-formulations or bio-fertilizers are defined as preparations containing beneficial microorganisms intended to enhance crop nutrient availability, nutrient acquisition, or plant growth through biological processes. This encompasses AMF, PGPR, associative or endophytic nitrogen fixing microorganisms, phosphate solubilizing microorganisms, cyanobacteria, and defined microbial consortia (Halo -mix, Halo -PSB, Halo -azo, Halo-zinc, Halo-Cal-D) and some decomposers like Halo-CRD/ Halo-CaRe. Organic amendments without a deliberate microbial component are considered only where they interact directly with microbial inoculation. The scientific basis for microbial fertilization is established. PGPR can contribute through nutrient mobilisation, associative nitrogen fixation, siderophore production, phytohormonal effects, root modification and stress signaling (Grover *et al*., 2021) [13]. AMF expand the soil volume explored by roots through extraradical hyphae and can improve phosphorus acquisition and water relations (Püschel *et al*., 2021). However, the presence of a beneficial mechanism in laboratory conditions does not guarantee an agronomic response in farmers' fields. African evidence increasingly shows that soil properties, native microbial communities, genotype, inoculant quality, fertilizer regime, and season determine field performance (Aloo *et al*., 2021; Koech *et al*., 2024a) [3, 19].

The purpose of this review is therefore to move beyond the general claim that biofertilizers are sustainable alternatives to mineral fertilisers. It evaluates what is known for grass crops in sub-Saharan Africa, identifies factors responsible for variable responses, and proposes conditions under which microbial inoculants are most likely to deliver agronomic and economic value.

Methodology

A structured critical literature review with narrative evidence synthesis was undertaken. Literature searches were conducted using Google Scholar and web indexed scholarly articles. Search concepts combined bio fertilizer, AMF, PGPR, microbial inoculant, phosphate solubilizing microorganisms, nitrogen fixation and the major grass crops in U.P and, where appropriate. Priority was given to the peer reviewed studies published from the year 2020 to 2026; while older landmark reviewed, papers were retained when they provided foundational required concepts and mechanisms. African fieldbased studies received the greatest evidential weight, followed by African greenhouse, and controlled studies. Evidence that was generated outside Africa was used mainly to explain mechanisms and formulation of hypotheses and was not treated as equivalent to U.P. field efficacy.

Studies were eligible for the core synthesis when they strictly evaluated a defined microbial inoculant or bio fertilizer in a grass crop as well as production system relevant to grass crops and reported at least one agronomic, nutritional, physiological or soil response. Studies based solely on no microbial organic inputs, nonagricultural systems and laboratory assays without plant responses, or inadequately described interventions were excluded from the core synthesis. Evidence was classified into three levels: the mechanistic studies, the controlled pot or greenhouse experiments, and finally the field experiments. Field studies were given the greatest practical weight because the inoculants must survive, colonize, and function within native soil communities under variable weather and management. Multi location and multi season evidence was considered stronger than a single site observation. Because the studies differed substantially in crop, strain, dose, soil, the fertilizer regime, and response variables, effect sizes were not statistically pooled. For each relevant study conducted, attention was given to country and agroecological context, crop, microbial group, application approach, fertilizer regime, soil characteristics, experimental environment and principal responses. Responses were grouped as follows: plant growth, biomass or grain/forage yield, nutrient concentration and uptake, nutrient use efficiency, stress tolerance, soil biological properties and economic or adoption outcomes. This approach allowed comparison of biological potential with agronomic reliability while recognising substantial heterogeneity in the evidence base.

Results and Discussion

Soil fertility context and rationale for biological nutrient management

Soils in U.P. are diverse, but many production systems experience low nutrient stocks or low nutrient availability (Ikazaki *et al*., 2024) [17]. Nitrogen and phosphorus are especially important constraints, while potassium, sulfur, and micronutrient deficiencies occur in particular environments. Soil acidity can restrict nutrient availability and root development, whereas alkaline or calcareous conditions can reduce phosphorus and micronutrient availability. These limitations interact with low organic matter and erosion, making nutrient management a continuing process rather than a onetime fertilizer decision (Dimkpa *et al*., 2023) [9]. Mineral fertilizers remain essential for closing large nutrient deficits. Microorganisms do not create phosphorus or potassium in quantities equivalent to crop removal; their principal value is to modify nutrient cycling, mobilise existing pools, improve root acquisition, and, in some cases, contribute biologically fixed nitrogen (Nabi, 2023) [28]. The strongest agronomic rationale is therefore integrated nutrient management rather than a contest between 'chemical' and 'biological' agriculture.

