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Review

Ditching Phosphatic Fertilizers for Phosphate-Solubilizing Biofertilizers: A Step towards Sustainable Agriculture and Environmental Health

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Abstract: Chemical phosphatic fertilizers are mainly produced from phosphate rocks, a natural reserve that is depleting rapidly. These chemical phosphatic fertilizers are polluting the environment at an alarming rate as a result of injudicious application to farmlands. On the other hand, phosphate-solubilizing biofertilizers (PSBs) are often considered better alternatives to industrial phosphatic fertilizers in many ways. PSBs are microorganisms capable of solubilizing insoluble forms of phosphate into soluble plant-usable forms. This paper is written with the objective of discussing the impacts of phosphatic fertilizers and making the case for why we should shift to PSBs instead. Phosphatic fertilizers have numerous impacts on the environment (water bodies, land resources, and air), and micro- and macro-organisms, including humans. Chemical fertilizers also tend to be more expensive, especially for farmers in developing countries. On the contrary, PSBs tend to be safer and way more beneficial than their chemical counterparts in that they are environmentally friendly and cheaper options of availing plant-usable phosphorus. PSBs are also involved in other beneficial roles such as the production of phytohormones and secretion of anti-phytopathogenic metabolites. The phytohormones enhance plant growth and the metabolites render crops immunity against phytopathogens. Hence, it is vital to replace chemical phosphatic fertilizers with PSB inoculants both to prevent the irreversible impacts of chemical fertilizers and to take advantage of the numerous benefits of PSBs. Moreover, it does not seem as if there is an option given the fact that the global phosphate reserve is depleting and the impact of fertilizer on the environment is worsening as time goes by.

Keywords: PSB; environment; fertilizer; phosphate

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1. Introduction

The soil phosphorus content varies from 200 to 2000 kg ha^{-1} of the upper 15 cm of soil, with an average of about 1000 kg ha^{-1} [1]. Worldwide, 5.7 billion hectares of land contain very little available phosphorus for sustaining optimal crop production [2]. The air is 78% nitrogenous gas, which can be biologically available to plants, but we cannot say the same for phosphorus [3]. Phosphorus can naturally be found in the soil only in insoluble forms: insoluble inorganic phosphorus and insoluble organic phosphorus. Unfortunately, crop roots absorb phosphorus in their soluble forms only, mainly as $H_2PO_4^-$ and HPO_4^{2-} depending upon soil pH [4]. Consequently, only a small fraction (1 ppm or 0.1%) of soil phosphorus is readily available to plants. By contrast, the total phosphorus level of soils is no more than one-tenth to one-fourth of nitrogen, and one-twentieth of potassium [5].

Regardless, as a consequence of continuous applications of excessive phosphatic fertilizers, most agricultural soils generally contain massive reserves of accumulated insoluble phosphorus [6]. Soon after the application of chemical phosphatic fertilizer or manure phosphate, it comes in contact with the soil and a series of reactions take place. This makes the large portion of the inorganic phosphate applied less soluble and less available to crops [7]. In acid soils, phosphorus becomes less available by forming a complex with aluminum (Al) or iron (Fe) or with calcium (Ca) in calcareous soils [8]. Consequently, most agricultural soils have large accumulation of phosphorus, which plants cannot use, as the greater part of it (95 to 99%) is present in the form of insoluble phosphates [9].

These accumulated phosphates in agricultural soils are estimated to be sufficient to sustain maximum crop production worldwide for at least a century [10]. However, instead of coming up with ways to utilize these reserves, chemical fertilizers are still vastly produced and used worldwide to satisfy the phosphorous needs of the agriculture sector [11]. On top of that, as fertilizer production is dependent upon fossil energy sources, continuous use of chemical fertilizers has become a matter of great concern, not only because of the diminishing availability of costly inputs but also due to environmental health concerns.

This has led to the search for environment-friendly and economically feasible alternative strategies for improving crop production and sustaining the environment. In light of this, the subject of mineral phosphate solubilization by phosphate solubilizing biofertilizers (PSBs) are brought to the forefront to reduce the production and use of chemical fertilizers. Biofertilizers are strains of living microbes that are applied to seeds or soils to increase the mobility and availability of plant usable nutrients [12,13]. PSB is one of such biofertilizers capable of solubilizing insoluble forms of phosphorus into a soluble form that the plants can use. PSB could be phosphate-solubilizing bacteria (PSBa), phosphate-solubilizing fungi (PSF), or phosphate-solubilizing algae (PSA) [13].

