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Review

Connecting Bio-Priming Approach with Integrated Nutrient Management for Improved Nutrient Use Efficiency in Crop Species

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Abstract: The increasing demand for qualitative and varietal foods by the consumer society is a big concern for energy production, and utilization of that energy in a judicious manner for sustainable management of resources is a big challenge in the eminent future. Existing resources (land, water, fertilizer, etc.) and their socioeconomic aspects warrant the farming community to adopt alternative strategies aimed at enhancing the use efficiency of inputs and improve the environmental quality. The adaptability of microbes to thrive in different environments has prompted scientists to introduce microbial intervention in the agricultural processes. Bio-priming has the potential to fulfill many objectives of the modern production system with the use of beneficial microorganisms in an eco-friendly manner. Interestingly, it also plays a crucial role in enhancing the nutrient use efficiency of crops. There is rising evidence of a paradigm shift from the use of a single microbe to a consortium approach for efficient rhizosphere engineering in the context of sustainable agriculture. Our understanding of different signaling cascades, rhizosphere chemistry, and other mechanisms of plant–microbial interactions will frame suitable strategies to harness the best ecosystem services including improved resource use efficiency.

Keywords: bio-priming; energy prices; nutrient mining; nutrient use efficiency; soil quality

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1. Introduction

The production system of the agriculture sector is highly influenced by the fertilizer industry (huge energy-intensive sector) and escalating energy prices [1,2]. Our dependency on energy extracted from fossil fuels has tremendously increased, which is evident from the energy involvement during the production of nitrogen (N), phosphorus (P), and potassium (K) fertilizers, consuming approximately 60.6, 11.1, and 6.7 MJ/kg energy, respectively [3,4]. The subsidy policy in this sector has resulted in indiscriminate production and use of fertilizers, neglecting the management principles of nature conservation. Consequently, the natural resource base has been impaired, especially affecting the soil system through accelerated nutrient depletion, salinity, acidity, erosion, etc. [5,6]. Further, low use of organic amendments and secondary nutrients and micronutrients have aggravated the fertility of soils. Nutrient mining is in practice to an extent that cereal crops remove about 20 to 30 kg N, 4 to 8 kg P, and 18 to 40 kg K for producing one tonne of grains [7]. The balance sheet comprising the addition and removal of nutrients presents a negative nutrient budget in the majority of the Indian soils [8]. Among crop plants, the nutrient use efficiency is found to be <50% in most agro-ecological regions [9]. Standing on such a situation, i.e., the huge crisis of energy and declining nutrient use efficiency in the modern agricultural systems, it is apprehended that both energy requirement and nutrient use efficiency are scientific tools to evaluate the performance or efficiency of our production system.

A number of pre-sowing seed treatment technologies, namely, priming, pelleting, and coating, were developed to improve the quality of seed and its performance under different growth conditions [10]. These involve the introduction of seeds with physical, chemical, and biological agents to stimulate their germination and overcome all germination-related problems [11,12]. The phenomenon of priming is executed by giving an initial stimulus of an eliciting factor to plants to sharpen their "stress memory" so that they remain prepared to defend themselves during future stress events [13–15]. Future stress is referred to different biotic and abiotic stresses that a plant may encounter in different growth stages. Seed priming, by definition, is a pre-germination physiological method in which the seed is treated with natural and synthetic compounds to partially activate the process of germination [16,17]. A plethora of such methods have been established and categorized on the basis of priming agents used. Basically, they emphasize the conditioning of seeds achieved by soaking the seeds in water (hydropriming), osmotic solutions or solutions of low water potential composed of polyethylene glycol (PEG) (osmopriming) or salts (KCl, NaCl, $CaCl_2$, KH_2PO_4, $CaSO_4$, etc.) (halopriming), plant growth hormones (hormonal priming), mineral nutrients (nutrient priming), solid or semisolid medium (solid matrix priming), prior to germination [17,18]. Biological priming or bio-priming has evolved as a new technique keeping in mind the environmental and economic concerns of priming agents in order to harness higher resource use efficiency [1,19]. The process of priming follows controlled imbibition in order to start the metabolic process of germination, but the actual germination and emergence of the seminal roots are prevented [11,20,21]. Other advanced seed technologies such as seed coating and seed pelleting are in the practice for improving the performance of seed by incorporating some physical modification in seed [22]. In seed coating, active ingredients such as plant growth regulators, nutritional elements, fungicides, insecticides, and other chemicals are applied to the seed surface using adhesive polymers without much alterations to its original shape or size, while seed pelleting emerged as an advanced form of this coating technology, in which the morphology is changed to a standard shape (mostly spherical or oval) during coating of seed in an inert material to smoothen the process of planting [22]. The complexity and cost effectiveness involved in seed coating mechanisms are important factors in popularizing seed priming interventions.

Existing scientific literature presents the evidence of the linkages among fossil fuel consumption, changing climate scenario, degradation of soil quality, and food and nutritional security has triggered the process of degradation of the natural resource base, marginal productivity, and low use efficiency of fossil-based inputs [2]. In order to achieve stability and sustainability in the agriculture production system, there is a high requirement for the adaptation of environmentally friendly technologies. The demands of India's present population (1.37 billion) are satisfied with 283.37 million tonnes (Mt) food grains, but by 2025, the population is estimated to be 1.4 billion requiring a supply of more than 300 Mt food grain production. Thus, it is obvious that the consumption of nutrients (NPK) from fertilizers will increase (35–40 Mt) from the present rate (30 Mt), and an extra requirement of 10 Mt nutrients has to be fulfilled from organic sources and microbial resources [2]. In the present study, due care was taken to document the available information regarding the negative nutrient budget and bio-priming mediated nutrient use efficiency of crops.

2. Nutrient—An Energy-Intensive Sector

The relationship between agriculture and energy grew stronger with increasing populations, the decrease in the availability of arable land, and our constant desire to improve living standards. Categorizing the energy requirements of agricultural operations into direct (land preparation, intercultural operations, irrigation, harvesting, processing, and transportation) and indirect (manufacturing, packaging, and transportation of costly inputs such as fertilizers and pesticides) energy use give the detailed energy scenario in our production system [23]. In the Indian economy, the chemical fertilizer industry represents one of the most energy-intensive segments. Fertilizer production is dependent on energy derived from fossil fuels, e.g., natural gas, coal, oil, naphtha, etc. During the production of N, P, and K fertilizers about 60.6, 11.1, and 6.7 MJ/kg energy, respectively, is consumed [3,4]. For producing 1 tonne (t) urea, there is a need for four barrels (1 barrel = 190.932 L) of crude oil [24], and the production of two bags of urea burns 100 L of oil. These industries are gaining momentum after the liberalization and globalization policies of the government, coupled with the introduction of subsidy schemes (Rs 70,000 crore in 2017–18), generating huge investments in the sector [25]. The growth of Indian agriculture accelerated with the achievement of "self-sufficiency" in food grain production by supplying the essential nutrients to plants [1]. Looking at the present rate of energy expenditure, escalating energy prices, and dwindling natural resources, it is high time to perform an energy audit (input–output relationship) so as to analyze the efficiency of the resources and save the extra dosages of fertilizers and energy sources from being drainage.