Major Bio fertilizer groups and mechanisms

AMF form symbiotic associations with the roots of many grasses. Their extraradical hyphae extend beyond the nutrient depletion zone surrounding roots and can improve acquisition of phosphorus and some micronutrients while influencing water relations and soil aggregation (Shukla *et al*., 2025) [34]. Field evidence indicates that AMF can increase phosphorus fertilizer efficiency by 15.33% (Baloch & Baloch, 2026) [4], but the response depends on soil phosphorus, fertilizer management and competition with indigenous AMF(Buzo *et al*., 2023; Koech *et al*., 2024b) [6, 19]. PGPR comprise functionally diverse bacteria that colonize the rhizosphere or plant tissues. Their mechanisms include phosphorus mobilisation, associative nitrogen fixation, siderophore production, hormone modulation, ACC-deaminase activity, root architecture modification, and induced stress responses (Etesami & Adl, 2020) [10]. These mechanisms are complementary, but laboratory traits such as phosphate solubilization halos or hormone production should not be interpreted as proof of field efficacy. Field performance depends on colonisation, competition, soil chemistry, moisture, genotype, and application timing (Mitter *et al*., 2021) [24]. Nitrogen fixing microorganisms associated with grasses include associative and endophytic diazotrophs. Their contribution to cereal nitrogen supply is generally less predictable than symbiotic fixation in legumes and should therefore be evaluated using plant nitrogen uptake; recovery and nitrogen use efficiency rather than yield alone. In flooded rice, cyanobacteria and Azolla provide additional biological nitrogen pathways (Akhtar *et al*., 2021) [2]. A Tanzanian field study illustrates the value of integrating Azolla and rice straw with mineral nutrients rather than assuming complete mineral nitrogen replacement (Marzouk *et al*., 2024) [22]. Phosphate solubilizing microorganisms mobilize poorly soluble phosphorus through organic acid production, chelation, and phosphatase activity. Their potential is greatest where total soil phosphorus is present but plant availability is restricted by fixation or precipitation. Their practical value is therefore likely to be greatest when combined with appropriate phosphorus management, organic matter, and pH correction (Mjokwe *et al*., 2025) [25]. Microbial consortia combine organisms with complementary functions, such as AMF and PGPR or nitrogen fixing and phosphorus mobilizing bacteria. The ecological rationale is strong because plant nutrition and stress response involve multiple processes (Ikan *et al*., 2025) [16]. However, consortia also increase formulation, compatibility, and quality control requirements. Synergy should consequently be demonstrated experimentally rather than assumed from the number of organisms included.

Evidence across major grass crops

Among crops in U.P., maize has the strongest evidence base supporting bio fertilizer utilization. Field studies in Benin and Kenya have shown that rhizobacterial inoculation combined with reduced mineral fertiliser can improve maize growth and yield (by 25%), supporting the concept of nutrient complementation rather than automatic fertilizer replacement (Adoko *et al*., 2022; Nyamboga *et al*., 2025) [1, 30]. A Kenyan study further demonstrated that AMF responses differed among sites, seasons and maize genotypes, including effects on phosphorus uptake, highlighting site × genotype × inoculant interactions (Koech *et al*., 2024b) [19]. These findings support targeted rather than blanket inoculation, particularly in phosphorus deficient or drought prone environments and under reduced fertilizer programs. Evidence for sorghum is more limited and geographically fragmented. Its importance in semi-arid systems makes improved root development (20% higher overall, growth) (Mulugeta *et al*., 2025) [27], phosphorus acquisition, and stress tolerance attractive targets, but trials should test inoculants under realistic low and moderate fertilizer conditions. For pearl millet, multi-location trials across rainfall and soil gradients are particularly important because water availability strongly affects microbial activity and plant response. Rice represents a distinct microbial environment because flooding alters redox conditions, nutrient transformations and root microbe interactions (Wang *et al*., 2024) [35].