Emphasis is, therefore, being placed on the possibility of greater utilization of unavailable soil phosphorus wherein PSB could play a pivotal role in availing insoluble phosphorus to plants [14]. In addition to providing phosphorus to the plants, PSB is also known to augment the growth of plants by stimulating the efficiency of biological nitrogen fixation and enhancing the availability of other trace elements [14,15]. Thus, this paper aims at discussing the benefits of using PSB and the impacts of chemical phosphate fertilizers to stress the need for making a transition.

2. Why Ditch Phosphatic Fertilizers?

The massive production and utilization of industrial phosphatic fertilizers and large accumulation of inorganic phosphates in agricultural soils poses a variety of problems against the environment, economy, and human and animal health. Some of these multidirectional (direct and indirect) threats of chemical phosphatic fertilizers are discussed in the following sections. This is to make the case against the use of chemical fertilizers in general or phosphatic fertilizers in particular.

2.1. The Impact of Phosphatic Fertilizer on Water Bodies and Land Resources

The prominent impact of phosphatic fertilizers on the environment comes in the form of eutrophication [15]. Eutrophication is the pollution of surface water as a result of leaching of agricultural fertilizers, farmyard manures, and discharge of treated and untreated municipal sewage containing phosphates and nitrogen into water bodies [16,17]. When fertilizers such as phosphorus are leached into water bodies they result in increased aquatic plant and algal growth, oxygen depletion, pH variability and disruption of the food chain [18,19].

This in turn leads to decreased water clarity, potent algal toxins, death of desirable fish species, clogging of water treatment plant filters, bad taste, and odor problems. This would cause the water to be unusable for recreation, navigation, fishing, drinking, or any other purposes for that matter [20,21]. One of the most famous examples of eutrophication is "the great stink" of London in 1958 [22]. It was so famous because the extreme smell of the high nitrogen- and phosphate-containing human wastes and industrial discharges floating over the river Thames went on to disrupt the British parliament.

The range of phosphorus concentrations that cause eutrophication is between 0.01 to 0.03 mg L^{-1} [23]. However, far higher concentrations of phosphorus were frequently reported in ground and surface waters around the world. Application of excessive phosphorus containing chemical fertilizer and manure into agricultural lands in India led to very high concentrations of phosphates. The phosphate content mounted up to 4.23 mg L^{-1}, 3.89 mg L^{-1}, 6.7 mg L^{-1} in groundwater, lake, and channel waters, respectively [24]. Phosphorus in drainage water in southern Florida has contributed to the accelerated eutrophication of lakes and water conservations as it carries with it a total phosphorus concentration ranging between 0.25 mg L^{-1} and 1.03 mg L^{-1} [25]. However, the contribution of the agriculture sector (chemical phosphatic fertilizers) as a phosphorus source for eutrophication in developed countries seems to be smaller compared to other sectors. For instance, of the total 60 kt yr^{-1} phosphorus load to Great Britain waters, households contributed 73% of it, whereas the share of agriculture was only 20% [26].

Mitigating algal blooms and other symptoms of eutrophication and its devastating impact on the environment depends primarily on reducing inputs of phosphorus more than any other nutrient [27,28]. To achieve this this, we have to look for ways to reduce the excessive chemical phosphatic fertilizers that go into farmlands. However, this should be carried out thoughtfully without causing significant crop yield loss or even with the objective of increasing yield. This is where PSBs come in to save the day.

Activities related to phosphatic fertilizer production is also known to cause land degradation. For instance, in China, around 475 km^2 of land was occupied for phosphate mining without reclamation [29]. Nearly 110 Teragram (Tg) phosphogypsum was dumped and 1.8 billion m^3 of groundwater was used annually in the processing of phosphate rock (PR) and the wastewater was discharged without treatment [29].

The range of environmentally hazardous metalloids such as Cd, Pb, Hg, U, Cr, and As, among others, contained in superphosphates and RP leave soils toxic and uncultivable over time, as they tend to last long in the soil [30]. Since most of the heavy metals are non-essential to plants, they become toxic and suppress growth, yield, and physiological functions of crop plants upon uptake [31]. Heavy metal pollution of soil and air decreased the fresh herbage and essential oil yields of mint plant by 9–16% and 14%, respectively [32]. Soil pollution by heavy metals such as Cd, Pb, and Ni has been shown to affect tomato crop yield, chlorophyll and carotene content, as well as soil fertility [33]. Heavy metals have also been shown to affect the distribution, diversity, and activities of agriculturally important microorganisms including *Proteobacteria*, *Firmicutes*, and arbuscular mycorrhizal fungi (AMF) [34–36]. Thus, heavy metal residues from the phosphatic fertilizer and other industries compromise the fertility of the soil and turn it completely uncultivable overtime.