3. Nutrient Mining

Mining of inherent nutrient reserves is a common phenomenon in soil mainly because of suboptimum and/or unbalanced application of plant nutrients. The term "nutrient mining" is applied "when the quantity of soil nutrients removed by a crop from an agricultural field exceeds the amount of the nutrient that is recycled back and/or replenished to the field" [8]. This is also known as a negative balance between nutrient input and output, which causes depletion of native soil fertility and eventually limits the crop yield. A considerable amount of plant nutrients is removed from the soil with the continuation of intensive cropping systems. The requirement for more chemical fertilizers is evident from the fact of progressive reduction in partial factor productivity of fertilizers, i.e., 13.4 (1970) to <3.5 kg grain/kg NPK (2010) [26]. In the earlier section (introduction), we have mentioned the nutrient mining capacity of cereals. Specifically, the consumption of N, P, and K nutrients in the production of 1000 kg grains is reported to be 14.6, 2.7, and 15.9 kg, respectively, for rice (*Oryza sativa* L.) [27] and 22.8, 4.4, and 19.0 kg, respectively, for wheat (*Triticum aestivum* L.) [28]. In the case of horticultural crops, the annual nutrient removal of N + P_2O_5 + K_2O is stated to be 500–1000 kg [29]. Cabbage (*Brassica oleracea* var. *capitata* L.) and cauliflower (*Brassica oleracea* var. *botrytis* L.) remove 112 kg N, 28 kg P_2O_5, and 112 kg K_2O, and 250 kg N, 100 kg P_2O_5, and 350 kg K_2O, respectively, in one hectare of land. The nutrient balance equation is also favored toward the negative side by other factors causing loss of soil nutrients, e.g., volatilization, leaching, fixation, erosion, etc. Nutrient mining is also triggered by the adoption of faulty management practices including farmers' fertilizer practices, which are mostly based on perception, N-driven, or peer-influenced, state recommendations establishing general ratio (4:2:1) for N, P_2O_5, and K_2O application in most soils or crops, and other practices such as removal of crop residues from the fields and low application of organics (manures, biofertilizers) and micronutrients in soil (Figure 1) [30–32].

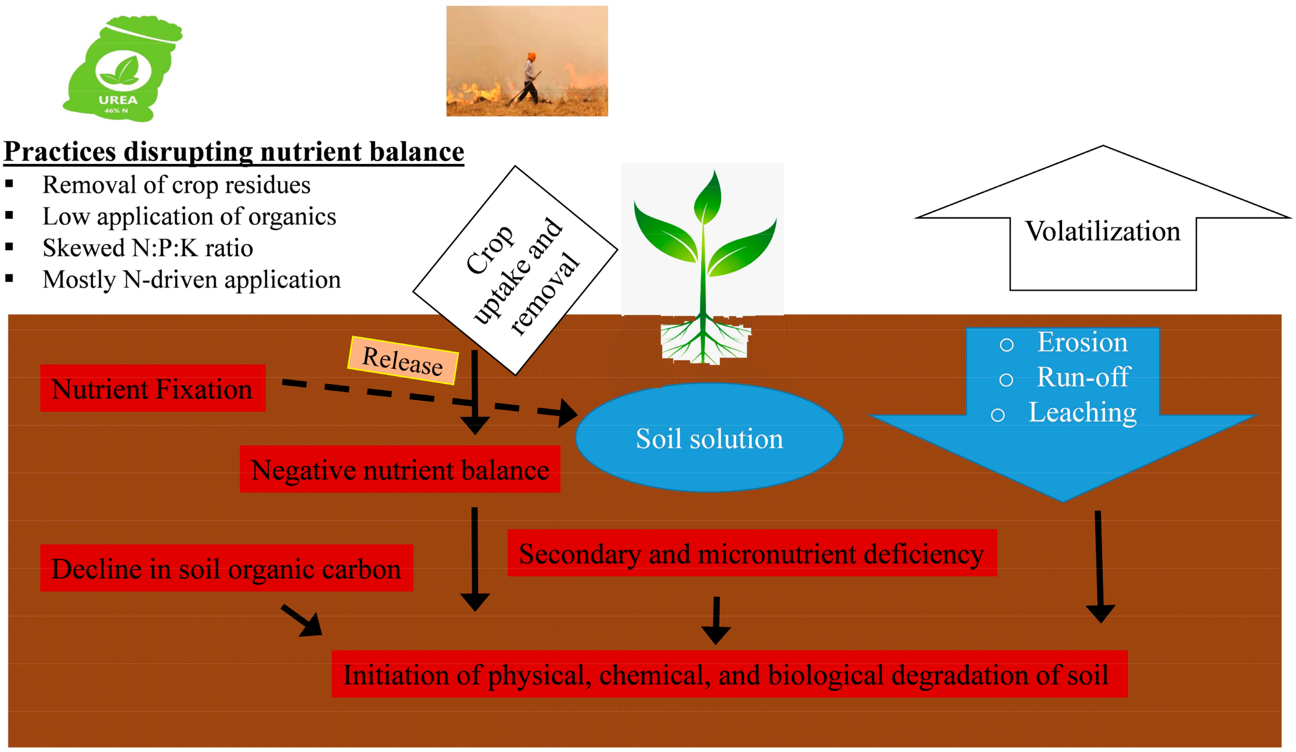

Figure 1. A conceptual framework for negative nutrient balances and nutrient mining.