Azolla and cyanobacteria are consequently relevant biological nitrogen inputs, while PGPR may contribute to nutrient acquisition and stress regulation. The effectiveness of microbial technologies in rice is likely to depend on water regime, cultivar, timing of inoculation and mineral nutrient management (Marzouk *et al*., 2024) [22]. SSA specific wheat evidence remains less extensive than maize evidence. AMF and PGPR may improve phosphorus acquisition, root development, and stress tolerance, but recommendations should remain conditional until more multi location field studies are available. Forage grasses are best evaluated using different criteria, with biomass production and feed quality being more important indicators of performance than grain yield (Hungria *et al*., 2021) [14]. Dry matter production should therefore be assessed alongside crude protein, mineral concentration, fiber fractions, digestibility, and nutrient recovery. Long term repeated cut experiments are particularly important for perennial or pasture systems (Ghani *et al*., 2025) [12].

Biofertilizers and nutrient use efficiency

Nutrient use efficiency provides a stronger basis for evaluating microbial inputs than yield alone. An inoculant that maintains yield with a lower mineral fertilizer rate may provide greater agronomic value than one that increases yield only under full fertilization. Relevant indicators include agronomic efficiency, partial factor productivity, apparent recovery efficiency, physiological efficiency and internal utilization efficiency (Sarkar *et al*., 2021) [33]. Studies should clearly state the reference treatment and denominator used. Experimental designs should include, where feasible, an uninoculated full fertilizer treatment, an inoculated reduced fertilizer treatment, and an inoculated full fertilizer treatment. Such comparisons help distinguish nutrient substitution from improved nutrient recovery or general growth stimulation. Evidence from field maize also shows that AMF can improve the efficiency of applied phosphorus under some conditions, but the magnitude is not universal (de Souza Buzo *et al*., 2023b) [6].

Climate stress, soil conditions, and microbial reliability

Climate stress can change how well bio fertilizers perform. Under drought conditions, nutrient movement through the soil is reduced, making improved root exploration particularly valuable. AMF can help plants access a larger volume of soil, while PGPR may promote root development and support the plant's response to stress (Igiehon *et al*., 2021) [15]. Under combined drought and heat, selected PGPR have shown promising physiological responses in maize, although controlled environment evidence should not be treated as proof of field scale yield benefits (Notununu *et al*., 2024) [29]. Soil acidity provides another important context. Low pH can constrain phosphorus availability and root growth through aluminum toxicity. Liming changes both soil chemistry and the microbial habitat, creating a case for testing pH correction, phosphorus management, and microbial inoculation together. The effectiveness of microbial inoculants depends not only on their ability to increase yield, but also on how soil pH and nutrient availability influence the benefits gained from applied nutrients (Lv *et al*., 2024)

Field efficacy is ultimately a context dependent outcome of interactions between the microbial inoculant, soil environment, climate, plant genotype, and management practices, rather than a fixed characteristic of the product. Indigenous microorganisms, soil minerals, moisture, temperature, genotype, inoculum viability and fertilizer management all influence microbial colonization and function. These interactions help explain why promising laboratory candidates often show inconsistent responses under field conditions. African reviews identify formulation, regulation, research capacity and commercialization as persistent constraints to the development of reliable bio fertilizer systems (Aloo *et al*., 2021; Massawe *et al*., 2025) [3, 23].

Soil health, formulation, economics, and adoption

Bio fertilization may influence soil biological processes, aggregate formation, nutrient cycling, and soil organic carbon. A global meta-analysis of 59 studies comprising 267 observations reported an average increase of 0.44 g C kg^{-1} soil following bio fertilization, alongside significant positive effects on several microbial groups and cereal based systems (Just *et al*., 2024) [18]. Because this evidence is global rather than SSA-specific, the result should not be interpreted as a guaranteed carbon benefit in African fields.