2.2. Health Hazards of Phosphatic Fertilizer Processing

Activities related to phosphatic fertilizer production including RP mining, processing, and using phosphatic fertilizers containing natural radioactive elements pose a threat to the public wellbeing [37]. Many studies worldwide have been carried out to assess the risk of the phosphorus industry to humans and the environment. Most of these studies considered radon gas to be the most significant hazard to workers and the public in the mining areas and phosphatic fertilizer factories. This is mainly because the radiation dose due to inhalation of radon daughters can be relatively high [38–40]. For instance, elevated levels of radio activity and relatively higher concentrations of ^{210}Po and ^{210}Pb in soils, plants, and surface waters were found in the vicinities of phosphate mines, processing factories, and export facilities in Syria [41]. This elevated levels of both ^{210}Po and ^{210}Pb in the area resulted from the decay of radon gas present in phosphate ores. In another study in the Safaga Quusein region on the Red Sea, relatively high levels of ^{226}Ra, ^{238}U, ^{210}Po, and ^{210}Pb were reported in areas involved in phosphate mining activities [42]. Air emissions (gaseous and particulates) from a PR processing plant in the Thessaloniki area of northern Greece have resulted in collective dose commitment to the lung tissue of 2 x 10^{-9} person Gy y^{-1} for ^{238}U [43]. Cattle and other animals also die upon consumption of water contaminated by algal toxins caused by wastes released by phosphate factories and this inflicts economic losses to the farmers [44].

The varying level of innate cadmium contained in PR, which is transferred to phosphatic fertilizer products during the manufacturing process causes kidney disease, "Itai-Itai'" and other adverse effects [45]. Ingestion of cereals produced on soils loaded with heavy metals from such industries have been shown to cause carcinogenic and non-carcinogenic risks to humans [46]. Generally, nearly 16 elements, potentially hazardous to human health, were found associated with PR and fertilizers [47].

2.3. The Global Hike in Phosphatic Fertilizer Prices

Depletion of PR resources and quality phosphatic reserves has led to an increase in the price of phosphatic fertilizers. Fertilizer production was insufficient during the years 2007–2008 due to the increase in world agriculture, which led to a big rise in demand for phosphate-derived fertilizers [48]. The price in USD in 2008 increased about 800% more than in 2007. This is partly due to the growing demand for phosphatic fertilizers for crop production and from other sectors [49].

According to the world bank, the price of phosphatic fertilizers has drastically increased by 92.6% just between 2017 (89.69 USD mt^{-1}) and the present, 2022 (172.82 USD mt^{-1}) (Figure 1). The rise in the price even mounts up to 292.7% when the trend between the year 2000 (44 USD mt^{-1}) and 2022 is taken into consideration [50]. This dramatic increase in phosphatic fertilizer price is attributable to the increasing costs of production and has its implications on the rising cost of crop production, and hence world food prices [51].

Figure 1. Global trends in phosphatic fertilizer prices 2017–2022 [50].

The Ukraine–Russia war has introduced another era of fertilizer price hike, making the fertilizer price difference before and after the war ridiculous [52]. This is mainly because Russia and Ukraine are among the top global producers of agricultural commodities including fertilizers. The effect of the war on fertilizer prices is more pronounced on farmers from developing countries in particular. For instance, a quintal of DAP (diammonium phosphate) fertilizer in Ethiopia had a price tag of USD 32.69 (1700 ETB) in the early months of 2022; now, it has almost tripled to USD 86.53 (4500 ETB) [53]. The retail price of NPK fertilizer in Gambia and Senegal more than doubled in the first quarter of 2022 regardless of government subsidies [54].

Such increase in fertilizer price causes adverse effects on farmers and consumers, making chemical fertilizers unaffordable. Such sudden shift and incline in price is a warning sign that a dreadful disruptions in fertilizer markets could occur in the future [55]. Numerous studies also confirm that the volatility of fertilizer prices has moved into a new, high-price regime. Improved nutrient use efficiency of crops and the introduction of new technology for enhanced nutrient recycling from different sources can set up the solution to the high-price issues [51,55]. Therefore, to afford and overcome the demand issues and prevent the environmental catastrophes from phosphatic fertilizers, the time has come to think of other alternatives. This alternative should focus on efficient management of phosphorus resources and ways to supply crops with usable phosphorus through PSB.