Nutrient Mining in Indian Soils

Agricultural soils of India are reported to have ~10 Mt annual nutrient (N + P_2O_5 + K_2O) gaps [33], and the practice of rice–wheat system in the Indo–Gangetic Plains (IGP) alone estimated to cause an annual nutrient mining of ~20 Mt [34]. Subba Rao and Sammi Reddy [35] projected that the picture of the nutrient gap in the country may increase to 22 Mt in 2025. As per the balance sheet considering additions and removals, the positive balance has been found for N and P on a gross basis, while on a net basis, the negative NPK balance is common here [36]. The negative balance of 10 Mt is accounted for 19% N, 12% P_2O_5, and 69% K_2O. Evaluating the NPK fertility status, Muralidharudu et al. [37] found 93% (for N), 91% (for P), and 49% (for K) soils of India were deficient in these macronutrients. The cases of widespread deficiency are also noted in secondary nutrient, e.g., sulfur (S) to the extent of 41% and micronutrients, e.g., zinc (Zn), boron (B), iron (Fe), molybdenum (Mo), manganese (Mn), and copper (Cu) to the tune of 48, 33, 12, 13, 5, and 3%, respectively [38]. The mismatch between removal and replenishment of nutrients was also apparent in the long-term studies of the rice–wheat system conducted in the IGP, mostly revealing the negative apparent balance of K [39]. Allocation of government subsidies for urea is >70% and only 35% for diammonium phosphate (DAP), tempting farmers to apply more urea, and consequently, there begins the imbalance in fertilizer use. This was reflected in multilocation cultivators' field with major cropping systems, including Kaushambi of Uttar Pradesh showing 73.0, 6.4, and −150.0 kg/ha of apparent balance for N, P, and K, respectively, in the rice–wheat system [40]. Application of N often exceeds the recommended rates, P remains suboptimum or below recommendation, and K, secondary, and micronutrients are almost neglected. Negative nutrient balance (−31.5 N, −3.68 P, and −183.0 K kg/ha/yr) was observed in the pearl millet (*Pennisetum glaucum* L.)−mustard (*Brassica juncea* L.) cropping system of Gwalior (Madhya Pradesh), even with the application of recommended NPK doses [41].

4. Nutrient Use Efficiency

The current global demand for fertilizer nutrient use is about 117 Mt of N, 45 Mt of P_2O_5, and 35 Mt of K_2O [42]. The utilization rate or recovery of an applied nutrient is often low (Table 1). Rising prices of fertilizer, stagnation in crop prices, and increasing concerns about environmental degradation with nutrient loss have kept the fertilizer sector under tremendous pressure of enhancing nutrient use efficiency (NUE). The concept of NUE is gaining importance in evaluating the performance of crop production systems [26,43,44]. The primary goal of nutrient management is to provide optimum nutrition to the crops while minimizing the nutrient losses from the soil. Quantitative measurement of the nutrient uptake (amount) by the plant in respect to nutrient addition (amount) in the soil is defined as NUE. Various environmental factors such as soil dynamics (moisture content, leaching, fixation, runoff, fertility status, etc.), plant characteristics (nutrient absorbing capacity, age, cultivars, or root morphology), and climate (sunlight, precipitation) and management practices such as agronomy (selection of crop and variety, sowing time, tillage, irrigation, etc.), and nutrient management (selection, amount, time, and method of fertilizer application) affect NUE [9,45,46].

Table 1. Nutrient use efficiency in the agricultural ecosystems [2,26,47].

Nutrient	Efficiency (%)
Nitrogen	30–50
Phosphorus	15–20
Potassium	50–60
Sulphur	8–12
Zinc	2–5
Iron	1–2
Copper	1–2
Manganese	1–2
Boron	2–3
Molybdenum	2–5

Fertilizer consumption in India has augmented from 0.70 Mt (1950–51) to 26.75 Mt (2015–16), where the share of N, P_2O_5, and K_2O is 17.37, 6.97, and 2.40 Mt, respectively, depicting skewed nutrient application in the ratio of 7.23:2.91:1 [48]. Both imbalance and deficit in fertilizer application affect production levels of crops, while their use in larger quantities has economic issues, which could be saved if used optimally. Substantial cutting in nutrient requirements by adaptive farming practices will enhance the incomes of farmers by increased crop productivity and reduction in costly inputs [49,50]. Increasing the efficiency of nutrients by just 2–3% can save tonnes of fertilizers and huge investments (billions) annually at the national level. The coefficient of utilization is expressed on yield, recovery, or removal basis. From the farmer's point of view, NUE is crop output (yield) per unit of nutrient input. Scientists have integrated the response of the production system with nutrient uptake or loss (Table 2). Thus, agronomic efficiency (AE), physiological efficiency (PE), apparent recovery efficiency (ARE), partial factor productivity (PFP), and partial nutrient balance (PNB) are common parameters of NUE to quantify the economic output in terms of nutrient resource utilization [51,52].

Table 2. Integrative indices and application of nutrient use efficiency. Source: [44,51,53].

Parameter	Calculation	Assessment	Typical Values for N in Cereals
Agronomic efficiency (AE)	AE (kg/kg) = $(Y - Y_0)/F$	Economic production (grain) gained or lost per unit of nutrient input	10–30
Physiological efficiency (PE)	PE (kg/kg) = $(Y - Y_0)/U - U_0$	Yield gained or lost per unit of nutrient uptake	30–60
Apparent recovery efficiency (ARE)	ARE (%) = $(U - U_0)/F \times 100$	Proportion of nutrient uptake per unit of nutrient input	30–50
Partial factor productivity (PFP)	PFP (kg/kg) = Y/F	How productive is this cropping system in comparison to its nutrient input?	40–80
Partial nutrient balance (PNB)	PNB (kg/kg) = U/F	Quantity of nutrient being taken out of the field to the amount of nutrient input	<1.0 = more supplied than removed; >1.0 = more removed than supplied

Y = crop yield (harvested portion) in kg with applied nutrient in kg; Y_0 = crop yield (harvested portion) in kg with no applied nutrient (control); F = amount of nutrient (fertilizer) applied in kg; U = nutrient uptake (kg) in harvested portion of the crop with applied nutrients (kg); U_0 = nutrient uptake (kg) in harvested portion of the crop with no applied nutrient.