Effective formulation and rigorous quality control are essential for translating bio fertilizer technologies into reliable and commercially viable products (Díaz *et al*., 2025). Products must maintain microbial identity, viability, and functional performance through storage, transport, and application. Quality assurance should include identity, viable cell or propagule concentration, contamination status, shelf life stability and efficacy against a defined specification. For AMF, propagule density and infectivity are particularly important; for bacterial products, strain identity and viable counts are necessary but not sufficient (Salomon *et al*., 2022) [32]

Economic performance is equally important. Farmers need information on cost per hectare, expected yield response, labor requirements, availability, and risk. Partial budgets should compare added income with inoculant cost, application labor, and changes in mineral fertilizer expenditure, while sensitivity analysis should consider poor, average, and favorable seasons (Chaika & Korotkova, 2025) [5] . The most practical and defensible pathway for bio fertilizer adoption begins with diagnosing the key production constraints, matching microbial functions to those constraints, verifying product quality, integrating inoculants with mineral and organic nutrient management, and monitoring both agronomic and economic performance. For example, AMF may be considered where phosphorus acquisition is limiting; PGPR where root development, nutrient mobilization, or stress tolerance is targeted; and Azolla or cyanobacteria in appropriate rice systems. Such technologies should be embedded in integrated soil fertility management rather than promoted as standalone replacements for essential nutrients

Conclusion and Recommendations

Bio-formulations or bio-fertilizers offer promising opportunities to improve the productivity and sustainability of grass based cropping systems in U.P., particularly through enhanced nutrient acquisition, root development, nutrient use efficiency, and stress resilience.

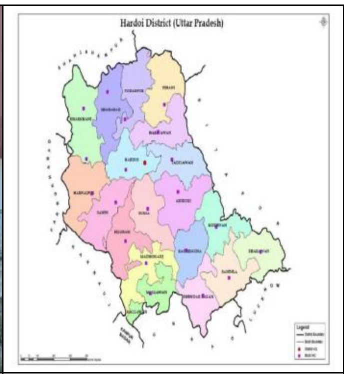
However, their performance is highly context dependent, varying with microbial type, crop genotype, soil properties, climate, and nutrient management practices. Maize currently has the strongest evidence base, while important gaps remain for sorghum, pearl millet, rice, and wheat and forage grasses. Future research should therefore move beyond controlled environment demonstrations towards well designed, multi-location, and multi-season field evaluations under realistic farmer conditions. Priority should be given to locally adapted microbial strains, reliable formulation and quality control, and integration of inoculants with mineral and organic nutrient management.

Research should also evaluate genotype with microbe interactions, nutrient use efficiency, co-inoculation strategies, long term soil health effects, and economic returns under different seasons and production environments. Such efforts would strengthen the evidence required to develop site-specific bio fertilizer recommendations and support their reliable adoption by U.P. farmers.

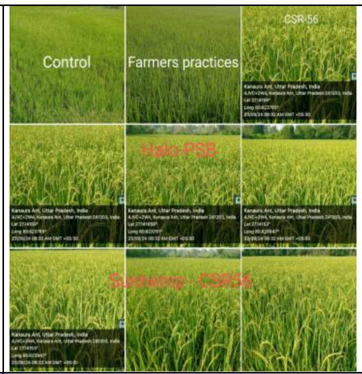
Conflict of Interest

The author declares no conflict of interest that could have influenced the interpretation, synthesis, or presentation of the evidence discussed in this review.

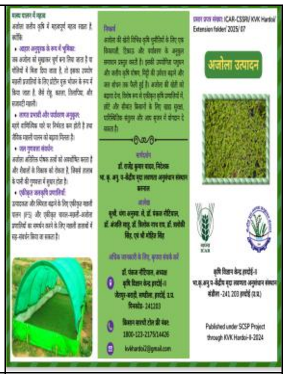
Preparation of bioformulation in FYM



District Map of Hardoi, U.P..



Effect bioformulation in rice


Extension folder on Azolla

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