2.4. Depletion of Global Phosphate Rock Reserve

Even if we ignore the impacts and drawbacks of using chemical phosphatic fertilizers and decide to go on with business as usual, that will not be an option, as the global PR reserves are depleting. The terms PR reserve and PR resource are of particular importance when discussing the production and the future of chemical phosphatic fertilizers. A PR reserve is a PR that can be economically produced at the time of the determination using existing technology. On the other hand, a PR resource is a PR of any grade that may be produced at some time in the future [56]. Scientists have warned about future phosphate scarcity for decades if not centuries. Meadows [57] suggested that certain resources including PR are in finite supply on planet earth and that one day they could be depleted. The global PR reserves would probably last until only two generations from now; it would begin to run out within the coming 75–100 years and be completely exhausted by the end of the 22nd century [58].

According to United States geological survey studies (USGSS), Morocco and the West Sahara (WS) region possess the world's largest PR reserves, around 50 billion tones (t). This accounts for 70% of the total global share and 15.92% (35.5 million t) PR mine production per annum. China follows distantly with a total PR reserve of 3.2 billion mt (4.51%). However, it is the leading phosphate-producing country globally, with an annual production of 95 million t (42.6% of the total annual production). Around 91% of the planet's known PR reserves are found in ten countries only (Morocco and WS, China, Egypt, Algeria, Syria, Brazil, South Africa, and Saudi Arabia) (Table 1). Thus, looking into the trends of PR reserves in these countries past and present is one way of getting an insight into the current global status of PR reserves. Sadly, numerous studies through time have reported the depletion of the PR reserves in these countries and the need to conserve and use them in a sustainable way [59,60].

Table 1. Global phosphate rock reserves and production status.

Country/Region	Reserve		Mine Production			
			2019		2020 estimation	
	Billion t	Global Share (%)	Million t	Global Share (%)	Million t	Global Share (%)
Morocco and WS	50	70.42	35.5	15.92	37	16.30
China	3.2	4.51	95	42.60	90	39.65
Egypt	2.8	3.94	5	2.24	5	2.20
Algeria	2.2	3.10	1.3	0.58	1.3	0.57
Syria	1.8	2.54	2	0.90	0.36	0.16
Brazil	1.6	2.25	4.7	2.11	5.5	2.42
South Africa	1.4	1.97	2.1	0.94	2.1	0.93
Saudi Arabia	1.4	1.97	6.5	2.91	6.5	2.86
Australia	1.1	1.55	2.7	1.21	2.7	1.19
United States	1	1.41	23.3	10.45	24	10.57
Finland	1	1.41	0.995	0.45	1	0.44
Jordan	0.8	1.13	9.22	4.13	9.2	4.05
Russia	0.6	0.85	13.1	5.87	13	5.73
Kazakhstan	0.26	0.37	1.5	0.67	1.5	0.66
Peru	0.21	0.30	4	1.79	4	1.76
Uzbekistan	0.1	0.14	0.9	0.40	0.9	0.40
Tunisia	0.1	0.14	4.11	1.84	4	1.76
Israel	0.057	0.08	2.81	1.26	2.8	1.23
Senegal	0.05	0.07	3.42	1.53	3.5	1.54
India	0.046	0.06	1.48	0.66	1.5	0.66
Vietnam	0.03	0.04	4.65	2.09	4.7	2.07
Togo	0.03	0.04	0.8	0.36	0.8	0.35
Mexico	0.03	0.04	0.558	0.25	0.6	0.26
Other countries	0.84	1.18	1.14	0.51	1.1	0.48
World (total)	71		223		227	

USGSS (United States Geological Survey Services).

Global consumption of phosphate fertilizers and industrial uses is projected to increase to 49 million tons in 2024 from 47 million tons in 2020 [61]. In another prediction back in 2009, the world production is expected to reach a peak around the year 2033 with an annual production of 203 Mt of phosphatic fertilizers [62]. On top of this, PR use efficiency in fertilizer production is very poor across the different countries possessing high PR reserves and leading phosphatic fertilizer producers. For instance, a study found that the PR utilizing efficiency is very low in China, i.e., from every 10 kg phosphorus in PR material, only 3.9 kg phosphorus was used to produce fertilizer, 5.6 kg of the residues were discarded at the mining site, and 0.5 kg was manufacturing waste [29]. Similar trend was observed in other top phosphatic fertilizer-producing countries [63].