Agronomic efficiency is a short-term index of the effects of nutrient addition on the productivity of crops [43,54]. For extracting the long-term contribution of nutrient inputs to crop yield, there is a necessity of conducting long-term experiments that consider the fertilization history. The response of hybrid crops in AE was greater than non-hybrids to P and K applications in Tamil Nadu [55]. Increasing the rate of P_2O_5 application from 75 to 100 kg/ha enhanced 2.3 to 4.7 kg grain/kg P_2O_5 in non-hybrid rice, while in hybrid rice, it upsurged from 5.2 to 11.8 kg grain kg/P_2O_5. In cotton (*Gossypium hirsutum* L.), application of K_2O at 150 kg/ha resulted in an increment of AE in hybrid variety (8.8 kg grain/kg K_2O) than non-hybrid crop (5.9 kg grain/kg K_2O). Implementation of ecological intensification in maize (*Zea mays* L.) resulted in AE of N (AE_N) from 20.6 to 51.8 kg/kg with an average of 39.7 kg/kg in a five-year experiment (2009–2013) in China [52]. However, farmer's practice failed to show this trend ranging from 9.5 kg/kg in 2009 to 39.3 kg/kg in 2013 with the average being 26.9 kg/kg, i.e., 32% lower than the sustainable ecological intensification practices. This is mainly due to the adoption of the high rate of fertilizer application without splitting the dose during the growing seasons. The AE_N of cabbage was noticed to be 25.1 kg/kg at Chukalying in the Central Highlands of Kenya [56].

Physiological efficiency signifies the plant's ability to convert the nutrients assimilated from the source (soil and fertilizer) into economic yield [51]. Looking at the ever-increasing costs of chemical fertilizers and their utilization pattern by the plants, integrated nutrient management is often adopted. Substitution of 50% recommended dose of nitrogen (RDN) and 25% RDN through farmyard manure (FYM) recorded higher physiological N use efficiency (PNUE) than 100% RDN through urea in a cotton-based cropping system of New Delhi [57]. Increasing the levels of N (i.e., 50, 100, and 200 kg/ha) application decreased the PNUE of rice genotypes remarkably in the fertile field of Pantnagar [58]. For the Krishna Hamsa genotype, the supply of above-stated N levels recorded 34.93, 28.59, and 20.93 PNUE.

Apparent recovery efficiency describing the number of nutrients taken up by the plant on the basis of the rate of nutrient addition is a good indicator of the potential loss of a nutrient in a cropping system or efficiency of the adopted management practice [43]. Global data of experimental plots on recovery of applied N by the crops showed 46% for rice, 57% for wheat, and 65% for maize [59]. Following the principles of the 4R Nutrient Stewardship, developed by the International Plant Nutrition Institute, is the key to minimizing nutrient losses and maximizing the NUEs. These include four basic aspects of nutrient management, i.e., right source, right rate, right time, and right place. The relationship between N use efficiency and water use efficiency is positive linear in nature [60,61]. Application of 80 kg N/ha in a sandy loam soil of Punjab enhanced N use efficiency when there was an assured supply of water up to 300 mm, but with 120 kg N/ha, the use efficiency of N remains unaffected under irrigation regimes of 50 and 125 mm. It increased markedly with an increased water supply of 300 mm. In general, the average N recovery efficiency in farmers' fields is around 20–30% for rainfed regions and 30–40% for irrigated regions [62]. Phosphorus uptake by crops is less influenced by moisture regimes as compared to N and K; the placement of fertilizer has more impact on P uptake.

Partial factor productivity makes a comparison of yield in terms of the proportion of fertilizer input added [44]. It addresses the query "How productive is this cropping system in comparison to its nutrient input?" Over the years, worldwide data of PFP of N (PFP_N) has reduced from 245 kg grain kg/N (1961–1965) to 52 kg grain kg/N (1981–85) in cereal production, and at present, it is ~44 kg grain kg^{-1} N [51]. Sustainable practices in maize cultivation in China increased PFP_N from 48.1 to 69.7 kg/kg (average 62 kg/kg) within five years (2009–2013) of study [52].

Partial nutrient balance is the ratio of the number of nutrients taken out or removed by the crop to the quantity of nutrient input added in soil [54]. A five-year field experiment of rice conducted in Hyderabad showed positive and higher PNB of N and P in organic production systems over conventional systems [63]. Long-term trials of maize-based cropping systems, including cabbage, recorded positive partial balances for N, P, and K in organic high input systems; however, the balances were zero or negative for N and K in conventional high input systems of Kenya [64]. Groundnut (*Arachis hypogaea* L.)–finger millet (*Eleusine coracana* L.) crop rotation of thirteen years in rainfed Alfisols of Karnataka revealed greater PNB of N and P with conjunctive use of FYM at 10 t/ha and 50 or 100% NPK than the use of 100% NPK alone [65]. Biofertilizer (*Pseudomonas striata* + *Glomus fasciculatum*) application improved apparent P balance in the alluvial soil of New Delhi irrespective of the P sources (DAP, rock phosphate), even at 50% recommended dose of P in soybean (*Glycine max* L.)–potato (*Solanum tuberosum* L.) cropping system [66].

Other available techniques for estimating NUE consider plant available nutrient converted to yield. Nitrogen use efficiency calculated from fresh matter yield per unit available N (above-ground total plant N + residual soil mineral N) showed 173.9 kg/kg in organically fertilized (lupine (*Lupinus angustifolius* L.) seedlings + seed meal) white cabbage grown in Ruthe (Germany) [67].

5. Bio-Priming Mediated Nutrient Use Efficiency

Microbial-assisted management of nutrients is a sustainable, cost-effective, and eco-friendly option under diverse agroecosystems (intensive, integrated, or organic systems). Such practices protect the environment from nutrient losses (runoff, denitrification) and pollution (eutrophication, land degradation). Rhizospheric interactions modulate root architecture, mobilize nutrients, and improves NUE [68,69]. Here, we have highlighted the role of primers in the enhancement of NUE in crops.

5.1. Nitrogen Use Efficiency

Fertilizer-dependent efficacy of primers in improving NUE is well reported. The recommended dose of NPK fertilizers (120:100:60) applied at 25, 50, 75, and 100% showed enhancement in N use efficiency in the manner of 115, 52, 26, and 27%, respectively over corresponding controls (uninoculated) in wheat crop, when the seeds were inoculated with *Pseudomonas fluorescens* for conducting a field experiment in Faisalabad, Pakistan [70]. Significantly greater apparent nitrogen recovery efficiency (23.19%) was noted in wheat grown in the alluvial soil of the IGP under pot culture when the seeds were bio-primed with *Trichoderma harzianum* strain BHU51, and fertilizer was applied in the manner of 3/4th N and full recommended dose of P and K, compared to the full recommended dose of NPK

(120:60:60 kg/ha) or half N combined with full PK [68]. Duarah et al. [71] reported that a reduction in the dose of NPK fertilizer application and seed bacterization can considerably enhance the NUE (NPK).