Such hikes in phosphatic fertilizer demand and poor PR utilization efficiency are leading to further depletion of PR resources and reserves. Consequently, it is very crucial to make a transition from production and utilization of industrial phosphatic fertilizers towards other sustainable alternatives. A shift, primarily towards phosphate solubilization by PSB, would help in sustaining our PR reserve, the environment, agriculture, and food production.

3. Phosphate Solubilizing Biofertilizers

PSBs are microorganisms capable of converting the insoluble phosphatic compounds—including, but not restricted to $AlPO_4$, $FePO_4$, and $Ca_3(PO_4)_2$—into soluble forms such as HPO_4^{2-} and $H_2PO_4^-$ [9,64]. The role of rhizospheric microorganisms in mineral phosphate solubilization was known as early as 1903 [65]. Since then, there have been extensive studies on mineral phosphate solubilization by naturally abundant rhizospheric microorganisms. Important PSBa genera include *Bacillus*, *Pseudomonas*, and *Micrococcus* [66]. On the other hand, *Aspergillus* and *Penicillium* are the prominent fungal genera capable of solubilizing phosphate [67]. The nematophagous fungus *Arthrobotrys oligospora* was also tested positive in vitro and in vivo for its ability to solubilize different types of rock phosphate [68].

PSBs can be detected and isolated upon incubation on solid plates containing insoluble phosphate, as they form clear halo zones around their colonies [69]. Most of the strains of PSB exhibit variation with regard to their phosphate-solubilizing activity. Therefore, they are repeatedly sub-cultured to test the persistence of their phosphate-solubilizing potential [66,70]. Once the efficient PSBs are selected, they are tested for their ability to solubilize insoluble phosphate under a liquid culture medium. Finally, the selected efficient PSB cultures are used for making the inoculants and their performance under pot/field conditions is tested. Furthermore, the microbial inoculants are passed through biosafety tests in order to avoid human, animal, and environmental health risks before being released as biofertilizers.

PSB is ubiquitous, whose number may vary from soil to soil. PSB can be found in rhizosphere, the rhizoplane, and also in other environments, such as rock phosphate deposit area and marine environments [71]. In soil, PSBa constitutes 1–50% and PSF accounts for 0.5–0.1% of the total respective population [72]. Generally, in the soil PSBa outnumbers PSF by 2–150 times [73]. The highest proportion of PSBa is concentrated in the rhizosphere and is known to be more metabolically active than those isolated from sources other than the rhizosphere [74]. Conversely, the salt-, pH-, and temperature-tolerant PSBa have been reported to be maximum in the rhizoplane followed by the rhizosphere and root free soil in alkaline soils [75].

A wide range of both bacterial and fungal genera have been revealed to contain several strains with a proven phosphate solubilization activity. The genera containing the prominent PSBa population such as *Chloroflexi*, *Proteobacteria*, *Actinobacteria*, and *Acidobacteria* were found to be dominant in Vietnamese soil [76]. Gene sequencing results of isolates of PSBa revealed that genera belonging to the phylum actinobacteria (such as *Streptomyces*, *Microbacterium*, *Angustibacter*, *Kocuria*, *Isoptericola*, and *Agromyces*) dominate Indian soil [77]. *Mycobacterium* strains were also revealed to be effective phosphate solubilizers and plant growth promotors [78]. The PSBa *Bacillus cereus* and *Vagococcus carniphilus* belonging to the phylum firmicutes were isolated and proved effective for the task [79]. Bacterial strains belonging to the genera *Cyanobacterium*, *Westiellopsis*, and *Anabaena* were shown to be efficient extracellular mineral phosphate solubilizers [80,81]. Filamentous fungi and yeast strains, mainly *Penicillium* and *Aspergillus*, are among the most dealt fungal phosphate solubilizers [82]. Different strains of yeast including *Geotrichum capitatum*, *Geotrichum candidum*, and *Rhodotorula minuta* have also demonstrated a varying level of phosphate solubilization activity [83].

Distribution and activity of PSB is affected by similar factors affecting any other soil microbial communities including soil pH, aeration, salinity, heavy metals, temperature, moisture content, concentration of iron ore, and C and N sources [72,84]. The distribution and diversity of PSBa have been shown to be highly influenced by soil physiochemical properties. The abundance of PSBa belonging to the phyla Acidobacteria, Firmicutes, and Planctomycetes were positively correlated with silt content and total soil nitrogen, whereas strains belonging to Proteobacteria had negative relationship with sand content [76]. Heavy metals also affect the survival and activity of PSB, hence initiating the need for screening heavy metal tolerant PSB strains. For instance, forty uranium tolerant PSBa falling under three phyla, Firmicutes, Proteobacteria, and Actinobacteria were isolated from polluted soils [85]. However, most of all soil/media pH seems to be the most important factor influencing microbial phosphate solubilization activity, especially that of PSBa [86]. Regardless of all these factors, studies have reported presence of effective PSB in the soils of almost every corner of the world (Table 2).

Table 2. Reports of isolation and characterization of effective PSB around the globe.

Genera of Isolated PSB	Type of PSB	Area/Region	Target Crop/ Rhizosphere	Number of Strains Isolated	Reference
Pseudomonas	PSBa	Cameroon/Africa	palm tree	3	Fankem, et al. [7]
Actinomyces	PSBa	Egypt/Africa	Wheat, faba bean and clover	9	Faried, et al. [87]
Trichosporon, *Rhodotorula*, *Cryptococcus*, *Zygoascus*, *Penicillium*, *Neosartorya*, *Candida*	PSF	Ethiopia/Africa	Teff	7	Gizaw, et al. [88]
Bacillus, *Brevibacterium*, *Arthrobacter*, *Fictibacillus*	PSBa	Kenya/Africa	-	34	Wafula, et al. [89]
Bacillus, *Staphylococcus*, *Microbacterium*, *Burkholderia*	PSBa	Senegal/Africa	-	12	Christian, et al. [90]
Talaromyces, *Aspergillus*	PSF	China/Asia	Bamboo	2	Zhang, et al. [91]
Pantoea, *Burkholderia*	PSBa	S. Korea/Asia	Tomato	2	Walpola and Yoon [92]
Aspergillus	PSF	India/Asia	Mangrove plants	2	Arulselvi, et al. [93]
Rhizobium	PSBa	Iran/Asia	-	198	Alikhani, et al. [94]
Aspergillus, *Penicillium*, *Talaromyces*	PSF	Japan/Asia	-	16	Islam, et al. [95]
Enterobacter, *Klebsiella*	PSBa	Colombia/S. America	Radish	2	Lara, et al. [91]
Fusarium, *Aspergillus*	PSF	Brazil/ S. America	-	2	Matias, et al. [96]
Serratia, *Pseudomonas*	PSBa	Turkiye/Europe	Maize	2	Ateş, et al. [97]
Entrobacter, *Borkholderia*, *Arthrobacter*, *Beijerinckia*, *curtobacterium*	PSBa	USA/N. America	Soybean	20	Alice, et al. [98]

4. So Why Shift to Phosphate Solubilizing Biofertilizers?

Many arguments can be made to support the idea of transitioning from chemical phosphatic fertilizers towards PSBs. These would include the obvious sustainable phosphate solubilization using PSB and its other concomitant benefits discussed below.

4.1. The Role of PSB in Cutting Crop P-Fertilizer Requirements

The PSBs have been proved to be economically sound alternative to the more expensive and environmentally pollutant chemical fertilizers and possess a greater agronomic utility [65,99]. Inoculation with PSB has been shown to increase the efficiency of different forms of both inorganic and organic fertilizers. PSBa increased the available phosphorus from the organic fertilizer olive residue and manure by 97.8% (28.3 mg kg^{-1}) and 3.5% (35.14 mg kg^{-1}), respectively [64]. This is compared to sole application of olive residue (14.31 mg kg^{-1}) and organic manure (33.96 mg kg^{-1}). Well, this reveals that PSB inoculation can reduce the amount of manure going out to farmlands, thereby preventing its impact on the environment. Though they most often ignored and the focuses are mainly on chemical fertilizers, manures are one of the prominent contributors to the greenhouse gas methane [100,101].

Bacillus FS-3 and *Aspergillus FS9* inoculation resulted in phosphatic fertilizer savings of up to 149 kg P ha^{-1} and 102 kg P ha^{-1}, respectively, for the same amount of strawberry fruit yield gained when 200kg P ha^{-1} was applied [102]. This shows how PSBa inoculation increases the efficiency of inorganic fertilizer, leading to a reduced fertilizer requirement and its subsequent impacts on the environment [103,104]. The same study revealed that inoculation of *Bacillus FS-3* increased phosphorus uptake and promoted the uptake and concentration of other nutrients including N, K, Ca, and Fe in strawberry fruits and leaves. Thus, PSBa could actually play a role in reducing the requirement of chemical N, k, Ca, and Fe fertilizers as well [102].