5.2. Phosphorus Use Efficiency

Phosphorus is mostly fixed into the soil making complexes with different metals; solution P substantially decreases limiting its availability for plant uptake. The bacterial and fungal communities involved in improving P use efficiency have an important PGP trait known as P solubilization, i.e., they solubilize the unavailable or fixed P in the soils to available forms of P. Strains isolated from the soil are screened on the basis of their ability to solubilize P. Inoculation of wheat seeds with *P. fluorescens* and NPK fertilizer application at 25, 50, 75, and 100% recorded 102, 56, 57, and 21% enhancement in P use efficiency, respectively over corresponding uninoculated treatments in wheat field studies [70]. Seed priming with a conidial suspension of *T. harzianum* at 1×10^8 spores/mL significantly increased the P uptake of sunflower (*Helianthus annuus* L.) in a greenhouse study [72]. Compared to control, application of the bio-agent enhanced about 59% P uptake. Wheat seeds inoculated with several strains of *Bacillus* spp. at 10^8 to 10^9 CFU/mL under varying P-sources revealed higher grain P uptake with DAP application, compared to rock phosphate (RP) and RP-enriched compost both in pot (113 mg/pot) and field (3.82 g m^{-2}) conditions [73]. The study also validated that plant growth-promoting rhizobacteria (PGPR) with dual PGP activities [P solubilization and ACC (1-aminocyclopropane 1-carboxylic acid) deaminase activity] are better in improving P use efficiency of P fertilizer than PGPRs possessing a single PGP trait. Kaur and Reddy [74] reported that the seed inoculation with P solubilizing bacteria (*Pseudomonas plecoglossicida* and *Pantoea cypripedii*) and RP fertilization resulted in a profound effect on P uptake of wheat and maize in the organic field of Punjab. Utilization efficiency of P in chili (*Capsicum annuum* L.) was enhanced (4–29%) when phosphate solubilizing bacteria (PSB) was added at 10^8 CFU/mL by root dipping method [75].

5.3. Potassium Use Efficiency

Fodder maize showed higher uptake (40.5 kg/ha) of K with the addition of *Bacillus mucilaginous* as biological K fertilizer through seed coating method and application of a full dose of NP (120:90 kg/ha) than the alone application of full NP (K uptake: 30.9 kg/ha) in rainfed conditions [76]. Seed treatment with *T. harzianum* isolates increased 62% uptake of K in sunflower grown in greenhouse conditions [72]. Bacterial isolates (*Pseudomonas orientalis*, *Rahnella aquatilis*, and *Pantoea agglomerans*) isolated from Iranian soils containing mica and illite minerals proved their K solubilizing ability by augmenting the K use efficiency in terms of AE, PE, ARE, etc. in rice grown under pot conditions [77]. Application of 50% K fertilizer along with the isolates increased all the NUE parameters except PE, which showed increment with all the isolates when the chemical fertilizer was not applied. Physiological efficiency varied among the isolates (with and without fertilizer treatment) in the following order: *Pantoea* sp. (32.99 and 128.20 g/g) > *Pseudomonas* sp. (27.70 and 89.54 g/g) > *Rahnella* sp. (35.89 and 81.73 g/g). Agronomic efficiency was found to be highest (20.67 g g^{-1}) with *Pantoea* sp. + 50% K fertilizer treatment. Maize seeds bio-primed with suspensions of K solubilizing bacteria (*Agrobacterium tumefaciens*) at ~10^8 cell/mL showed a positive influence on K uptake in the alluvial soil of Varanasi located under the IGP region [78].

5.4. Bio-Priming Mediated Use Efficiency of Other Nutrients

Root dipping of tomato (*Lycopersicon esculentum* Mill.) seedlings in liquid containing *T. harzianum* at 11.90×10^6 CFU/mL enhanced the mineral content (Fe, Mn, Zn, and Cu) of fruits [79]. Entesari et al. [80] observed bio-priming of soybean seeds with rhizospheric fungi (*Trichoderma* sp.) prior to sowing improved the micronutrient status of crop (Table 3). Seedling roots of broccoli (*Brassica oleracea* var. *italica* L.) inoculated with suspensions of *Bacillus cereus* at 10^8 CFU/mL for 1 h prior to transplanting and application of manure and RP enhanced the leaf nutrient concentrations of Mn and Zn to the tune of 36.4% and 56.7%, respectively, in farm soil of Anatolia, Turkey [81]. The micronutrient concentrations of cabbage seedlings were considerably influenced by *B. subtilis* TV-17C, especially in Fe (36.6 µg/g) and Mn (4.29 µg/g) content [82]. Pal and Singh [83] documented higher Fe (6.39 mg kg^{-1}), Mn (0.13 mg/kg), Zn (0.263 mg/kg), and Cu (0.197 mg/kg) content in okra [*Abelmoschus esculentus* (L.) Moench] fruits when 10% of chemical fertilizers were supplemented with seed priming with *T. harzianum* NBRI 1055 in pot culture conducted in Varanasi. Full dose of N:P_2O_5:K_2O applied at 120:120:75 kg/ha recorded 5.76 mg/kg Zn, 0.11 mg/kg Mn, 0.189 mg/kg Zn, and 0.152 mg/kg Cu. Recently, a field experiment involving seedling bio-priming with *P. fluorescens* and *B. subtilis* and 75% of recommended NPK fertilizer dose recorded improved Fe and Zn content in red cabbage [*Brassica oleracea* var. *capitata* f. *rubra* (L.) Thell] heads [84]. A partial list of different primers that influence the NUE in crops is presented in Table 3.

Table 3. Nutrient use efficiency of crop species as influenced by the bio-priming intervention.