Wang et al. [105] studied the role of different plant growth-promoting rhizobacteria (PGPR) (P-solubilizers, K-solubilizers, and N-fixers) in reducing chemical fertilizer doses commonly used by farmers on wheat. No significant difference was found in soil available N, P, K, as well as N, P, K uptake by the plant between PGPR combination +75% fertilizer and 100% fertilizer without PGPR. This shows that although the efficacy of it may depend on numerous other environmental factors, inoculation of PGPR projecting phosphate solubilizing ability plays a role in cutting crop fertilizer requirement.

Co-inoculation of PSB has also been shown to reduce chemical phosphorus application by 50% without any significant reduction in the grain yield of maize [106]. Wheat grain yields failed to significantly differ when supplied with different strains of PSBa with and without calcium phosphate fertilizer [107]. This implicates the possibility of avoiding the chemical fertilizer 100%. Here, it all comes down to a choice of whether to use the phosphatic fertilizer or PSB as both fertilizer options had a statistically equal effect on most of the growth parameters of the wheat crop. Well, all this implies that PSB could partly or fully replace chemical phosphatic fertilizers in promoting growth and yield of crops. Unlike chemical phosphatic fertilizers, PSB also plays a role in boosting the uptake of other important plant nutrients.

4.2. PSB as Phytohormone Producers

Phytohormones are organic compounds that are produced at one part of the plant and move to other parts causing physiological responses, such as growth [108]. Most PSBs have been shown to also possess the ability to produce growth-promoting hormones such as indole acetic acid [109], cytokinin, and gibberellins [110]. The PSBa strain *Bacillus tequilensis* has been reported to secrete plant growth hormones such as abscisic acid, auxin, and gibberellins (GA1, GA3, GA5, GA18, and GA19), and its inoculation on soybean improved shoot biomass, leaf structure, and photosynthetic pigment under heat stress [111]. Many strains of PSBa under the bacterial genus *Pseudomonas* were shown produce phytohormones such as indole acetic acid [109] and gibberellins [112]. Reduction in the level of abscisic acid, as well as an increment in the jasmonic acid and salicylic acid content in the rhizosphere were reported as a result of PSB inoculation [113].

The prominent phytohormone produced most frequently by PGPRs including PSB is IAA. Numerous bacterial genera such as *Pseudomonas*, *Mycobacterium*, *rhizobium*, and *Bacillus* uphold the ability to produce IAA. IAA influences numerous processes of the host plant ranging from phytostimulation to pathogenesis [114]. Enhancement in seed germination and physiomorphological changes have been reported in the orchids that were treated with IAA-producing PGPRs such as *Azospirillum brasilense* and *Bradyrhizobium japonicum* [115]. PSBa isolated from aerobic rice grown in Penang Malaysia was able to produce IAA [116]. The same study revealed that PSB with IAA-producing abilities applied as biofertilizers has elevated root expansion through lateral and adventitious root formation, thereby increasing surface area for increased uptake of nutrients and water. Apart from regulating cellular processes, IAA also stimulates vascular bundle formation and nodule formation [117]. All this shows the contribution of PSBs not just as soluble phosphate providers but also as growth promoters through the probable production of phytohormones, something chemical phosphatic fertilizers cannot do, of course.

4.3. PSB as Biocontrol against Plant Pathogens

In addition to their role in availing soluble phosphorus to crops and phytohormone synthesis, most PSBs have been shown possess lethal features against several soilborne pathogens. The prominent mechanism through which PSBs do so is by secretion of metabolites such as siderophores, lytic enzymes, and the production of acids (HCN and other organic acids). These acids possess the ability to suppress the growth and survival of various phytopathogens [118,119].

Siderophores are secondary metabolites that have low molecular weight (<10 KD), produced and utilized by bacteria and fungi in iron (Fe) acquisition and as biocontrol agents [119,120]. They are produced in response to iron deficiency that normally occurs in neutral-to-alkaline pH soils [121]. The mechanism behind the suppression of fungal pathogens by PSBa is through the production and release of siderophores that compete for and deprive the fungus of the essential iron needed for its survival and reproduction.

Lytic enzymes produced by PSBa serves as biocontrol by attacking pathogen cell walls at different levels of its growth and development by excreting cell wall hydrolases [122,123]. *Bacillus* is one of the prominent PSBa capable of producing numerous lytic enzymes including amylase, esterase, lipase, protease, cellulase, pectinase, chitinase, gluconase, protease, and chitosanase, which were shown to be highly effective against different phytopathogenic fungi [124]. Two strains of *Bacillus*, *B. mojavensis* and *B. thuringiensis* were shown to be effective in inhibition of biomass (30.4%) and spore germination (33.1%) of the fungus *Aspergillus niger* through the production of chitinase and protease [125].

The simultaneous role of several other bacteria and fungi, as both phosphate solubilizers and biological controls against various plant pathogens, is further reviewed and discussed in Vassilev et al. [126]. All this shows that PSBs can play a role in averting the adverse impacts of chemical pesticides applied as a control against various pathogens, on soil fertility, human health, and the environment. This implies that PSBs do not only protect the environment from pollution by chemical fertilizers, but pesticides too, a role which is very crucial to sustainable agriculture and the environment.

4.4. PSB as Crop Abiotic Stress Reliefers

Inoculating plants with PSBs has become a subject of interest, especially when it comes to dealing with varying abiotic stresses including, drought, salinity, metal toxicity, etc., in this era of climate change [127–129]. The mechanisms by which PSBs help plants overcome such stress include, but are not limited to, the production of phytohormones, improvement of nutrient uptake, initiation of osmolytes and antioxidant build up, downregulation or upregulation of stress-responsive genes, and enhancement of root morphology [130]. Addition of PSBa to the soil significantly enhanced the immobilization rate of Pb and Cd from 69.95 to 80.76% and from 28.38 to 30.81%, respectively, thereby removing heavy metal toxicity [131]. Jiang et al. [132] isolated six PSBa isolates that can grow under saline conditions of up to 1.5 M NaCl with a potential to be used as bioinoculants to protect plants against salt stress.

Inoculation of the plant *Quercus brantii* with two strains of PSBa (*Microbacterium* sp. (M.) and *Streptomyces* sp.), individually and in combination, significantly enhanced growth and physiological traits of seedlings under a water-stressed condition [133]. Inoculation of PSBa were shown to improve physiological parameters of tomato crop including the proline, protein, chlorophyll, and relative water content under water stressed condition [134].

Inoculation of foxtail millet with the strains *Acinetobacter calcoaceticus* and *Penicillium* sp. efficiently ameliorated the adverse effects of drought on the crop by enhancing accumulation of glycine betaine sugars and decreasing lipid peroxidation [135]. Yield and several yield related parameters of green mung crop were also improved as a result of inoculation with the PSBa strain *Bacillus polymixa* under drought stress [136].

5. Conclusions and Prospects

Our environment, including the land, air, soils, and water bodies, are becoming polluted with chemicals from different sectors, especially industry and agriculture. This situation is not showing any sign of slowing down or betterment. Pollutants in the forms of chemical phosphatic fertilizers can be regarded as both industrial and agricultural in origin, as they are produced in factories and utilized on farms. Hence, it is important to reduce both the production of chemical fertilizers in industries and the amount applied on farmlands in order to tackle the environmental (eutrophication, land degradation, and air pollution) and human health hazards. To achieve this, the focus must be pointed towards ways of enhancing crop phosphorus use efficiency and facilitating the uptake of the huge amount of accumulated insoluble phosphorus by plants. Doing so helps to reduce:

✓ The amount of phosphatic fertilizers needed to be applied to the farmlands;
✓ The purchase of chemical phosphatic fertilizers, especially helping farmers in developing countries;
✓ The extent of the phosphates that leaches to the water, causing eutrophication and health hazards to both micro- and macroorganisms, including human beings;
✓ Industrial phosphatic fertilizer production leading to conservation of PR reserves and prevention of the environmental catastrophe.

Although it is important to explore as many alternatives as possible, the principal aim of studies on this matter should be targeted at manipulation of PSBs in every way possible in order to maximize their efficiency. This is because PSBs provide crops beyond phosphorus, as some of them possess important features such as conferring crop protection against pathogens and promoting overall growth and internal functions. It is evident that PSBs do not only protect the environment from the impacts of chemical fertilizers, but also from even more hazardous chemicals such as pesticides. Consequently, it is important to study the various aspects of PSB extensively, not just to replace chemical phosphatic fertilizers but also to harness the associated multiple benefits that contributes to sustainable agriculture and environmental health.

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