Crop	Primer	Experimental Conditions	Nutrient Use Efficiency		Reference
			Macronutrient	Micronutrient	
Fodder maize	*Bacillus mucilaginous*	Field	Increase in N (11.20%), P (13.58%), and K (31.06%) uptake	-	[76]
Wheat	*Pseudomonas fluorescens*	Field	Increase in N use efficiency (26%) and P use efficiency (57%)	-	[70]
Chickpea (*Cicer arietinum* L.)	*Pseudomonas striata* + *Piriformospora indica*	Pot	Enhanced P content (27.78%)	-	[85]
Rice	*Staphylococcus epidermidis* + *Pseudomonas aeruginosa* + *Bacillus subtilis*	Pot	Increase in N (36.10%), P (104.76%), and K (102.20%) content	-	[71]
Broccoli	*Bacillus cereus*	Field	Enhanced K (18.6%) content	Enhanced Mn (36.4%) and Zn (56.7%) content	[81]
Wheat	*Bacillus* spp.	Pot and field	Increase in grain P uptake to 77% and 85% under pot and field conditions, respectively	-	[73]
Tomato	*Trichoderma harzianum*	Field	Enhanced K (20.62%) content	Enhanced Fe (33.84%), Mn (28.57%), Zn (54.54%), and Cu (23.07%) content	[79]
Sunflower	*Trichoderma harzianum*	Greenhouse (25 ± 2 °C, 95% relative humidity)	Increase in N (30%), P (59%), and K (62%) uptake	-	[72]
Soybean	*Trichoderma harzianum* BS1-1	Pot	Increased N (15.90%) content	Increased Zn (8.23%) and Fe (57.83%) content	[80]
	Trichoderma virens As10-5	Pot	Increased N (31.17%) content	Increased Zn (21.67%) and Fe (14.82%) content	
Maize	*Pseudomonas plecoglossicida*	Field	Enhanced grain P (48.65%) uptake	-	[74]
Cabbage	*Bacillus megaterium* TV-91C	Pot	Increase in N (17.95%), P (10.28%), and K (5.01%) content	Increase in Fe (14.69%) and Mn (14.99%) content	[82]
	Bacillus subtilis TV-17C	Pot	Increase in N (10.26%), P (6.26%), and K (4.59%) content	Increase in Fe (27.97%) and Mn (10.85%) content	

Table 3. *Cont.*

Crop	Primer	Experimental Conditions	Nutrient Use Efficiency		Reference
			Macronutrient	Micronutrient	
Chili	*Pseudomonas stutzeri* + *Azospirillumbrasilense* + *Agrobacterium tumefaciens*	Pot	Enhanced P use efficiency (4–29%)	-	[75]
Wheat	*Trichoderma harzianum*	Pot	Higher apparent N recovery efficiency (23.19%)	-	[68]
Rice	*Pseudomonas* sp.	Pot	Higher apparent K recovery efficiency (150.4%)	-	[77]
Okra	*Trichoderma harzianum* NBRI 1055	Pot	Increase in N (49.18%), P (39.56%), and K (38.89%) content	Increase in Fe (69.04%) content	[83]
Red cabbage	*Pseudomonas fluorescens* + *Bacillus subtilis*	Field	Increased P (0.37%) and K (2.84%) content	Increased Fe (160.12 mg kg^{-1}) and Zn (34.18 mg kg^{-1}) content	[84]

6. Effect of Bio-Priming and Integrated Nutrient Management (INM) on Key Soil Functions Essential for Nutrient Cycling

6.1. Microbial Activity

Biological activity in soil is an index of the microbial population in soil along with their physiological efficiency. Higher microbial activity (biomass C, respiration, and urease activity) is noted in soil receiving organics + mineral fertilizers in comparison to fertilizers alone [86,87]. Dinesh et al. [88] studied the microbial variables of clay loam soil under three nutrient management regimes in turmeric cultivation, namely, integrated nutrient management (NPK + FYM), organic nutrient management (FYM + vermicompost + neem cake + ash + *Azospirillum* sp. + *Bacillus* sp.), and chemical nutrient management (NPK). About 29% and 31% higher soil biomass C, 16% soil respiration, and 29% and 27% higher dehydrogenase activity were recorded in organic nutrient management and integrated nutrient management, respectively, in comparison to chemical nutrient management. Soil biomass C increased from 285 to 314 mg/kg by increasing the levels (50–150%) of NPK, while integrating FYM with optimal amounts of NPK enhanced the biomass (346 mg/kg) by 16% than the optimal NPK (299 mg/kg) in an Inceptisol [89]. The microbial population also increased by increasing the NPK levels up to 150% (68 $\times$ 10^6 bacteria/g soil; 13 $\times$ 10^4 fungi/g soil) and an integrated approach (100% NPK + FYM) led to the highest population (76 $\times$ 10^6 bacteria/g soil; 14 $\times$ 10^4 fungi/g soil) in fodder cowpea rhizosphere. Mäder et al. [90] observed that application of root microorganisms in a consortium (*Glomus intraradices*, *Pseudomonas jessenii*, and *Pseudomonas synxantha*) improved soil quality in terms of soil enzyme activities (dehydrogenase, urease, and alkaline and acid phosphatase) in low-input areas of India (Uttarakhand, Uttarakhand, and Haryana). Rock phosphate application in combination with seed bio-inoculant (*Pseudomona splecoglossicida*) significantly enhanced the rhizospheric bacterial population (3.8 $\times$ 10^8 to 5.2 $\times$ 10^8 CFU/g soil) of wheat from the first year to the second year as compared to absolute control (2.0 $\times$ 10^6 to 2.4 $\times$ 10^6 CFU/g soil) and seed inoculation with *Pantoea cypripedii* + RP treatment (3.6 $\times$ 10^8 to 4.9 $\times$ 10^8 CFU/g soil) in loamy texture soil of Punjab [74]. This might be due to altered root exudation and availability of substrate (RP) for microbial proliferation (Figure 2). Metagenomic analysis revealed that sustainable agricultural practices or organic intervention enhanced richness, decreased evenness, and altered the microbial community composition or microbiota structure of soil when compared with conventional systems [91,92].

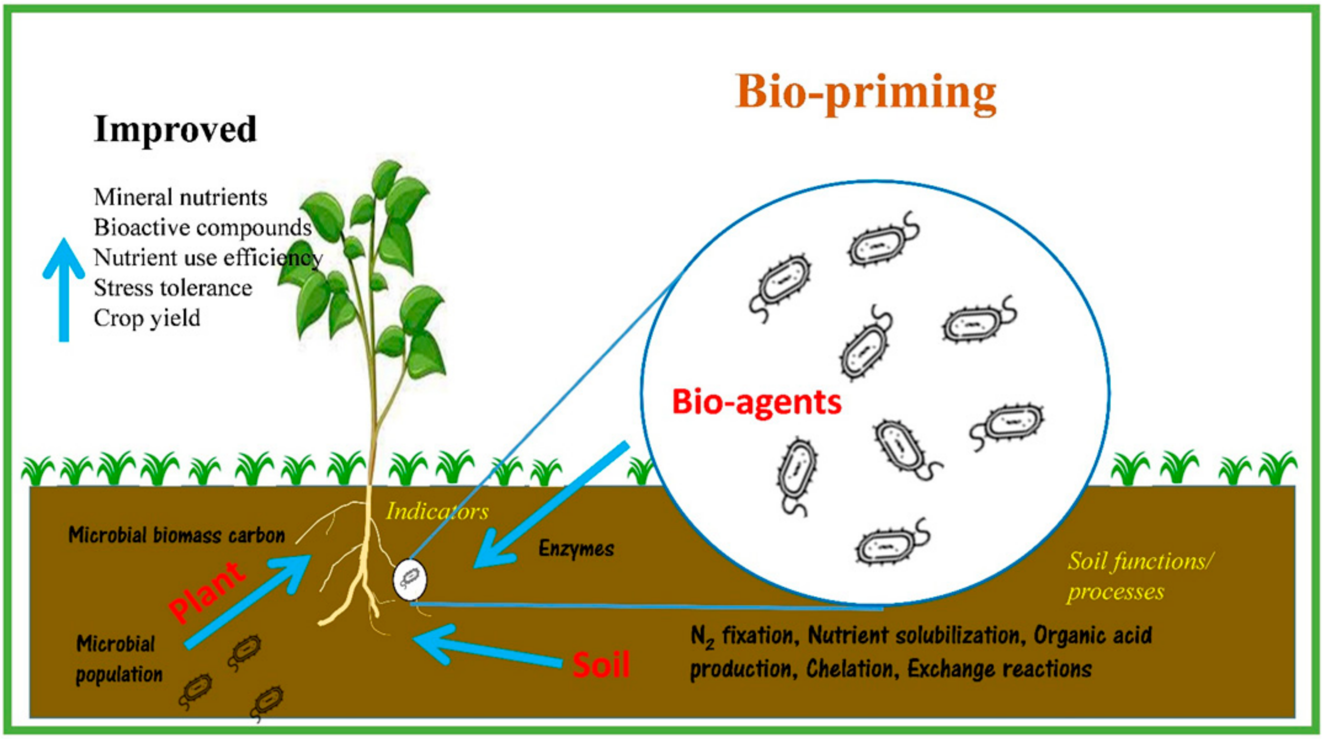

Figure 2. A conceptual model of bio-priming for soil health management.

6.2. Soil Fertility

Inefficient management of nutrients can also cause low fertility of the soil. An efficient integrated approach can contribute a lot toward improving the nutrient status of the soil. Narayanamma et al. [93] observed an increase in available NPK in postharvest soil of cauliflower with the application of biofertilizers. Soil fertility in cabbage growing soil of West Bengal was evaluated by Sur et al. [94] under INM practices. They found that the application of organic manure at 4 t/ha instead of 10 t/ha was sufficient to produce desirable effects in soil. Fertilization of NPK at 150:26:66 kg ha^{-1} + organic manure at 4 t/ha + Zn at 0.5 kg/ha increased the status of pH (7.56 to 7.60), organic carbon (0.80 to 0.96%), available N (398.70 to 400.86 kg/ha), and available K (354.98 to 358.22 kg/ha) during the two-year study period; a slight decrement was noted in available P (15.43 to 15.39 kg/ha). The treatment also enhanced the status of cationic micronutrients (e.g., Fe, Mn, Zn, and Cu) in the soil (new alluvial). *Bacillus megaterium*, when added with sugar beet residue, recorded an improvement in total organic carbon and N contents under *Lavandula dentata* L. (a small shrub) cultivation, by 39% and 38%, respectively [95]. Seed inoculation (*Pseudomonas plecoglossicida* and *Pantoeacypripedii*), along with RP fertilization, resulted in the increase of organic carbon (28 to 48%) and available P (86 to 147%) in wheat soil from the first year to the second year [74]. This might be due to enhanced microbial biomass carbon and the release of organic acids (Figure 2) for P solubilization or chelation of cations by acid groups (hydroxyl and carboxyl). Microbial consortium (*Bacillus subtilis* + *Bacillus* sp.), along with 100% chemical fertilizers (254 kg N/ha, 77 kg P_2O_5/ha, and 350 kg K_2O/ha), resulted in the highest available N (284.2 kg/ha), available P (50.4 kg/ha), and available K (285.8 kg/ha) in a capsicum field trial conducted in sandy loam soil of Solan, Himachal Pradesh [96]. Nutrient status under the integrated system of *B. subtilis* showed 272.1 kg N/ha, 48.3 kg P/ha, and 284.2 kg K/ha; *Bacillus* sp. recorded 273.9 kg N/ha, 48.7 kg P/ha, and 284.5 kg K/ha; and 100% NPK without microbes showed 255.7 kg N/ha, 43.6 kg P/ha, and 283.8 kg K/ha. Seed inoculation with PSB recorded higher organic C (5.0 g/kg), available N (252 kg/ha), available P (34.5 kg/ha), and available K (335 kg/ha) in postharvest soil of mustard (*Brassica juncea* L.) over uninoculated plots (4.5 g/kg, 250 kg/ha, 32.7 kg/ha, and 335 kg/ha, respectively) in sandy loam soil [pH 8.10, electrical conductivity (EC) 0.79 dS/m] of Udaipur located in Rajasthan [97]. The inoculated plots showed lower pH (7.71) and EC (0.41 dS/m) than uninoculated plots (pH 7.85, EC 0.43 dS/m). Sandy clay loam soil under the pearl millet-mustard system showed maximum available N (253 kg/ha) and P (32.3 kg/ha) status in 100% NPK + FYM + *Azotobacter* + PSB treatment, while removal of FYM from this management practice led to 206 kg N/ha and 27.1 kg P/ha [41]. The available P in calcareous soil of China increased by 7.21% in a Chinese cabbage field experiment due to inoculation of PSB (*B. cereus* YL6) [98]. Secretion organic acids and phosphatases by YL6 have dissolved the insoluble P in soil. Maize field studies including *B. subtilis* (10^7 cell density/mL) + 80% NP and 100% NPK (60 kg N ha^{-1}, 30 kg P_2O_5 ha^{-1}, and 20 kg K_2O/ha) + FYM recorded higher nutrient status (304.90 kg N/ha, 32.80 kg P/ha, and 334.12 kg K/ha) in the microbial treatment than the nonmicrobial treatment (271.71 kg N/ha, 26.40 kg P/ha, and 319.38 kg K/ha) applied in sandy loam soil of Solan [99].

7. Economics and Energy Approaches in Integrated Nutrient Management

Seed bio-priming is emerging as a common method of inoculation as soil application requires a higher proportion of bio-inoculants contradicting the economic profitability of the farming systems. The application of biofertilizers increased the benefit–cost ratio (B:C) from 1.95 to 2.96 in cauliflower cultivation [93]. *Bacillus mucilaginous*, applied as biological potassium fertilizer through seed coating method and a full dose of NP fertilizer, recorded higher net return in maize cultivation than application of full NPK and full NP [76]. Net returns in cauliflower–cauliflower–pea system followed the order of 100% NPKB + FYM (Rs 462883/ha/year) > 50% NPKB + FYM + Biofertilizers (Rs 213401/ha/year) > 50% NPKB + FYM (Rs 208253/ha/year) in on-farm trials of Himachal Pradesh [100]. Economic verification of the cabbage field trial in Pantnagar (Uttarakhand) recorded a higher B:C ratio and net benefit only in fertilization treatments; the insignificant contribution of FYM may be ascribed to poor decomposition rate in the winter season [101]. Target yield (250 q/ha) based fertilization gave a better economic response over general fertilizer recommendations. Although gross return and net return in soybean–potato cropping system was significantly higher in 100% recommended dose of P + biofertilizers (*Pseudomonas striata* + *Glomus fasciculatum*), net B:C ratio was significantly superior in both doses (50% and 100%) of recommended P applied through DAP [66].

Sustainable agriculture requires proficient management of energy inputs. Input–output energy efficiency in apple production was studied in Iran by Fadavi et al. [23]. Estimation of energy input (101,505 MJ/ha), energy productivity (0.23 MJ/ha), net energy (−56,320 MJ/ha), and output–input energy (0.44) revealed that the energy requirements in apple orchards were mostly from the indirect (71%) and nonrenewable (96.7%) sources, indicating the necessity of alternative energy resources for increasing the efficiency. Mihov and Tringovska [102] documented that biofertilizer application in greenhouse tomato cultivation augmented the total energy input (100.30 GJ/ha), total energy output (119.48 GJ/ha), energy productivity (0.99 kg/MJ), and energy output–input ratio (1.19) than the control or conventional fertilization (98.45 GJ/ha, 90.52 GJ/ha, 0.77 kg/MJ, and 0.92 kg/MJ, respectively). Wheat production in Iran generated total energy inputs of 47.08 GJ ha^{-1} or 47,078.50 MJ/ha, in which the contribution of chemical fertilizers is ~31.19% for energy equivalents of 14,653.67 MJ/ha and FYM is ~9.71% for energy equivalents of 4574.68 MJ/ha [103]. Calculation of total energy output and energy output–input ratio showed 92,785.56 MJ/ha and 1.97, respectively. The total energy input (2632.4 MJ/ha) in sesame production of north-central Nigeria is mainly generated by human labor (637.0 MJ/ha) and organic manure (555.0 MJ/ha) energy equivalents of 24.2% and 21.1%, respectively [104]. The energy output and use efficiency ratios were estimated as 13,750.0 MJ and 5.2, respectively. Energy saving of 970 to 1670 KJ was found in okra production with the adoption of bio-priming treatments using *T. harzianum* (NBRI 1055) in comparison to 100% chemical fertilizers consuming about 4320 KJ/unit [83]. Seed bio-priming, in combination with 70, 75, 80, and 90% chemical fertilizers, consumed 2650, 2840, 3005, and 3350 KJ energy/unit, respectively.

8. Nutrient Kinetics Involved in Integrated Nutrient Management

The utilization of mineral fertilizers, biofertilizers, manures, or composts is dependent on our understandings of the mineralization pattern of nutrients. Laboratory incubation experiments with kinetic models are common tools to study the mineralization–immobilization of a nutrient in cycles of soil. The total N mineralization was about 45–48% greater in integrated nutrient management involving NPK + FYM and organic nutrient management involving FYM + vermicompost + neem cake + ash + *Azospirillum* sp. + *Bacillus* sp. in comparison to chemical nutrient management [88]. Integrated addition of organic manures (compost, vermicompost), and NPK fertilizers resulted in higher C and N mineralization rates than soil amended with organic manures or treated with 100% chemical fertilizers [105]. Amino acids are considered as a potential plant-available N source [106]. Mineralization of C and N increased with the advancement of the incubation period, but the rate was higher only during the initial stages. The alluvial soil of New Delhi falling under the IGP showed greater mineralization of N as per the first-order exponential model when treated with RP-enriched composts in comparison to 100% NPK fertilizers [107]. Studying the mineralization or release capacity of soluble P fertilizers (single superphosphate, DAP) and insoluble RP, Abbasi et al. [75] found that the initial (0 days) P release of soluble P fertilizers was very high and mineralization over a period of 60 days recorded decrement of 73.3 to 13.5 mg P/kg in single superphosphate and 68.4 to 14.1 mg P/kg in DAP, and it remained around 6.2 mg P/kg in RP. No significant effect was noticed on P mineralization with the combination treatments of RP and soluble P fertilizers; however, the addition of PSB and RP released 9.8 mg P/kg, and the best result (24.2 mg P/kg) was found when poultry manure was added to the treatment (PSB + $\frac{1}{2}$ RP + $\frac{1}{2}$ poultry manure). Farm soil (clayey loam) of Nagaland showed an increase in available P status under incubation (90 days) with the addition of PSB (*B. polymyxa*) in conjunction with different P sources (single superphosphate, RP); nevertheless, the higher values were detected with RP [108]. Soil rhizobacteria play a significant role in nutrient uptake and promote plant growth [109–113]. Furthermore, biostimulants as foliar application reduce the fertilizer requirements in crops [114–118].

9. Conclusions

There is growing advocacy and interest in the use and popularity of bio-agents as a supplement within the framework of integrated plant nutrition systems apart from its added routine biotic stress moderation. Application of bio-inoculant as a primer is a well-demonstrated mechanism in synergizing a stimulus in the rhizosphere, which facilitates biochemical nutrient cycling, enzymology, and partitioning/translocating, which, in turn, improves crop performance under a changing climate regime. Being a pragmatic technology with indigenous competitive values, the farm validation under multilocational trials is going to be a gigantic task facing technical challenges in the feasibility and scaling up of this small intervention. Sensitization regarding the storage/viability of microbes is also another prerequisite for the success of this technology. Further, multidisciplinary research is required on the issues of consortium priming based on metagenomics studies and a wide range of suitability under variable climate and environment. These have been a renewed interest in the form of seed bio-priming as a supplement in integrated nutrient management possibly by the marriage of biology and chemistry, which will definitely trigger consistent and promising performance of crop under a wide array of conditions.

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